Infrastructure for sustainable development

Daniel Adshead

School of Geography and the Environment

Linacre College

University of Oxford



A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Trinity Term 2020

Abstract

The long-term planning of infrastructure systems will be crucial in the quest for sustainable global development given the role it can play in achieving a wide range of social, economic, and environmental outcomes. While there is an increasing body of research addressing the need for global investment in infrastructure, there remains a gap in aligning the infrastructure planning process with performance outcomes defined by the global development agendas: the Sustainable Development Goals (SDGs) and the Paris Agreement on climate change.

This thesis develops an interdependent modelling approach for national infrastructure that links specific investments and policies to progress toward development and climate targets. As part of this approach, a robust indicator set aligned with the SDGs is developed. In addition, a systematic process to define infrastructure portfolios – or 'strategies' – to meet desired outcomes, is outlined. Two country case studies are used to demonstrate and apply these methods in the context of addressing key development challenges. In the first, a 28 percent decline in average SDG achievement across infrastructure-linked targets by 2030 is estimated in the absence of interventions in the energy, water, wastewater, and solid waste sectors. In the second, a feasible path to achieve SDG and Paris targets is demonstrated using a portfolio of strategic interventions in these four sectors, arrived at through an interdependent planning process drawing on participatory methods.

Furthermore, at the global scale, a means of aligning mitigation action in infrastructure and land use sectors – defined by each country's Nationally-Determined Contributions – with a range of development outcomes defined by the SDGs is developed, illustrating the contextual

approach required for national infrastructure planning. This is particularly relevant given the lack of quantified ambition in the current commitments of the 195 signatories to the agreement: 23 percent of countries report no quantified sectoral targets across the energy, transport, waste, agriculture, and forestry sectors, and a further 16 percent define only qualitative targets.

The studies contained in this thesis contain important insights for infrastructure researchers, practitioners, and decision-makers in national governments as we mark ten years, or the 'decade of delivery' in which extensive progress toward sustainable development outcomes must be achieved.

Acknowledgements

Firstly, I would like to express my appreciation to my supervisor, Professor Jim Hall, for providing me the opportunity to take on this challenge and for offering direction and advice throughout the course of my thesis. I am also very grateful to Dr. Scott Thacker for his guidance and friendship over the last four years and for dedicating much time and energy toward my research. I extend my thanks to Professor Nick Eyre, Dr. Dustin Garrick, and Dr. Alex Money for their helpful feedback during earlier assessments of this thesis.

I am very fortunate to have been a part of the Infrastructure Transitions Research Consortium (ITRC) and to have had the chance to interact with many impressive and accomplished researchers around the UK and in other countries. Many ITRC team members provided me with technical help or general advice along the way, including Dr. Will Usher, Dr. Raghav Pant, and Tom Russell. Thanks in particular to Miriam Mendes for keeping everything running as smoothly as possible in the programme; to 'dream team' member Lena Fuldauer for laughs and great memories during even the most intense work trips; and to the rest of the ITRC lads for making the many days of work in the department enjoyable.

I would also like to acknowledge the United Nations Office for Project Services for supporting my studies while providing enriching opportunities to apply my research in new and interesting environments. Through UNOPS, I have been fortunate to meet and work with numerous colleagues on exciting projects in Copenhagen, Curaçao, Saint Lucia, and Ghana. In addition, I recognise the financial support provided by the European Union's Horizon 2020

research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 681228.

I am grateful to the Environmental Change Institute for being my home over the past four years (sometimes too literally), and for providing opportunities for research exchange, teaching, and plenty of social events. I am extremely fortunate to have experienced Oxford life and to have made many great friends along the way, at the department, college, and around the university. I also thank my colleagues at the University of Cape Town and the EfD South Africa for doing their best to welcome me to a new city and country during a challenging year. Thanks to Suzanne for keeping me well-fed and hydrated on good South African wine during the final push on this thesis.

Finally, I owe a great deal of thanks to my parents, who have always encouraged me to challenge myself and who have provided unconditional love and support for my endeavours over the course of my life.

Table of Contents

Abstract ***2***

Acknowledgements ***4***

List of figures ***9***

List of tables ***11***

Chapter 1: Introduction ***12***

1.1. Background and context **12**

1.2. Definitions and scope **16**

1.3. Research gaps **20**

1.4. Research questions and objectives **21**

1.5. Outline of the thesis **24**

Chapter 2: Literature review and methods used ***27***

2.1 Assessing the performance of infrastructure **28**

2.2. Cross-sectoral infrastructure systems modelling **30**

2.3. Participatory planning approaches to infrastructure **33**

2.4. Infrastructure and sustainable development **36**

2.5. Integrated assessment and scenario approaches to climate and development **39**

2.6. Climate-compatible development **42**

2.7. Infrastructure planning under future uncertainty **43**

2.8. Improving on existing approaches to cross-sectoral infrastructure planning **46**

Chapter 3: Delivering on the Sustainable Development Goals through long-term infrastructure planning ***50***

3.1. Abstract **51**

3.2. Introduction **52**

3.3. Methods **59**

3.3.1. Targeting SDGs with strong links to the provision of infrastructure services 60

3.3.2. Identifying attributes of infrastructure in the context of SDG targets 61

3.3.3. Deriving a sustainability metric for infrastructure 65

3.3.4. Quantifying levels of target achievement 67

3.3.5. Using SDG indicator assessment to inform long-term infrastructure planning 69

3.3.6. Calculating SDG target achievement across infrastructure strategies 70

3.4. Application **70**

3.5. Results and discussion **75**

3.6. Conclusion 85

Chapter 4: Infrastructure strategies for achieving the global development agendas in small islands 89

4.1. Abstract 90

4.2. Introduction 91
4.2.1. Saint Lucia's infrastructure challenges 93

4.3. Methods 96
4.3.1. Select key targets in order to align infrastructure planning with the Sustainable Development Goals, the Paris Agreement, and national policy priorities. 98
4.3.2. Evaluate current performance of the infrastructure system 99
4.3.3. Assess the key factors that will drive the need for new infrastructure investments and policies 99
4.3.4. Compile strategic options to outline the range of potential interventions that can be undertaken in the country. 101
4.3.5. Generation of infrastructures strategies composed of selected and sequenced cross-sectoral infrastructure interventions 102

4.4. Results 103
4.4.1. Electricity 104
4.4.2. Water supply 106
4.4.3. Wastewater 109
4.4.4. Solid waste 110
4.4.5. Cross-sectoral implications for the Sustainable Development Goals 114
4.4.6. Cross-sectoral implications for the Paris Agreement 117

4.5. Discussion 119
4.5.1. What have we learned from applying an integrated planning approach to a small island? 119
4.5.2. Dynamic and adaptive infrastructure planning has transferable principles that can be applied to a wide range of countries of differing sizes, contexts, and stages of development 123

4.6. Conclusion 125

4.7. Appendix: supplementary figures and tables 128

Chapter 5: Aligning mitigation actions with development challenges in updated Nationally Determined Contributions 130

5.1. Abstract 131

5.2. Introduction 132

5.3. Methods 140
5.3.1. Mitigation commitments in Nationally Determined Contributions 140
5.3.2. Linking mitigation action in infrastructure and land use sectors to progress in key SDG targets 143
5.3.3. Tracking SDG progress and emissions changes linked to NDC commitments 148

5.4. Results 150
5.4.1. Comparing mitigation ambition across 195 NDCs 150
5.4.2. Aligning mitigation actions with sustainable development gaps 152

5.5. Discussion 156
5.5.1. Significance for national governments 157
5.5.2. Academic research and the NDC framework 159

5.6. Conclusion 160

Chapter 6: Conclusions and final remarks 162

6.1. Thesis summary and main contributions 162

6.2. Contributions to research.....164

6.2.1. Emphasising the role of infrastructure in sustainable development 164

6.2.2. Novel contributions to infrastructure systems modelling..... 165

6.2.3. Planning for an uncertain future 165

6.3. Reflections on practical applications of the work.....166

6.4. Future extensions and applications 167

6.5. Implications for the SDGs and Paris: the 'decade of delivery'.....170

6.6. Mobilising infrastructure for a sustainable future.....171

References..... 172

Statements of authorship 198

List of figures

Figure 1 The National Infrastructure Systems Modelling (NISMOD) process developed by the UK Infrastructure Transitions Research Consortium (ITRC) **47**

Figure 2 A redeveloped national infrastructure planning process as a key component of broader global mitigation action..... **49**

Figure 3 Infrastructure-driven SDG performance at the national level..... **60**

Figure 4 Direct and indirect influence of infrastructure on 169 SDG targets **61**

Figure 5 Distribution of SDG sustainability dimensions for 31 infrastructure-linked targets **63**

Figure 6 Aggregated population scenarios for Curaçao, composed of residential population, stay-over tourism and cruise ship tourism..... **72**

Figure 7 Strategy portfolio required to meet relevant SDG targets by 2030 ..... **77**

Figure 8 Indicator contributions to full achievement of relevant SDG targets by 2030, using indicator targets defined with stakeholder input..... **79**

Figure 9 Target contribution to SDGs by 2030, showing trajectory to achievement of infrastructure-linked targets **82**

Figure 10 Indicator performance of SDG strategy in relation to stakeholder-defined targets under three scenarios of infrastructure demand for 2030..... **84**

Figure 11 Current and projected infrastructure capacity in relation to needs to 2030 across four key sectors in Saint Lucia **94**

Figure 12 Structure of the methodological process for the infrastructure assessment **98**

Figure 13 (a) Current electricity performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets..... **106**

Figure 14 (a) Current water supply performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets. **108**

Figure 15 (a) Current wastewater performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets. **110**

Figure 16 (a) Current solid waste performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets. **113**

Figure 17 Comparison of infrastructure strategy portfolios for current/inaction, business-as-usual, and sustainability target achievement for (a) electricity; (b) water supply; (c) wastewater; (d) solid waste..... **114**

Figure 18 Combined SDG performance to 2030 by strategy, calculated across 18 targets directly linked to the provision of infrastructure using scoring method developed by Adshead (2019) **116**

Figure 19 Emissions by sector compared to a 2010 baseline, showing a business-as-usual case and reductions attributed to emissions targets modelled in the electricity and waste sectors **119**
Figure 20 Long-term costs associated with inaction, business-as-usual, and a national sustainability strategy for Saint Lucia's electricity sector **122**
Figure 21 Combined residential and tourist population under a low, moderate, and high growth scenario, 2050 ..... **129**
Figure 22 Per capita greenhouse gas emissions by global development score for Non-Annex countries **133**
Figure 23 Potential country trajectories across the mitigation and development interface **136**
Figure 24 Geographical distribution of NDC commitment quantification across the energy, transport, waste, agriculture, and forestry sectors **141**
Figure 25 Breakdown of key sectoral targets and actions included in the mitigation component of first NDCs (2015) for 195 countries, grouped into five major infrastructure and land use sectors **151**
Figure 26 Range of most commonly quantified measures across the mitigation component of 195 NDCs **152**
Figure 27 Projected change in selected mitigation (y-axis) and development (x-axis) outcomes as a result of current NDC commitments for: (a) Renewable generation; (b) Access to clean cooking; (c) MSW generation; (d) Forest cover change **154**
Figure 28 Global alignment of NDCs with selected SDG outcomes, by income group. Degree to which NDCs: (a) contribute toward renewables-based generation; (b) achieve full access to clean cooking; (c) reduce current emissions associated with MSW; (d) commit to replacing deforested land (5 years) **156**

List of tables

Table 1 Contributions to identified gaps in long-term infrastructure planning methods made in this thesis **48**

Table 2 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 **73**

Table 3 Key infrastructure targets aligned with Saint Lucia's national policy priorities and international development commitments **128**

Table 4 Sectoral actions or targets from the NDCs as a means to measure progress toward selected SDG index indicators **145**

Table 5 Assumptions used to demonstrate changes in development outcomes and associated sectoral emissions reductions in four sectoral indicators **149**

Chapter 1: Introduction

1.1. Background and context

Large amounts of investment – by some estimates, up to $94 trillion – will be directed towards infrastructure globally in the coming decades, with the potential to profoundly influence global development outcomes (Bhattacharya et al. 2015; GI Hub 2017). A substantial share of these investments will be undertaken in the developing world to underpin the booming economies and growing aspirations of rapidly transitioning economies (OECD 2007). This offers great opportunities as well as risks for decision-makers, planners, and national policy makers: infrastructure systems may support development through the provision of key services that contribute to social and economic wellbeing. Conversely, poorly planned infrastructure may contribute to environmental degradation and lock in countries to unsustainable patterns of development for decades to come. Incorporating evidence-based decision-making in long-term infrastructure planning is thus crucial to harnessing its potential for global progress. However, despite major technical and engineering advances in physical infrastructure systems, current planning paradigms are ill prepared to navigate the increasingly complex and integrated systems defined by a human-dominated earth and progressively competing priorities (Chester, Markolf & Allenby 2019).

Infrastructure is essential to the functioning of modern economies in that it provides the backbone of economic capacity through the delivery of effective public services. In addition to its direct implications for economic growth, the quality of an infrastructure system impacts on other important aspects of society including human development, social inclusion and

environmental sustainability (OECD 2017a). As societal demand for infrastructure services adjusts, infrastructure systems must evolve and adapt to meet these needs effectively and efficiently.

Numerous global pressures and drivers will determine society's future needs for infrastructure. Demographic developments will define future numbers of infrastructure users, their spatial distribution across cities and countries, and the amount of infrastructure services they require to support their livelihoods and lifestyles (OECD 2017a). Future economic growth will be linked to long-term productive capability of economies and their consequent infrastructure service requirements (Hall et al. 2016), while increased globalisation will be accompanied by greater investments in infrastructure to lower barriers to trade and access to information (Alinsato 2015). Environmental factors, such as climate change, will play a large role in shaping future infrastructure needs, both by affecting the future supply of infrastructure such as energy or water resources, and by exposing physical infrastructure assets and networks to more frequent and intense natural hazards. Uncertainties around technological change will also affect future infrastructure demand: the potential for new technologies to develop over the next decades may alter the long-term demand curve for infrastructure services and may either create or reduce needs for additional infrastructure supplies or systems (NIC 2016).

In recognition of its global significance, infrastructure has maintained a front and centre role in major recent multilateral initiatives and high-level working groups. The World Economic Forum's cross-sectoral, multi-stakeholder Global Future Council (GFC) on Infrastructure convened in 2018 to deliver tools and guidance to help decision-makers in the procurement

and development of infrastructure projects (WEF 2019). The Group of Twenty (G20) countries has endorsed initiatives aiming to tackle infrastructure investment shortfalls as a way of lifting growth, job creation, and productivity (G20 2020), and have formally adopted the *Quality Infrastructure Investment (QII)* principles: sustainable growth and development, economic efficiency, environmental considerations, building resilience, social considerations and infrastructure governance (GI Hub 2019). In its flagship report, the Global Commission on the Economy and Climate (2016), comprising former heads of government as well as leaders in business, economics, and finance, argued for transformative change in infrastructure investment and development in order to address three central challenges: reigniting growth, delivering on the United Nations' 2030 Agenda for Sustainable Development ('Sustainable Development Goals' or 'SDGs'), and reducing climate risk as outlined in the Paris Agreement on climate change. The Commission argued that an ambitious agenda would be necessary to realise and deliver the 2015 development and climate goals, with the window of opportunity narrowing quickly to lock in a climate-smart, inclusive growth pathway. Major infrastructure decisions will thus play a central role in meeting these climate, growth, and development goals.

The year 2020 marks the 'decade of delivery', or the final ten years to accomplish the goals and targets of the SDGs (UN DESA 2020). Recent research has quantified the wide range of potential influences infrastructure may have on development outcomes – 72% of SDG targets can be influenced by the 'networked' infrastructure sectors of energy, transport, water, waste, and digital communications (Thacker et al. 2019). When this is extended to include buildings and facilities that provide services such as health care, education, and government services, this figure increases to 92% (Thacker et al. 2018). The G20's infrastructure entity, the Global

Infrastructure Hub, predicts that by the year 2030, an additional 27 percent will need to be invested above current trends in order to ensure global SDG achievement (GI Hub 2020).

The SDGs are not the only major global agenda with infrastructure at its core. The Paris Agreement on climate change, which committed signatory nations to work to keep the global temperature rise within this century to below two degrees above pre-industrial levels and to pursue efforts to limit it further to 1.5 degrees (UNFCCC 2015), is expected to require an additional USD 600 billion per year in infrastructure investment to ensure compatibility with the goals of the agreement (OECD 2018). The Sendai Framework for Disaster Risk Reduction, which formalises the building of disaster resilience into national policies, plans, programmes and budgets, relies on public and private investment in disaster risk prevention and reduction through both structural and non-structural measures (UNISDR 2015). The New Urban Agenda, adopted at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III), focuses on the planning, designing, financing, development, governance, and management of cities and human settlements to ensure sustainability and quality of life for the world's rapidly urbanising population (United Nations 2017).

The opportunity to harness the vast potential of infrastructure is being increasingly embraced by national governments focused on large-scale sustainable infrastructure programmes, with the added impetus of jumpstarting economic recovery in the wake of the COVID-19 pandemic. In countries from India (GoI 2019) to South Africa (SIDSSA 2020) to Colombia (Presidencia de la República de Colombia 2020), governments are committing to bold and ambitious infrastructure implementation strategies to deliver large-scale social and economic transformation. There is now a great need to strengthen approaches to cross-sectoral

infrastructure planning that can assist decision-makers, policymakers, and infrastructure practitioners in translating these political and financial initiatives into sustainable, resilient outcomes.

1.2. Definitions and scope

At the outset of this thesis, it is useful to address the definition of *infrastructure* and how it will be used in the context of the following studies. Broadly speaking, infrastructure refers to the interdependent facilities, systems, sites and networks that form the underlying foundation of societies, although it is commonly conceived as a set of public works, such as transportation and communication systems, which support human activities and essential services in a country or region (Cabinet Office 2010; Merriam Webster 2016). In contrast, the (US) President's Commission on Critical Infrastructure Protection (1997) has emphasized the role of the private sector in providing and benefiting from effective infrastructure services, defining the term as a "network of independent, mostly privately-owned, manmade systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services".

Baldwin and Dixon (2008) highlight the physical nature of infrastructure assets and their role underpinning a flow of services, defining infrastructure as a set of assets possessing certain characteristics that give rise to specific economic problems, such as market failure, that are pervasive across different economies. While emphasizing the "designed and built" definition of infrastructure as a set of technological systems bridging humans, communities, and their broader environment, Chester (2019) also includes the institutional arrangements that

correspond to infrastructure's physical structures. Taking a broader perspective, Frischmann (2012) emphasizes the functional role of infrastructure and extends its scope beyond traditional infrastructure categories to include a "set of resources defined in terms of the manner in which they create value". This incorporates non-traditional resources, such as environmental and intellectual infrastructure, that enable and support a range of activities in our lives. The inclusion of these additional functions of infrastructure is in line with the US Critical Infrastructure Assurance Office's refined definition comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide services essential to the economy, government, and society as a whole (The White House 1998).

The OECD (2015) describes *public infrastructure* as providing goods that meet fundamental needs not provided for by the market; this definition broadens the scope of infrastructure to include wider services to society such as health care and education. Facilities and services designated to provide these outcomes are also commonly termed *social infrastructure*, which has been formally defined as "the institutions and government policies that determine the economic environment within which individuals accumulate skills, and firms accumulate capital and produce output" (Hall & Jones 1999). This leads to further association of the term with the preservation of physical capital and economic growth through stronger institutions (Soares et al. 2018). As these institutions are generally housed in physical facilities such as government or educational buildings, these 'non-networked' components of the built environment are often included in the definition of infrastructure by practitioners (Murray 2019; UNOPS 2020).

These definitions suggest that many types of infrastructure can be classified as *merit goods* in that they generate strong public externalities or increase a system's competitive capacity when consumed (Becchetti et al. 2020). The operation of infrastructure systems as networks also imply that they achieve increasing returns to scale (Carlsson et al. 2013).

The UK Infrastructure Transitions Research Consortium (ITRC) works with a definition of infrastructure as a system of *assets* that provide infrastructure services; this narrower definition limits its scope to the provision of services in the following sectors: energy (for heat, lighting and transport), transportation (for the mobility of passengers and freight), water supply (to households and industries), waste management (both solid and wastewater), and digital communications (Hall et al. 2016). This aligns with earlier literature which has alternate terms for these interdependent systems, such as "utility networks" (Marvin & Graham 1993) or "lifeline systems" (O'Rourke 2007). The systematic nature of the interrelated components that enable infrastructure to provide these services lead to the concept of infrastructure as a 'system-of-systems'. The analysis and results in this thesis will therefore focus on these networked components of infrastructure, while recognising the need for services provided by the wider built environment to achieve development outcomes.

The term *infrastructure services* is central to this thesis in that it refers to the means by which the system of physical infrastructure assets, as outlined above, can deliver on societal needs. Often, little distinction is made between these services and the sectors that provide them, such as energy, water, or transportation (e.g. Briceño-Garmendia, Estache & Shafik 2004). However, others consider infrastructure services in terms of end-uses to households and businesses that infrastructure provides; in other words, the hygiene, thermal comfort,

communication, or accessibility that enables human and economic development to occur (Knoeri, Steinberger & Roelich 2016). Infrastructure thus facilitates derived demands: not the resource or service it provides, but the utility that that resource or service enables (Chester & Allenby 2019). This draws a distinction between the final services enjoyed by humans and their physical sources, such as buildings or energy (Cullen & Allwood 2010; Pauliuk and Müller 2014).

The significance of such a definition is partly that the technical conversion device or user technology that converts the output of infrastructure into a usable service or function will affect the amount of infrastructure required to meet a demand. For example, an energy-efficient lightbulb will use fewer watts to provide the same lighting service as a less-efficient device. Infrastructure services are therefore defined according to this justification throughout this work.

In the context of this thesis, the term *intervention* refers to any infrastructure policy or investment that may be implemented to contribute to meeting current or future infrastructure needs in one or more sectors. In the interdependent systems modelling used in the following studies, each intervention considered is assigned a capacity value and a potential year of implementation based on evidence provided by stakeholder advice or the literature. An intervention may serve to reduce annual demand in one or more infrastructure sectors (such as a policy to improve lighting efficiency in buildings) or may add capacity in the supply of an infrastructure service (such as the building of a new wastewater treatment plant).

An infrastructure *strategy* is used here to describe a portfolio of interventions designed to meet a pre-defined set of performance targets. A strategy may contain both demand- and capacity-side interventions, although the combination and magnitude of investments and policies in each strategy will be defined by the performance measures assessed – for example, a focus on meeting demand, ensuring environmental sustainability, reducing costs, or some combination of the three.

1.3. Research gaps

While studies on infrastructure and sustainable development have proliferated over recent years (see Chapter 2), certain themes have been explored to a much lower extent, or not at all, in the literature.

One of these regards the use of development outcomes as indicators of infrastructure performance, which is made complex by its range of sometimes-competing social, economic, and environmental dimensions. The common notion of the "infrastructure gap" as an economic concept denoting global investment needs in the built environment has dominated recent discourse on the topic (e.g. Bhattacharya et al. 2015; Woetzel et al. 2017). However, this metric does not distinguish between productive or wasted investment, nor does it incorporate the diverse outcomes countries aim to achieve through infrastructure provision (ITF 2017). This is particularly relevant given the fact that policy makers are increasingly seeking to address social and environmental challenges as key components of a country's prosperity, rather than focusing on economic growth alone (Raworth 2017; D'Alessandro et

al. 2020). This thesis aims to manage the trade-offs between the dimensions of sustainable development to provide infrastructure assessment beyond traditional indicators.

A second gap in the existing literature regards the degree to which national investment and policy interventions can be quantitatively translated into implications for the major global development agendas. Recent studies, such as Sachs et al. (2019a) and others discussed in Chapter 2, have begun to more thoroughly investigate gaps between current and optimal development progress and to define policy shifts required to achieve a range of outcomes. However, there is no body of research that definitively links infrastructure interventions at the national level to global development targets through a system-of-systems modelling approach. While recognising that a large number of infrastructure implications for sustainable development remain qualitative due to their complex nature, the studies in this thesis aim to bridge these broader areas of research. Given the highly interdependent nature of the infrastructure system, approaches that quantify the impacts of sectoral actions will be of interest to infrastructure decision-makers, funders, and practitioners.

1.4. Research questions and objectives

This thesis develops and demonstrates a novel framework for the long-term planning and assessment of national infrastructure, shifting the focus of infrastructure assessment from traditional indicators of national infrastructure performance to place key global development agendas at the heart of the planning process. Given the universal recognition of these global agreements and the outcomes they address, this work aims to provide a transferable

approach to understanding the implications of infrastructure decision-making at the intervention (investment or policy) level.

To achieve this general aim, this thesis develops three papers which form the core methodological and analytical components of this work. The first two focus on development-focused infrastructure planning at the national level and build on previous efforts to model interdependent infrastructure systems. The third takes a more global approach to consolidating national infrastructure planning with efforts to mitigate climate change as defined by the Paris Agreement. These papers inform an infrastructure planning process that is progressively based around the global agendas: first, by assessing system performance according to selected SDG targets; second, by defining and selecting infrastructure portfolios specifically to meet SDG and emissions reductions targets; and third, by demonstrating a means to use SDG target gaps to prioritise mitigation action in key infrastructure and land use sectors. Further explanation of the research gaps addressed by these papers and how they develop an overarching framework for national and global infrastructure assessment is contained in section 2.8.

The main research questions and specific objectives of each paper are identified as follows:

Research Question 1: How can the performance of diverse national infrastructure systems be explicitly assessed in the context of a globally accepted development framework – specifically, in terms of progress toward achievement of the Sustainable Development Goals?

Specific objectives:

- To characterise the importance of social, economic, and environmental dimensions of sustainability in national infrastructure assessment.
- To develop a new indicator framework, with the Sustainable Development Goals at its heart, that incorporates stakeholder preferences around context-specific development challenges.
- In applying this framework to a country case study, to identify feasible cross-sectoral solutions to meeting national and global development targets.

Research Question 2: How can the broad range of infrastructure policy and investment options available to decision-makers be organised into implementation strategies that align with global development and climate change targets?

Specific objectives:

- To formally outline the steps of a systematic, long-term national infrastructure assessment and planning process based on the previous performance indicator framework and using cross-sectoral infrastructure modelling.
- In addition to the SDGs, to incorporate Paris Agreement mitigation targets into the selection of interventions based on quantified commitments to emissions reductions in key sectors.
- To demonstrate the selection of differentiated portfolios of infrastructure interventions based on inputted performance criteria derived from a participatory stakeholder consultation exercise in a small island context.

Research Question 3: How can synergies between development and climate objectives be utilised to define appropriate cross-sectoral actions in national mitigation strategies?

Specific objectives:

- To enable comparison of diverse mitigation commitments across all countries' Nationally Determined Contributions (NDCs).
- To provide a framework that assesses countries' ambition (or lack thereof) for key mitigation actions in the energy, transport, waste, agriculture, and forestry sectors in the context of development gaps and needs.
- To test the framework using key indicators to determine the additional commitment required to achieve a trajectory toward development goal achievement and greenhouse gas emissions reductions.

1.5. Outline of the thesis

This thesis is structured in six chapters. This **first** chapter has set the context for an investigation into the role infrastructure can play in tackling some of the world's major development challenges and has defined the scope of some of the broader terms and themes dealt with in this work. Furthermore, it has outlined major research gaps on the topic and presented a set of linked research questions and specific objectives to be addressed over the course of the remaining chapters.

The **second** chapter contains a comprehensive literature review of past academic and applied research which have contributed to defining the themes and methods contained in this thesis. This includes an introduction to infrastructure assessment and performance indicators, as well as common approaches to modelling and planning infrastructure projects and systems,

including through participatory methods. The literature around infrastructure's role in sustainable development is exhaustively surveyed, as are recent approaches to integrate development outcomes with climate prediction scenarios. Methods for planning infrastructure investments and projects under future uncertainty are reviewed. Finally, the collective contribution of these past studies in defining the structure and methods of this thesis is summarised.

The **third** chapter responds to Research Question 1 by developing methodology for assessing national infrastructure systems performance in the context of the globally recognised Sustainable Development Goals agenda. The chapter demonstrates the selection of infrastructure investments and policies to achieve quantified SDG objectives in the small-island Caribbean country of Curaçao.

The **fourth** chapter responds to Research Question 2 by integrating this indicators framework into a systematic and transferable infrastructure assessment and planning process. Using the case study of another small-island country, Saint Lucia, the study outlines the formulation of optimised strategies to align the island's infrastructure performance with SDG targets and emissions commitments under the Paris Agreement on Climate Change.

The **fifth** chapter responds to Research Question 3, presenting a global framework for integrating development and climate ambition in national commitments under the Paris Agreement. This framework seeks to capitalise on synergies between actions to reduce greenhouse gas emissions and their potential to reduce gaps in development progress, guiding countries toward 'climate-compatible' development trajectories.

The **sixth** and final chapter discusses the implications of these studies for global development and climate research and policy, highlighting key implications and recommendations for infrastructure practitioners and policymakers, and suggesting future avenues of investigation building on the findings of this work.

Chapter 2: Literature review and methods used

This thesis makes a methodological contribution to aligning infrastructure decision-making with an overarching development narrative informed by key indicators and targets. Numerous approaches to modelling infrastructure to desired performance objectives have been advanced throughout the academic and applied literature. This section will provide a review of past academic and applied literature on the main methods and themes that have been used to develop the research questions, analyses, and results in this thesis.

At its core, infrastructure assessment builds on methods to develop robust infrastructure performance indicators. A number of approaches to indicator development and examples of past use are discussed in **Section 2.1**. These form a critical component of infrastructure systems modelling approaches; recent attempts to develop and apply these cross-sectoral modelling methods are outlined in **Section 2.2.** Uses of participatory planning approaches to infrastructure assessment, which bring together stakeholders to define a future vision and roadmap for infrastructure performance, are briefly summarised in **Section 2.3.**

The adoption of the Sustainable Development Goals as a broadly accepted global framework for development has, to a large extent, formalised global sustainability targets and objectives. As a result, much research has centred on understanding the linkages between the diverse themes that comprise them, and how this knowledge might be operationalised to deliver effective policies in the context of future uncertainties. These, and other issues of infrastructure planning in the development context, are addressed in **Section 2.4**. In recent years, the development of integrated assessment and scenario modelling to assess the need

for investment and policy interventions has enhanced the robustness of long-term planning under uncertain futures, with significant implications for decision-makers in major infrastructure and land use sectors. Key studies and approaches are summarised in **Section 2.5**. Relatedly, the need to consider climate and development goals in an integrated framework has led to research into 'climate compatible development', which is introduced in **Section 2.6**. The need to account for uncertainty in infrastructure planning has led to the development of other approaches based on adaptive modelling and pathways to achieve future objectives, which are reviewed in **Section 2.7**. This chapter provides a synthesis of these approaches and related studies, which provide a useful context for the specific methods developed in this thesis.

Finally, **Section 2.8** outlines how the studies in this thesis have incorporated various approaches to build on existing infrastructure assessment methodology.

2.1 Assessing the performance of infrastructure

Given the numerous dimensions of infrastructure performance, infrastructure assessment necessarily involves the application of multi-attribute valuation, an approach rooted in the decision-making literature (Hansson 1994; French et al. 2009). In early work on the topic, the National Research Council (1996) outlined a framework defining measures of infrastructure performance across four principal dimensions: service delivery, quality of service, regulatory concerns, and community/economic impacts. Notably, environmental indicators were loosely scattered between these broad dimensions rather than serving as a performance category in its own right. Efforts to provide a robust and convincing assessment of infrastructure

performance with respect to multiple attributes are noted throughout recent studies, drawing on a range of decision-making methods. For example, Dasgupta and Tam (2005) demonstrate a multi-layered approach, first eliminating alternatives that lack defined non-compensatory attributes such as regulatory compliance before subjecting the remaining options to judgment valuation based on categories of environmental and technical indicators. Bryce et al. (2014) develop a three-dimensional decision space to investigate infrastructure trade-offs in quality, cost-effectiveness, and environmental impacts, providing decision-makers with a tool to support complex and multi-objective problems. Scholten et al. (2015) use a multi-attribute utility theory (MAUT) intervention to address uncertainty in water supply infrastructure planning, outlining an objectives hierarchy and aggregating marginal utilities and weights to facilitate decision-making between stakeholder preferences.

There is no dearth of research on indicator selection for infrastructure performance assessment, although much of the existing literature relates to a single sector such as transport (e.g. Zegras 2006; Jeon et al. 2013), or focuses on a particular outcome attribute such as environmental sustainability (e.g. Shen et al. 2011; Pakzad, Osmond & Corkery 2017). Applying a more cross-sectoral perspective, Young and Hall (2015) consider four performance attributes, environment, service, social and financial, for the assessment of investment pathways. In traditional methods such as cost-benefit analysis, infrastructure performance has generally emphasised economic considerations (European Union 2015), over the social and environmental 'pillars of sustainability' (IADB 2018). However, in some cases, environmental or user quality criteria are prioritised over economic considerations, with economic criteria applied in a later implementation phase (e.g. Schmale, von Schneidemesser & Dörrie 2015). Using the example of electricity generation planning, Awerbuch (2006)

demonstrates that a robust assessment process based on cost considerations can simultaneously maximise security and sustainability objectives as part of an efficient generation portfolio.

Several in-depth frameworks for indicator development and use have also been developed. The OECD (2003) harmonises international environmental indicators using a *pressure-state-response* model, which aims to highlight cause-effect relationships and the interconnectedness of performance outcomes across environmental, economic, and other spheres. The model has been utilised to evaluate sustainability across a range of infrastructure types, including energy (Li & Li 2019), water (Kaur, Hewage & Sadiq 2020), and green infrastructure (Spanò et al. 2017). At a national level, Covec & Beca (2013) adopt the framework to outline a comprehensive set of infrastructure performance indicators, distinguishing between levels of infrastructure activity or quantity and performance measures such as productivity and efficiency. ICIF and iBuild (2015) provide a critique of current infrastructure performance indicators in the UK, suggesting next steps to develop metrics that better serve the needs of the UK's long-term strategic infrastructure vision. In the development context, Mäkinen (2020) assesses normalisation, weighting, and aggregation criteria in constructing a sustainability index based on the SDG targets for the energy sector.

2.2. Cross-sectoral infrastructure systems modelling

Infrastructure systems have increasingly become interdependent over time, due in part to their growth in scale and function, increase in number of components, and incorporation of differing technologies (Chester 2019). Rinaldi, Peerenboom and Kelly (2001) characterise

infrastructures as complex adaptive systems, connected at multiple points through a wide variety of mechanisms, which dramatically increase the overall complexity of the "system of systems". As a result, the degree to which the infrastructures are linked strongly influences the flexibility of the system to respond to changing conditions or to mitigate cascading failures. Modelling and analysis of an infrastructure component can therefore not be undertaken in isolation and must consider multiple interconnected infrastructures in a holistic manner. The potential consequences of these interdependencies are particularly relevant as infrastructures evolve and regulations governing their operation change (Brown, Beyeler & Barton 2004). However, in government, long-term national infrastructure planning has largely been conducted in a silo-based system with appraisal methods largely sector-specific, ignoring the interdependencies between sectors and networks (Young 2015).

A number of recent studies focus on the risk and resilience aspects of interdependent infrastructure networks at the national level, highlighting the importance of resilience engineering across key infrastructure sectors and developing a means to identify network vulnerabilities – and resilience enhancing options – across key interconnected sectors such as energy, water, and transport (Hickford et al. 2017; Pant et al. 2020). Systemic metrics have been developed and demonstrated as a means to characterise the resilience of infrastructure networks in the case of external shocks, and to facilitate the prioritisation of national investment decisions (Pant et al. 2018). The functional dependencies that exist across sectors are highlighted through disruption analysis that characterises the impacts of network failures across multiple components of the infrastructure 'system-of-systems' (Thacker et al. 2017). The potential for these infrastructure network disruptions to propagate spatially or geographically across multiple scales has further been evaluated (Zorn et al. 2020). These

disruptions naturally impact economic activity by affecting the businesses that rely on infrastructure services and have been assessed and quantified in the context of electricity failures and flooding (Koks et al. 2019). Studies assessing impact reduction of these climate shocks on infrastructure networks have considered adaptation options both in terms of physical protections and demand-side management (Bollinger & Dijkema 2016; Zorn, Koks & Eggimann 2020).

Studies have also highlighted the need for a multi-sector perspective when taking a long-term approach to planning infrastructure supply needs. Given the number of documented interdependencies between sectors, extensive research has sought to assess and quantify infrastructure requirements between components of the infrastructure system as well as their projected environmental impacts. Specific dependencies studied have included, among others: liquid fuel requirements for passenger and freight transport (e.g. Kahn Ribeiro et al. 2012; Merven et al. 2012); implications for the energy system of transport electrification (Baruah et al. 2014); energy needs for water supply and wastewater treatment (e.g. Plappally & Lienhard 2012; Majid et al. 2020); the impact of digitalisation on peak electricity consumption (Morley, Widdicks & Hazas 2018); wastewater reuse potential for drinking (Tortajada & van Rensburg 2019) and non-drinking (Adewumi, Ilemobade & van Zyl 2010) applications; and power generation potential from municipal solid waste (Moya et al. 2017).

In practice, however, infrastructure planning has not fully adopted cross-sectoral modelling approaches despite evidence from past research that demonstrates the benefits of joined-up government strategies and the elimination of inter-organisational boundaries (Kinder 2002). In the United Kingdom, a desire to reduce this fragmentation of infrastructure portfolios

within individual ministries or departments has led to the development of an autonomous governmental body – the National Infrastructure Commission – which has been given increased independence to coordinate infrastructure planning across sectors (NIC 2018). This model has been increasingly adopted internationally as a handful of national governments have begun to centralise infrastructure decision-making in integrated planning units that can draw on efficient and effective cross-sectoral thinking and solutions (PICC 2012; GoSL 2019; Treasury 2019).

Recent academic research has set out a roadmap developing specific methods for cross-sectoral infrastructure planning (Hickford et al. 2014; Otto et al. 2016; Hall et al. 2016). These principles have informed new, transferable approaches to infrastructure planning in the development context (Thacker et al. 2017; Adshead et al. 2018; Ives et al. 2019). However, linking these decisions to a holistic national plan for infrastructure, such as one aligned with the SDGs, has not yet been developed, with only limited analysis having been attempted in this area (Masterton et al. 2017; Adshead et al. 2020).

2.3. Participatory planning approaches to infrastructure

The development of cross-sectoral infrastructure modelling to achieve a national vision for infrastructure necessitates a consultative approach to decision-making that spans a wider range of stakeholders than traditional silo-based planning. This is particularly relevant given the long lifespan of many infrastructure assets and the lock-in effects that this implies for future development outcomes. In addition, the construction of an infrastructure asset, such as a road, will often necessarily have strong connections to the spatial and economic

development of the surrounding region, raising the stakes of the infrastructure project and increasing the number of stakeholders (Goluža 2019). Recent studies have identified shortcomings in representative decision-making around major infrastructure projects (Natarajan et al. 2019) and fragmentation among planners and stakeholders, even between sectors as closely linked as water and wastewater (Lienert, Schnetzer & Ingold 2013).

A wide body of research has emerged around 'participatory planning' as an approach to engage heterogeneous stakeholder groups to inform policy responses to climate change and sustainability (Cairns 2013; Srivastava & Mostafavi 2018) and to facilitate preference elicitation and consensus in infrastructure planning, especially when multiple or conflicting targets are involved (Bertsch & Fichtner 2016). This approach has demonstrated positive results in enhancing the quality of data collection and analysis (Kopperoinen, Itkonen & Niemelä 2014), as well as in encouraging buy-in to policy proposals (Robinson et al. 2011). By employing participatory processes, national governments can better plan infrastructure to meet the needs of local users and shape policies that prioritise key objectives, such as boosting energy access targets (Bisaga et al. 2018).

Participatory assessment techniques have been recommended as means of assessing the capacity and physical condition of infrastructure at a community level, monitoring for system failure, and engaging more stakeholders in the identification of sustainable development concerns and solutions (Hendricks et al. 2018). As a result, these types of methods have been shown to address social considerations of infrastructure provision such as inequality (Agyeman & Evans 2003) and health (O'Sullivan et al. 2013), and to allow alignment of the infrastructure planning process with a broader range of sustainable development targets

(Fuldauer et al. 2019). Where an infrastructure sector provides diverse services to its users, a participatory approach can help decision-makers navigate trade-offs in identifying new policies and investment priorities (Garrick et al. 2017).

Participatory planning approaches have been increasingly used at all levels of government to identify and address sustainability challenges. Within transnational decision-making bodies such as the European Union, the approach has been found to better identify environmental challenges and possibilities and to integrate policy, planning and implementation (Newig & Koontz 2013). On a more localised scale, Alawadi & Dooling (2015) suggest that participatory planning can promote the integration of economic, ecological, and social aspects of sustainable urban development by providing an adequate stream of information based on research, facts, evidence, needs, best practices, and past successes. The authors note that the lack of a central planning agency may severely constrain the effectiveness of this approach. Fordham (1999) examines decision-making structures for flood risk mitigation, noting that floodplain management is a multidimensional problem which has been ill-served in the past by a uni-dimensional, technical-engineering approach, and argues for an approach that incorporates more diverse and contextual knowledge, including social and cultural dimensions. Other studies find evidence that plans developed through participatory methods are more likely to be implemented and are done so in less time and at lower cost (Sultana & Abeyasekera 2008).

2.4. Infrastructure and sustainable development

Infrastructure's potential to achieve sustainable development outcomes has highlighted its prominence within the global development agendas (Thacker et al. 2018; Thacker et al. 2019). The Millennium Development Goals (MDGs), the precursor to the current SDGs, contained a relatively limited scope for infrastructure, with formal indicators covering only water and sanitation and access to phone services. Nevertheless, the underpinning role of a broader range of infrastructure sectors in delivering the pro-poor outcomes desired by the Agenda, across all stages of the infrastructure lifecycle, was well-established (Jowitt 2009). By providing basic social services, enabling economic growth, and reducing environmental impacts through efficiencies, significant linkages between infrastructure and the MDGs were defined (Modi et al. 2012). Furthermore, the importance of complementarity between infrastructure sectors in achieving development goals was recognised (Estache & Wodon 2014), with synergies demonstrated between access to infrastructure services and outcomes in MDG themes such as health and education (Leipziger et al. 2003; Cheng et al. 2012).

The formulation of the Sustainable Development Goals established a more explicit role for infrastructure outcomes as a pathway to global development, with numerous indicators covering 'networked' infrastructure sectors such as energy (SDG 7), water and wastewater (SDG 6), transport (SDG 11) and solid waste (SDG 12), as well as a goal devoted to resilient infrastructure itself (SDG 9). From the outset, the importance of integrating diverse areas within the framework was established (Nilsson et al. 2013), leading to extensive analysis and quantification of links, networks, and trade-offs between specific SDG goals and targets (Le Blanc 2015; Weitz et al. 2014; Zhou & Moinuddin 2017; Weitz et al. 2018; Fuso Nerini et al.

2019). These SDG interlinkages have also been assessed within the scope of key infrastructure sectors, such as energy (McCollum et al. 2018a). The leveraging of these synergies, and the careful negotiation of trade-offs, is considered crucial to the ability to attain the SDG agenda under different socioeconomic or climate scenarios (Pradhan et al. 2017).

Recent work has explored the interface between development objectives and specific infrastructure sectors (Bhaduri et al. 2016; UNESCAP 2017; Fuso Nerini et al. 2018). Numerous studies exist that draw quantified links between sectoral policies and the performance of specific indicators used to measure achievement across the SDG targets (i.e. Sachs et al. 2019b). These include impacts of energy use and efficiency on various health indicators (Smith et al. 2013); the relationship between road congestion and traffic accidents (Martin 2002; Sun et al. 2016; Retallack & Ostendorf 2019), the health and environmental risks of landfill emissions (Njoku 2019); or the effects of digital communications technology on education or human rights outcomes (Norlander 2013). The potential broader SDG impacts of interventions in development areas (Vladimirova & Le Blanc 2016; Nunes et al. 2016; Lucas et al. 2019) or major infrastructure projects such as China's Belt and Road Initiative (Hong 2016; Yin 2019) have similarly been addressed.

Despite this sectoral focus, the importance of a *systems thinking approach* to enabling a range of development benefits through infrastructure access has been emphasised (Mulugetta et al. 2019). An understanding of SDG linkages is also necessary to tackle socio-environmental challenges through approaches such as nature-based or natural climate solutions, which seek to avoid emissions and increase carbon storage through conservation, restoration, or other land management actions across a range of land use types (Griscom et al. 2017). These

measures can complement actions in the built environment and will be most effective if they target synergies and manage trade-offs between social and environmental outcomes (Cohen et al. 2020).

Despite these opportunities for targeted infrastructure intervention, uneven connections between the goals may undermine policy initiatives, indicating a highly complex process for nationally differentiated yet universal implementation of the SDGs (McGowan et al. 2019). Furthermore, despite the evidence of infrastructure systems being central to achieving the SDGs, the precise means of implementation remains a challenge due to complex barriers involving capital and long-term financing, balancing societal views, and navigating political structures (Chester 2019).

While overall infrastructure objectives are often similar across contexts, the institutional barriers to their achievement manifest in different ways depending on the local characteristics of the region. While many developing countries suffer from a lack of capacity to develop advanced infrastructure systems of their own, there is growing literature on the process of 'leapfrogging' – or bypassing less efficient or sustainable technologies in favour of more advanced ones. A number of studies have addressed the conditions necessary to facilitate these advanced technology transfers to developing countries, highlighting the infrastructure governance challenges commonly faced. Ockwell et al. (2008) discuss a number of institutional, legal and strategic considerations for policies on low carbon technology transfer to developing countries, highlighting a central role for policy interventions at the national level to overcome cost barriers and enable innovation, and at the international level to foster R&D and information-sharing and finance low carbon technologies directly or through carbon

pricing initiatives. Conditions for and barriers to the success of technological infrastructure solutions in achieving sustainable outcomes in developing countries, including market conditions, institutional capacity, government, stakeholders and utility infrastructure, have been thoroughly discussed (e.g. Fong 2009; Watson & Sauter 2011). These highlight the complexities of formulating an effective framework for global infrastructure provision, and the need to adapt "theoretical prescriptions" of infrastructure delivery to local contexts (Suleiman and Cars 2010).

However, successful instances of advanced technology transfer and infrastructure development are noted, particularly in rapidly emerging countries such as China and India, through close coordination between private, government, research, and financial bodies (Fu & Zhang 2011) and a focus on bottom-up technological learning, knowledge flows via relationships with foreign firms, domestic policy incentives and leveraging opportunities linked to international climate change policy (Watson et al. 2015). Still, domestic barriers continue to hamper sustainable infrastructure development, necessitating continued industrial and economic policy adjustments (Howell et al. 2014). Overall, these studies suggest that achieving high performing infrastructure systems based on sustainable and efficient technologies requires coordinated and vision-oriented governance incorporating its many stakeholders.

2.5. Integrated assessment and scenario approaches to climate and development

Scenario analysis methods developed over the last decade have provided a means by which to assess potential future social, economic, and environmental states of the world as a result

of human and natural influences (Moss et al. 2010), and to explore the long-term consequences of anthropogenic climate change and available response options (Kriegler et al. 2010). These are integral to informing appropriate actions across infrastructure and land use sectors in order to achieve climate targets and broader development goals (van Vuuren et al. 2015; Sachs et al. 2019a). By inputting various scenarios of emissions, concentrations, and land uses (e.g. 'representative concentration pathways'), this exercise can be used as basis for assessing selected actions as a means to address climate impacts and mitigation options (van Vuuren et al. 2011).

Pathways to achieving ambitious and interlinked sustainable development objectives through a wide range of interventions, such as technological measures and consumption changes, have been developed through backcasting approaches (PBL 2012). With regard to technological change, Bosetti et al. (2015) parameterize technology assumptions based on expert elicitation surveys within the energy sector, feeding them into an Integrated Assessment model to assess the potential implications of future technology change and its impact on global economic and environmental metrics. However, Baker et al. (2015) find that future returns to scale of R&D in technology are predicted to decrease, and that there is still uncertainty as to which technology categories stand to gain most from increased investment.

Recently, the *Shared Socioeconomic Pathways*, a set of narratives describing five alternate socio-economic scenarios underpinned by driving forces (Riahi et al. 2017), have been adopted by the IPCC as a means to describe futures of socio-economic development in the absence of climate policy interventions. These narratives provide useful tools for policymakers in terms of designing long-term strategies to keep global temperature change under two

degrees (Böhmelt 2017), with infrastructure decisions central to this endeavour. The importance of demand-side solutions to achieving these mitigation targets has been examined and quantified across several end-use sectors such as transportation, buildings, and agriculture (Creutzig et al. 2016).

In addition to meeting mitigation targets, scenario and pathways analysis have been used to identify transformational challenges required to achieve sustainable development within planetary boundaries (TWI2050 2018). Exploratory scenarios built on this past work can broaden the scope of potential solutions in order to model policy pathways to maximise SDG target achievement (Moyer & Bohl 2019). Such a modelling approach can account for uncertainties in infrastructure planning within a given sector. For example, recent studies have combined scenarios from integrated assessment models to develop assumptions around future technology drivers for water supply advancements (Graham et al. 2018); to explore how alternative technology choices in power sector decarbonization pathways compare in terms of non-climate environmental impacts at the system level (Luderer et al. 2019); and to project passenger transport carbon emissions pathways (Edelenbosch et al. 2017). Plausible mitigation scenarios derived from integrated assessment models can also help to inform investment needs required to achieve simultaneous progress toward the SDGs and Paris Agreement commitments (McCollum et al. 2018b; Rozenberg & Fay 2019). The use of integrated assessment to further explore interactions among all 17 SDGs has also been conducted (van Soest et al. 2019).

Although well embedded as an analytical exercise to support national sustainable development planning, scenario modelling requires continued improvement to handle the

complexities of implementing the broad and holistic SDG agenda at the national level. Allen, Metternicht & Wiedmann (2017) suggest iterative steps that may be incorporated in such a process: identification of priorities and targets; model selection; projection of a baseline scenario; and analysis of intervention options and pathways toward achieving the targets. This thesis develops an approach to infrastructure assessment and planning drawing on these steps and informed by many of the additional approaches and findings outlined in this chapter.

2.6. Climate-compatible development

Past research has investigated the extent to which high human development can be decoupled from energy use and carbon emissions (Steinberger & Roberts 2010) and whether the benefits of climate change mitigation outweigh the costs of abating greenhouse gas emissions (Hamilton, Brahmbhatt & Liu 2017). Questioning whether efforts to reduce emissions can result in a loss of human welfare, Reusser et al. (2013) find that most elements of development are not reliant on emissions activities, and thus are not greatly compromised by mitigation actions. Progress in reducing these emissions, the majority of which are associated with global infrastructure, is crucial to avoiding irreversible damage to climate and ecosystems, and by extension, development progress (Ryan-Collins, Ellis & Lemma 2011). Therefore, a broader framework that brings together mitigation and development objectives and targets is highly relevant to the studies in this thesis.

The concept of *climate-compatible development* was originated by Mitchell and Maxwell (2010) to describe development that simultaneously maximises the many human development opportunities facilitated by climate change mitigation and adaptation measures.

Subsequent studies (Suckall et al. 2015; England et al. 2018) have advocated evaluation of development projects across the three dimensions, identifying features of projects and their overall alignment with this 'triple-win' potential. The framework has seen application in combination with other methods, such as scenario development (Huxham et al. 2015) and participatory planning for climate change (Broto et al. 2015), or as a lens through which to undertake planning in certain productive sectors (Tanner et al. 2014; Harkes et al. 2015). However, Ficklin et al. (2018) present critiques of the concept of climate-compatible development, including its conceptualisation, reliance on economic and emissions metrics to assess trade-offs between the three dimensions, and lack of an emerging governance structure to underlie the triple-win landscape. Applying the framework to Nationally Determined Contributions (NDCs) of four countries, Scott et al. (2018) find that opportunities to identify synergies and the development co-benefits of mitigation actions could be missed due to the continued separation of NDC planning from national development policy.

2.7. Infrastructure planning under future uncertainty

In the context of uncertainty around the drivers of future infrastructure needs, a range of strategic planning approaches have been developed to help decision-makers make effective and adaptive decisions. These are particularly important given the long lives of infrastructure assets, the criticality of the services delivered, and the high costs associated with maintaining and upgrading infrastructure systems (Chester, Underwood & Samaras 2020). These approaches are generally applicable to various fields such as business, management, and engineering, but are highly relevant to decisions around infrastructure planning. For example, Dewar (2002) presents an 'assumptions-based planning' approach as a tool for identifying the

underlying assumptions of an organisation, explicitly bringing them into the planning process, and accounting for their change and potential failure in the uncertain future. Lempert et al. (2003) develop 'robust decision-making', as an approach to choosing near-term strategies that are robust across the widest range of plausible futures.

Techniques to build flexibility into major infrastructure projects can reduce the risks associated with future uncertainties. For example, 'real options' analysis has been extended from its original applications in finance to assess real-world projects in the context of decision making under uncertainty. De Neufville (2003) illustrates the range of applications of real options analysis in systems design and the way in which planners deal with uncertainty and risk. An extension of this, real 'in' options, aims to provide design flexibility in major engineering projects which share major features: long lifetimes, economies of scale, and uncertain future requirements (Wang & de Neufville 2005). These techniques have seen application to the planning of specific infrastructure systems. Cheng et al. (2011) use real options analysis as a means of developing clean energy strategies given uncertainties around lead times of government policies and capital investments, as well as future electricity demand. Pizzutilo & Venezia (2016) apply the technique to uncertainty around future transport investment projects.

Ben Haim (2006) outlines an 'info-gap' decision theory aiming to optimise a decision model's robustness to failure under severe uncertainty. These theoretical approaches form the basis of many studies on climate risk mitigation (e.g. Willows and Connell 2003; Hall et al. 2012; Weaver et al. 2013) and can be categorised by the dynamic nature or level of uncertainty inherent in each framework (Walker et al. 2013). Many of these decision-making methods

designed to incorporate complexities in infrastructure design fall into broader frameworks such as Cynefin or Deep Uncertainty, which can help infrastructure planners better account for the complexities or non-stationarity of climate change drivers (Helmrich & Chester 2020).

Approaches such as 'adaptive policymaking' can respond to new information over time and eliminate the need for ad hoc decision-making (Walker et al. 2001). This serves as a basis for new approaches to strategic infrastructure planning in particular sectors (Kwakkel et al. 2010; Marchau et al. 2010). The need for infrastructure planning approaches that draw on uncertainty analysis and scenarios to incorporate flexibility and adaptiveness into the process was identified by Kwakkel & van der Pas (2011), who assert that these approaches had seen little real-world application due to their efficacy not having been adequately established. Methods around uncertainty planning in various infrastructure sectors have proliferated in recent years, leading to pathways representations allowing decision-makers to better visualise tipping points, lock-ins, path dependencies, and the sequencing of infrastructure interventions over time (Haasnoot et al. 2012; Hasnoot et al. 2013; Wise et al. 2014; Fazey et al. 2016; Kingsborough 2016). These types of concepts are represented throughout this thesis.

Chester & Allenby (2019) recognise the need for flexible and agile infrastructure to adapt to the non-stationarity of the twenty-first century and recommend competencies and system properties to be integrated in novel planning techniques, including roadmapping, substitution of software for hardware, modularity of components, and transdisciplinary education. Building flexibility into infrastructure planning using approaches such as real options analysis can provide a more effective framework for responding to advances in knowledge about future climate or other drivers (Gersonius et al. 2013). Methods to address multiple objectives

for infrastructure, and to optimise their performance across transient future scenarios, have similarly been developed (Beh et al. 2015).

2.8. Improving on existing approaches to cross-sectoral infrastructure planning

The studies reviewed in this chapter contribute to a strong understanding of infrastructure systems and the way in which we can assess and plan them in the future. In spite of the sound approaches developed and applied to a range of infrastructure problems in different contexts and sectors, there remains much scope to improve the robustness of infrastructure assessment in the context of sustainable development.

The structure of this thesis builds upon an existing methodological process used in recent applications of infrastructure planning to a range of global contexts (Hall et al. 2016; Ives et al. 2018; Adshead et al. 2018). This process outlined a six-step series of analyses underpinned by targeted data collection and systems modelling capability (Figure 1). However, numerous gaps in the robustness of this process have been identified. Further, the framework can be extended from a national planning approach for a single country to highlight broader infrastructure gaps and interventions at the global scale, within the context of global mitigation commitments.

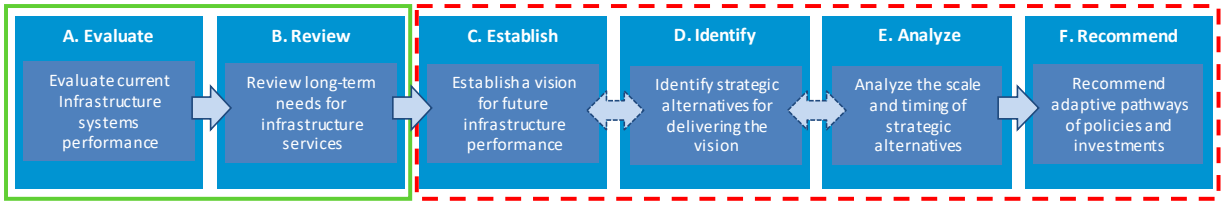


Figure 1: The National Infrastructure Systems Modelling (NISMOD) process developed by the UK Infrastructure Transitions Research Consortium (ITRC). Steps which are further developed in this thesis are outlined in red.

Table 1 summarises the current limitations of this process and identifies where they are addressed or extended in this thesis. Steps A and B of the NISMOD process have been largely achieved with no identified need for further development: (A) extensive data collection on infrastructure assets and annual demand for infrastructure services allows for current sector performance to be evaluated for existing metrics; (B) future scenarios of infrastructure driver growth, identified from government projections, international databases, or other literature, are combined with assumptions for per capita infrastructure use relevant to the particular context. These allow for future infrastructure needs to be identified. Selecting a range of these scenarios allows for the upper and lower bounds of these future needs to be estimated.

Step C, establishing a vision for future infrastructure performance, is improved upon in the first study of this thesis using theoretical approaches to indicator development and by establishing direct links to the SDG agenda. This also implies a reshuffling of the assessment process, placing the development vision as a first step. Step D, dealt with in the second study of this thesis, addresses the formulation of infrastructure strategies, which is lacking in the current approach: there is no systematic process in place, and prior strategic portfolios have been compiled using user judgment to categorise certain types of interventions based on characteristics such as cost or emissions. By systematising this step, systems modelling is

applied to select the type, size, and implementation date of feasible interventions to best meet performance targets developed collaboratively through participatory methods. Contributions to Steps E and F are also made in this second study: the performance of a strategy can be iteratively improved upon and adapted to define more suitable alternatives in terms of their scale, timing, feasibility, and responsiveness to changes in future demand.

Step	Status of assessment component	Current status and limitations	Addressed in paper
A	**Achieved**	Current sector performance can be evaluated for chosen metrics using collected data on asset capacity and annual user demand	**-**
B	**Achieved**	Projections and scenarios for infrastructure drivers are combined with data on per capita use to assess a range of potential future needs	**-**
C	**Gap remaining**	Metrics used for infrastructure performance assessment are not consolidated within a development narrative framework	**1**
C	**Gap remaining**	The national objectives used to derive performance metrics are not set out at the beginning of the assessment process	**1**
D	**Gap remaining**	No systematic strategy selection process exists to create portfolios of investments and policies for implementation	**2**
D	**Gap remaining**	User judgment is relied upon to assemble options into categorised strategies (e.g. efficiencies; capacity)	**2**
E	**Gap remaining**	Performance outcomes not used iteratively to inform optimal strategy selection	**2**
F	**Gap remaining**	Selection of interventions not adaptive to changes in strategy implementation (due to feasibility, demand uncertainty, etc.)	**2**
A-F	**Gap remaining**	Need to link role of the infrastructure planning process as a broader component of global mitigation action, in combination with other sectors such as land use	**3**

Table 1: Contributions to identified gaps in long-term infrastructure planning methods made in this thesis

This national long-term planning process gives us the means to perform an in-depth assessment of an *individual country's* current infrastructure and to determine appropriate future interventions. However, it is useful to place such a process in a global context, allowing broader comparisons across countries and the distribution of required interventions across different contexts to achieve the two global agendas addressed in this thesis. This also implies an extension of the scope of interventions beyond networked infrastructure assets to bring in other emitting sectors such as agriculture and forestry, which are aligned with UNFCCC

emissions categories. The policy solutions that emerge from such an analysis can thus be made more practical and suited to purpose, given the large levels of global emissions from land use. Drawing on approaches to address the mitigation-development interface, the final study in this thesis builds on links between infrastructure and the global development agendas, aiming to guide countries toward trajectories that are compatible with global mitigation commitments. Figure 2 illustrates how the steps of a robust infrastructure assessment process can feed into broader mitigation strategies, moving countries on a trajectory toward low-carbon development (shown as solid lines). Infrastructure strategies that are not aligned with both of these development agendas can lead to suboptimal outcomes both in terms of reducing emissions and achieving development targets. The diverse challenges faced by low (red), middle (blue), and high (green) income countries will help prioritise specific infrastructure policy and investment options for each country.

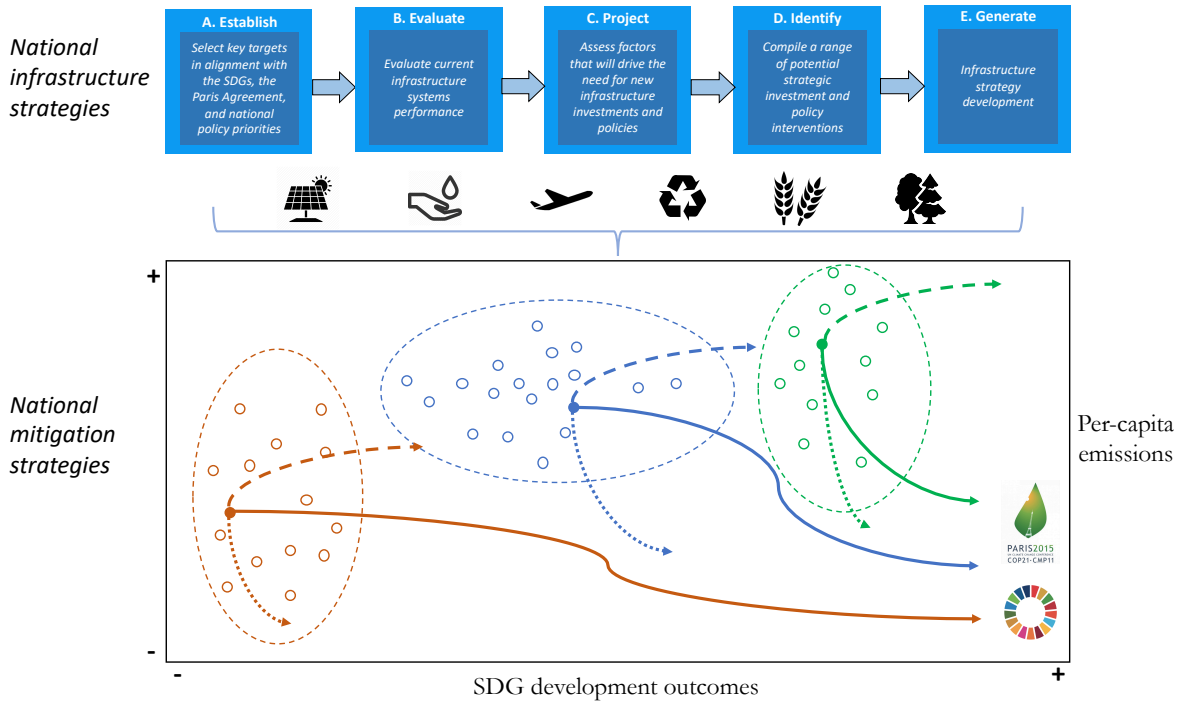


Figure 2: A redeveloped national infrastructure planning process as a key component of broader global mitigation action

Chapter 3: Delivering on the Sustainable Development Goals through long-term infrastructure planning

Daniel Adshead[a], Scott Thacker[a,b], Lena I. Fuldauer[a], Jim W. Hall[a]

a Environmental Change Institute (University of Oxford), South Parks Road OX1 3QY, Oxford, United Kingdom.
b United Nations Office for Project Services (UNOPS), Marmorvej 51, Copenhagen, Denmark.

This chapter addresses Research Question 1: *How can the performance of diverse national infrastructure systems be explicitly assessed in the context of a globally accepted development framework – specifically, in terms of progress toward achievement of the Sustainable Development Goals?* The chapter outlines an indicator framework to link decisions around specific infrastructure investments and policies to quantified progress on a range of SDG targets. The framework was applied in a case study to the small island country of Curaçao as a means of aligning targeted infrastructure decisions in the energy, water, wastewater, and solid waste sectors with national priorities and the Sustainable Development Goals.

Daniel Adshead designed the study, drafted the text, and performed most of the analysis. Scott Thacker provided comments and edits to the text and figures. Lena I. Fuldauer contributed to some of the analysis. Jim W. Hall provided methodological advice, comments and edits to the text. The study was supported by the United Nations Office for Project Services (UNOPS) and the Infrastructure Transitions Research Consortium (ITRC). The on-site research in Curaçao was facilitated by the Ministry of Traffic, Transport and Urban Planning.

Paper reference: Adshead, D., Thacker, S., Fuldauer, L.I. and Hall, J.W. (2019) Delivering on the Sustainable Development Goals through long-term infrastructure planning. *Global Environmental Change* 59.

3.1. Abstract

Through the provision of a range of essential services, infrastructure systems profoundly influence development. At a time of increasing global investment in infrastructure, there is a need to support practitioners in making informed choices in order to achieve progress toward sustainable development objectives. Using the 2030 Agenda for Sustainable Development (the SDGs) as a framework to structure infrastructure decision-making and trade-offs, this analysis develops a performance indicator system that assesses the potential development implications of a portfolio of infrastructure investments and policies. We develop metrics to assess the performance of infrastructure-linked targets. We then embed these metrics in a systems model that allows for the quantification of future infrastructure needs and the assessment of portfolios of infrastructure investments and policies that contribute to meeting these needs. These methods are applied to the small-island country of Curaçao, demonstrating the potential for meeting the SDGs through adoption of strategies of cross-sectoral infrastructure investments and policies in the energy, water, wastewater and solid waste sectors. In the face of growing demands for infrastructure services, we find that inaction with regard to infrastructure supply and demand will lead to a 28% decrease in average SDG achievement across these targets by 2030. We assemble a portfolio of interventions that provide infrastructure services across these four sectors that enable achievement of 19 SDG targets directly linked to infrastructure. These interventions imply scaling up of infrastructure where there are gaps in service provision, ranging from an overall 10% increase in the water sector to a 368% increase in waste sector infrastructure from current capacities by 2030. Achieving the SDGs does not necessarily imply more infrastructure: in the energy sector the sustainable policy implies demand reductions of 32% from current levels. Nearly 50% of the

assessed targets require intervention in more than one sector, emphasising the interdependent nature of the infrastructure system. The analysis addresses future uncertainties around the key drivers of residential population and tourism growth on the island by modelling infrastructure needs for alternate scenario projections. Averaged across the four sectors, these needs range from −14% (low) to +5% (high) in relation to the moderate projection. The analysis provides the first step towards a practical means of utilising infrastructure to deliver the SDGs, using quantitative indicators to underpin effective decision-making.

3.2. Introduction

Over the next decade, around $90 trillion will need to be spent on sustainable infrastructure assets globally (Bhattacharya et al. 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 2017b; 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 2017b). 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.

3.3. 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.

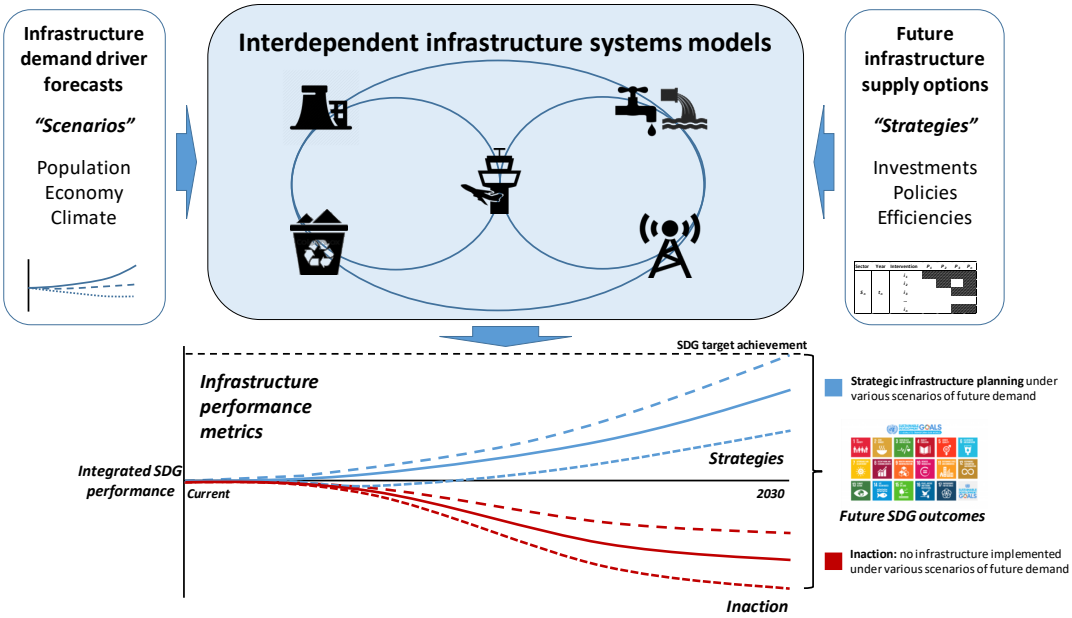


Figure 3: Infrastructure-driven SDG performance at the national level

3.3.1. 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.

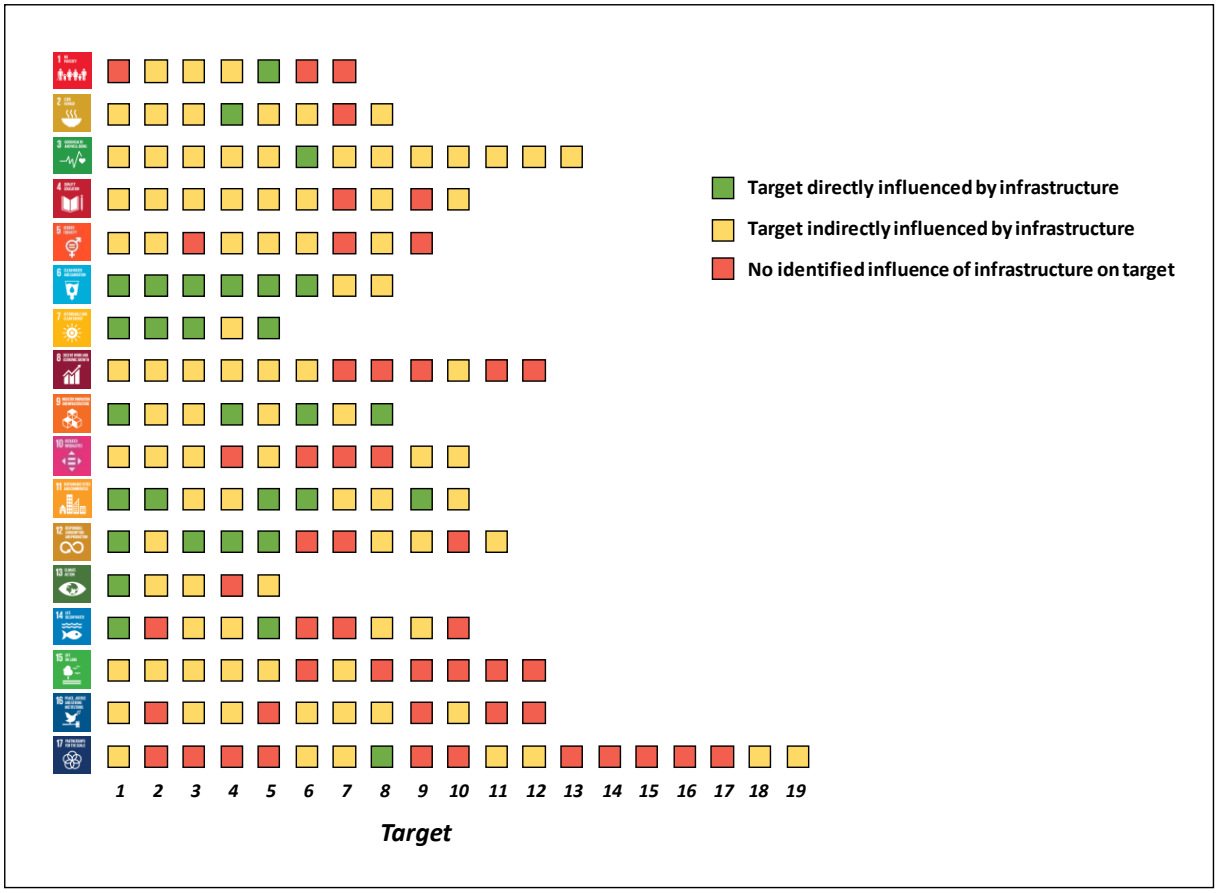


Figure 4: Direct and indirect influence of infrastructure on 169 SDG targets (adapted from Thacker et al. 2019)

3.3.2. 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.

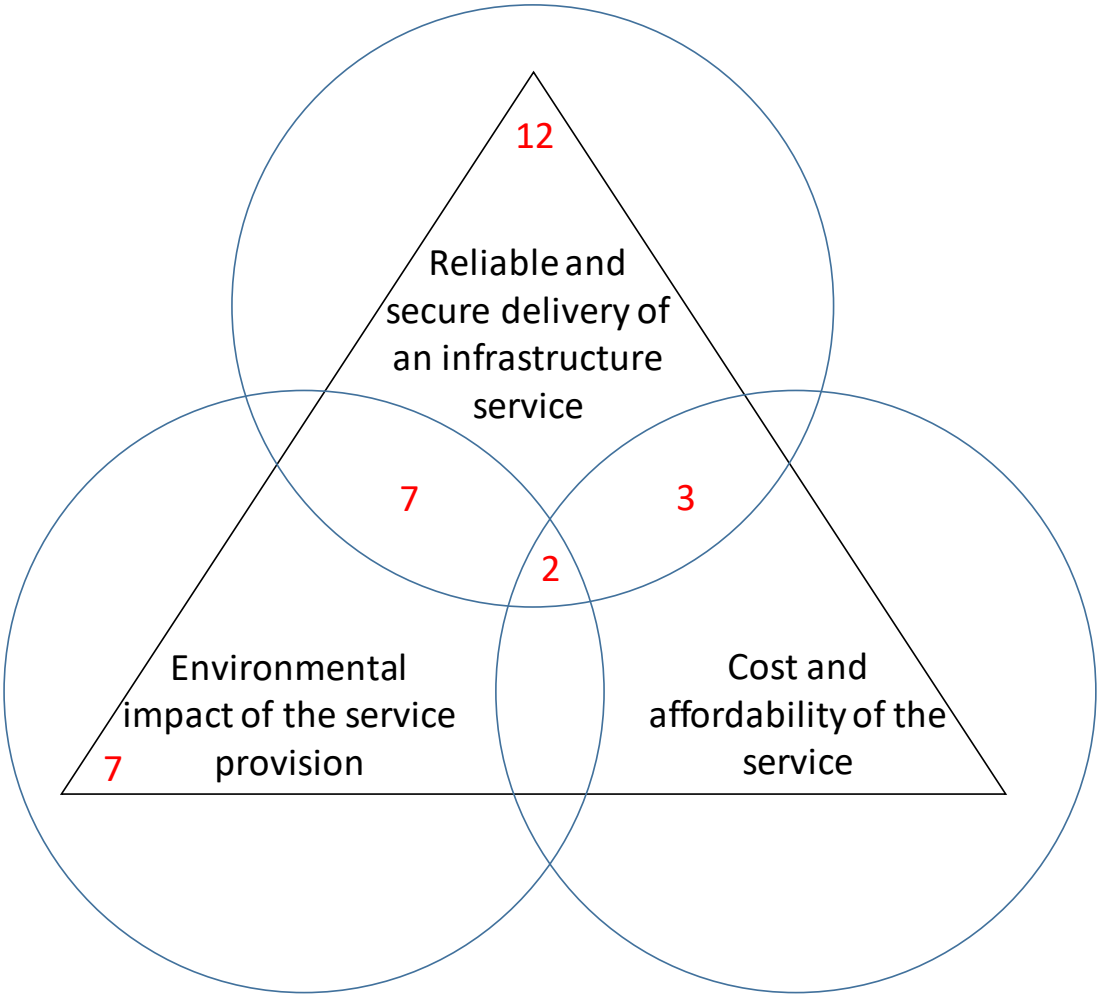


Figure 5: Distribution of SDG sustainability dimensions for 31 infrastructure-linked targets, highlighting trade-offs of infrastructure provision in the context of the trilemma concept

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.

3.3.3. Deriving a sustainability metric for infrastructure

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

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

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

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

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

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

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:

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

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:

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

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.

3.3.4. 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.

3.3.5. 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.

3.3.6. 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:

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

3.4. 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.

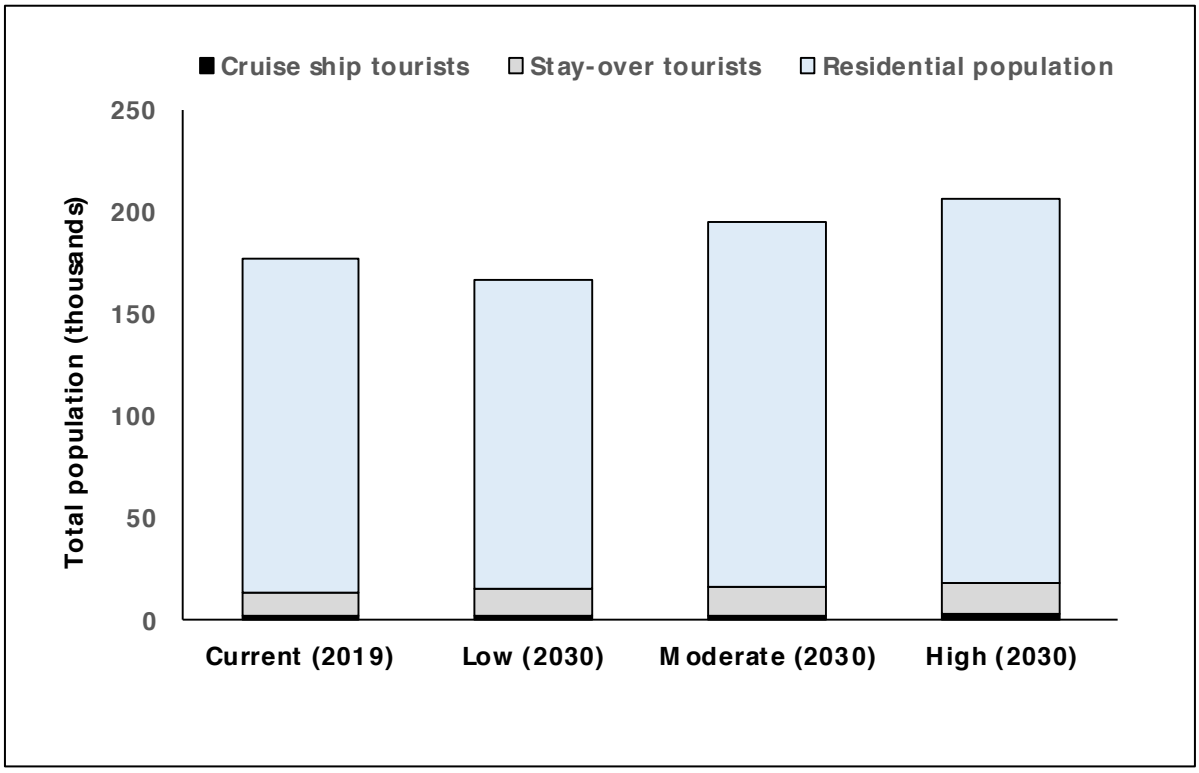


Figure 6: Aggregated population scenarios for Curaçao, composed of residential population, stay-over tourism and cruise ship tourism. Current total compared to 2030 projections for low, moderate and high demand drivers

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 upper bound of IEA recommendation as used in energy planning (e.g. OBG 2020)	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 2: 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:

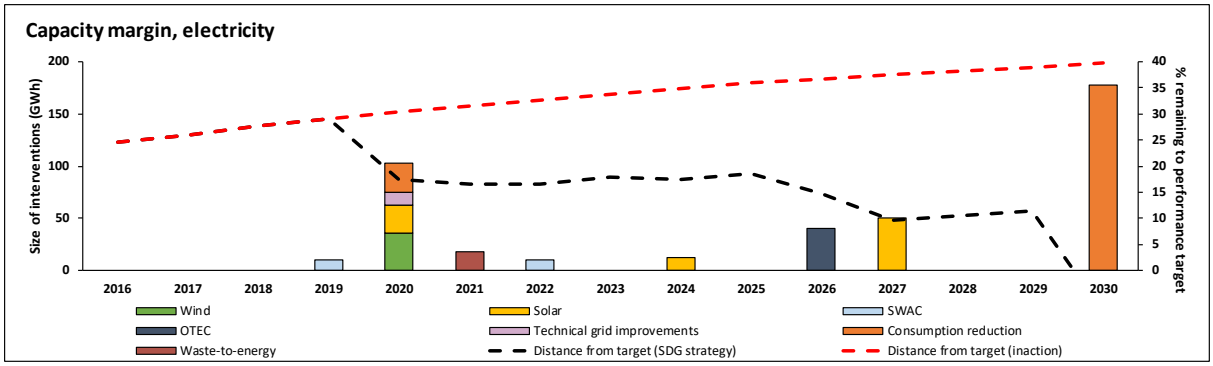
- Curaçao's energy sector is currently fossil fuel-dependent. In order to decrease economic vulnerability to changes in international fuel prices, the sector aims to decarbonise with the achievement of 50% renewable production by 2030.
- Water supply is currently at safe levels of provision though produced 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.

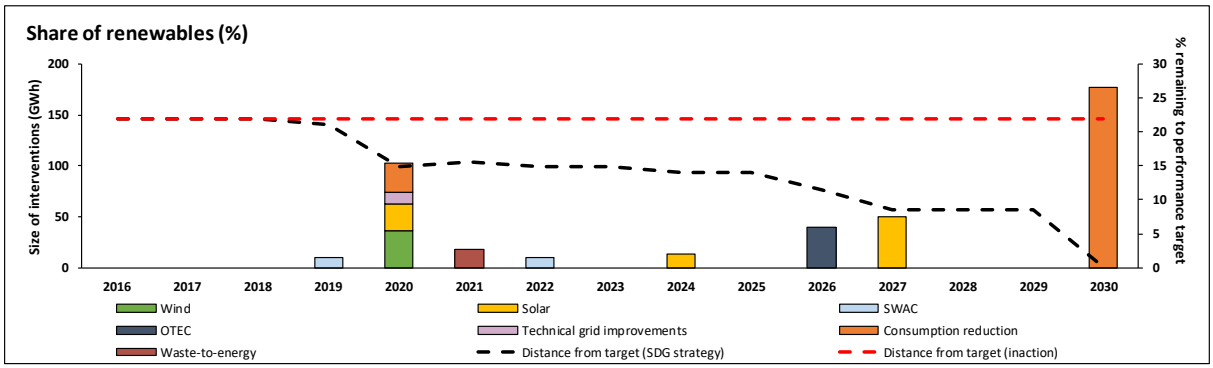
3.5. Results and discussion

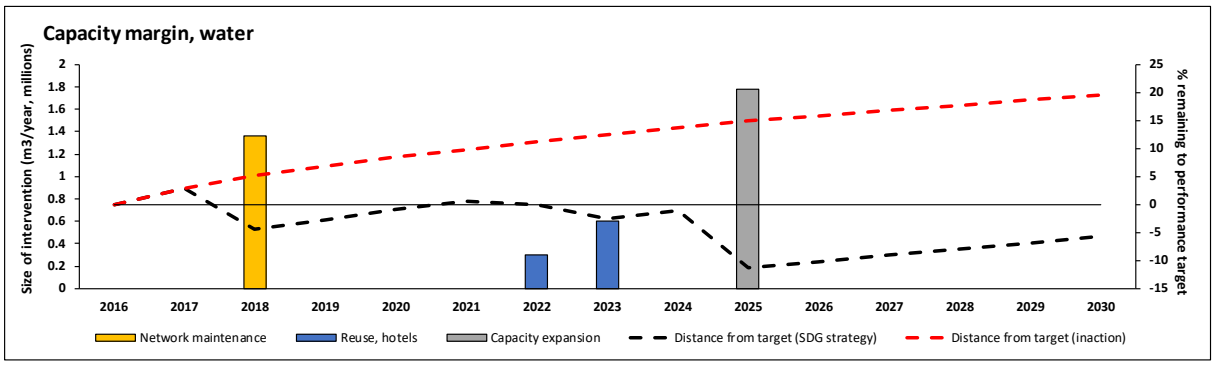
Using these priorities and other benchmarks we quantify optimal 2030 target performance for Curaçao across these indicators, corresponding to the desired achievement date for the SDG agenda. We focus our analysis on six indicators across the four sectors. With the exception of the wastewater treatment 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

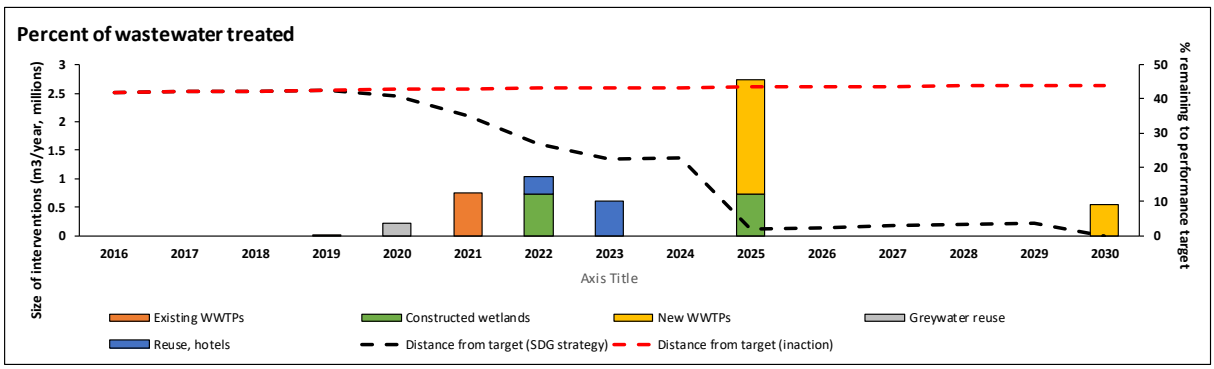
assignment of indicators and performance levels, we assemble a cross-sectoral portfolio of infrastructure interventions derived from options considered feasible in relation to the national context of Curaçao. This portfolio is structured around investments and policies that, once implemented, provide 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
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
Wind
Solar
SWAC
OTEC
Technical grid improvements
Consumption reduction
Waste-to-energy
Distance from target (SDG strategy)
Distance from target (inaction)


Capacity margin, water
Size of intervention (m3/year, millions)
% remaining to performance target
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
Axis Title
Existing WWTPs
Constructed wetlands
New WWTPs
Greywater reuse
Reuse, hotels
Distance from target (SDG strategy)
Distance from target (inaction)

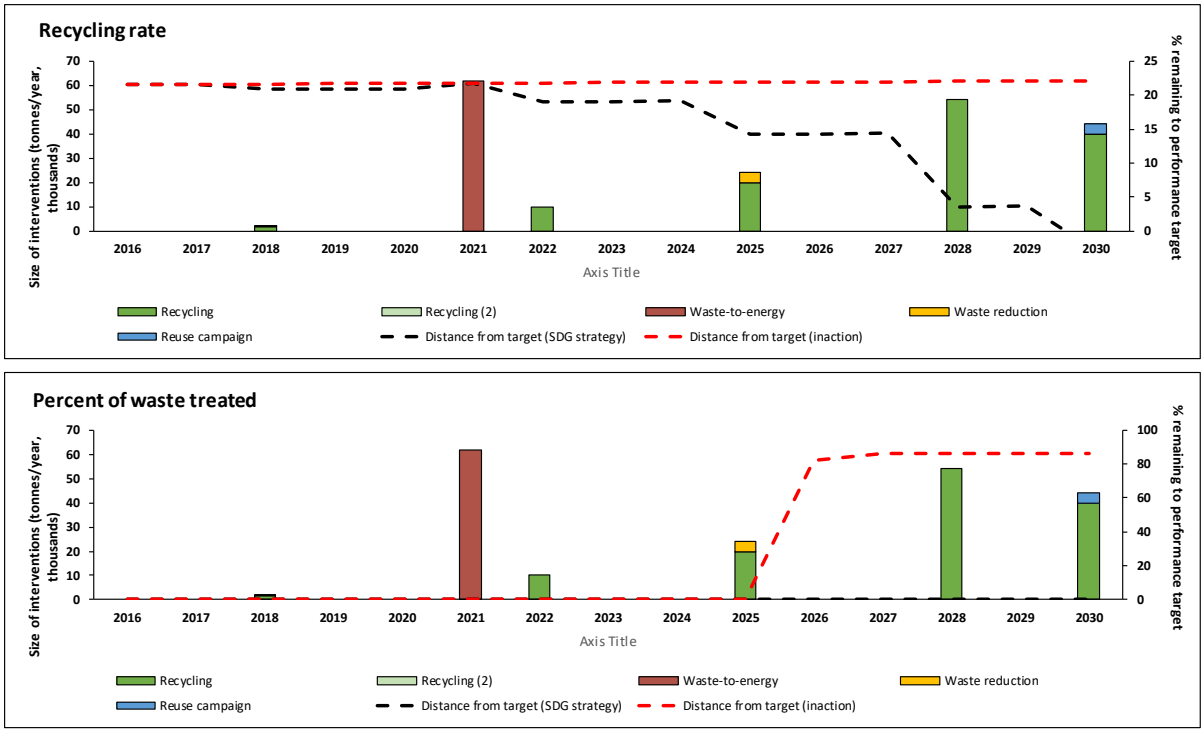


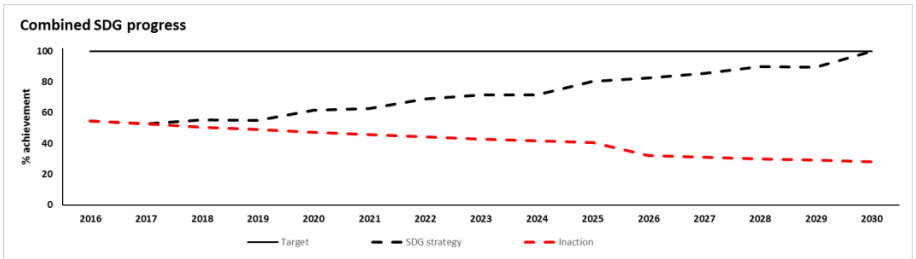
Figure 7: Strategy portfolio required to meet relevant SDG targets by 2030. Selected based on a moderate demand scenario for Curaçao's energy, water, wastewater and solid waste sectors. Energy sector interventions are converted from MW to GWh using appropriate load factors for each technology.

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.



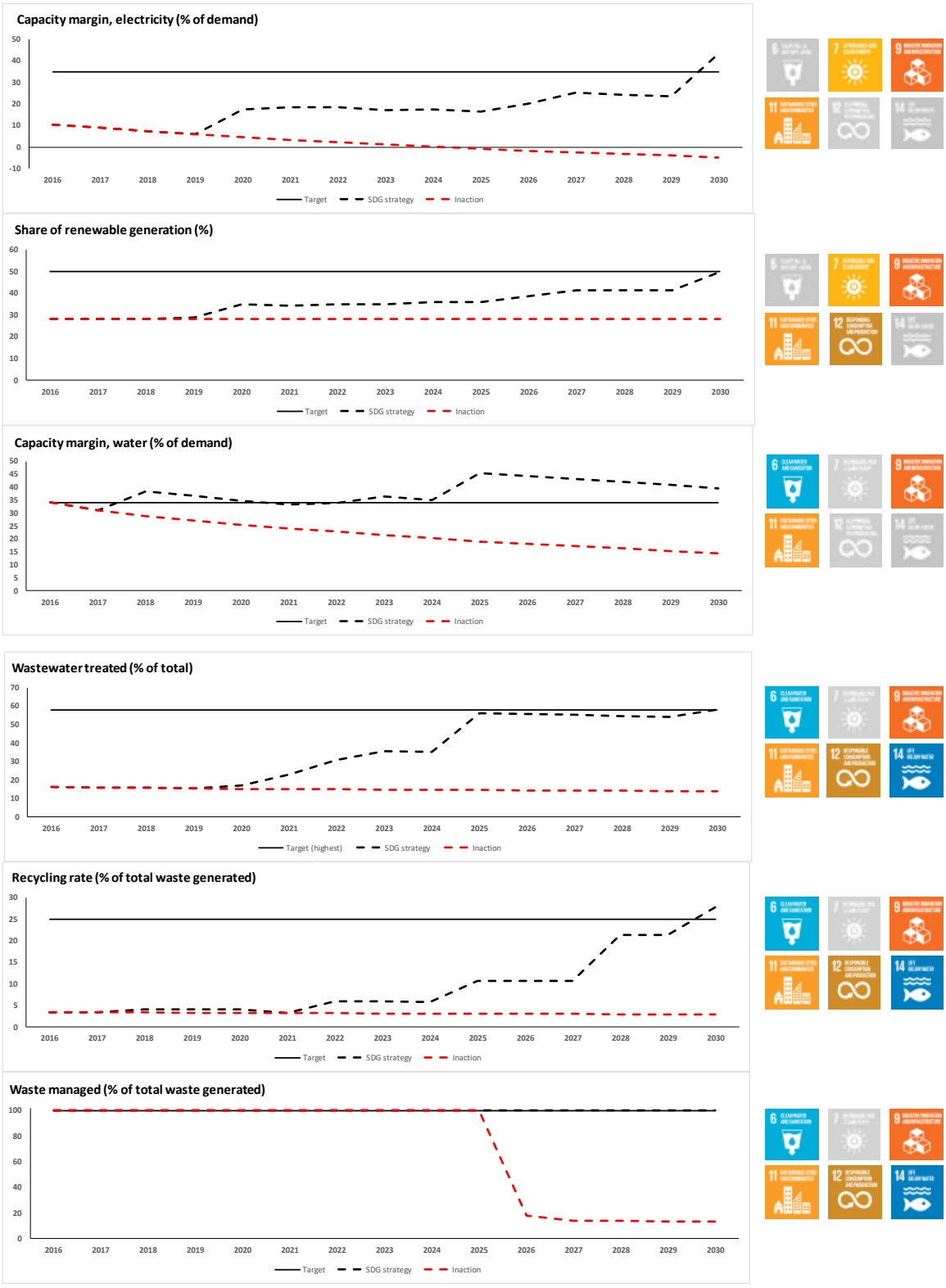


Figure 8: Indicator contributions to full achievement of relevant SDG targets by 2030, using indicator targets defined with stakeholder input

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.

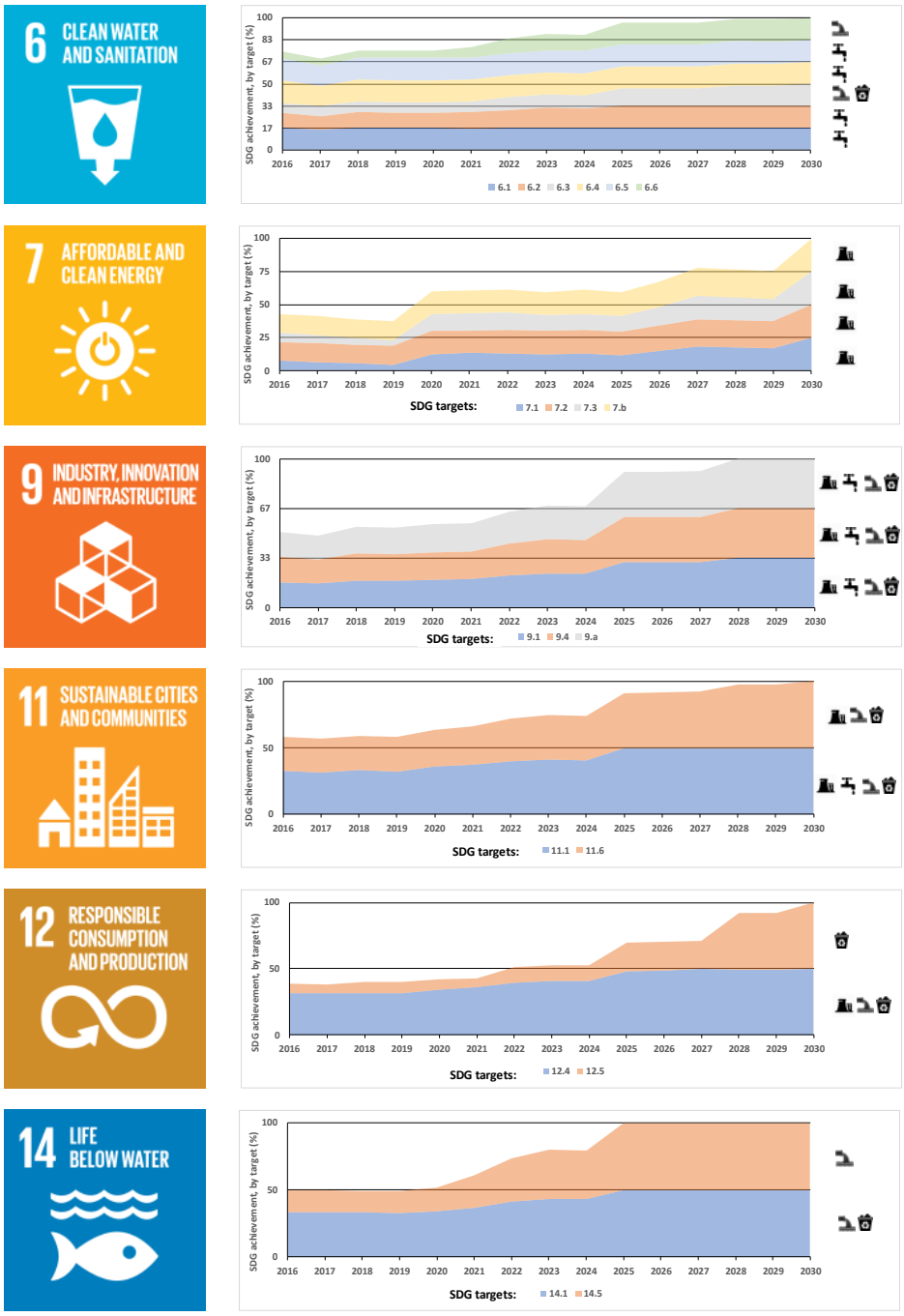


Figure 9: Target contribution to SDGs by 2030, showing trajectory to achievement of infrastructure-linked targets. Required sector inputs are displayed for each target along the right-hand side. The y-axis indicates achievement on a scale of 0-100 of all relevant targets in the SDG, and is therefore scaled according to the number of targets in each.

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.

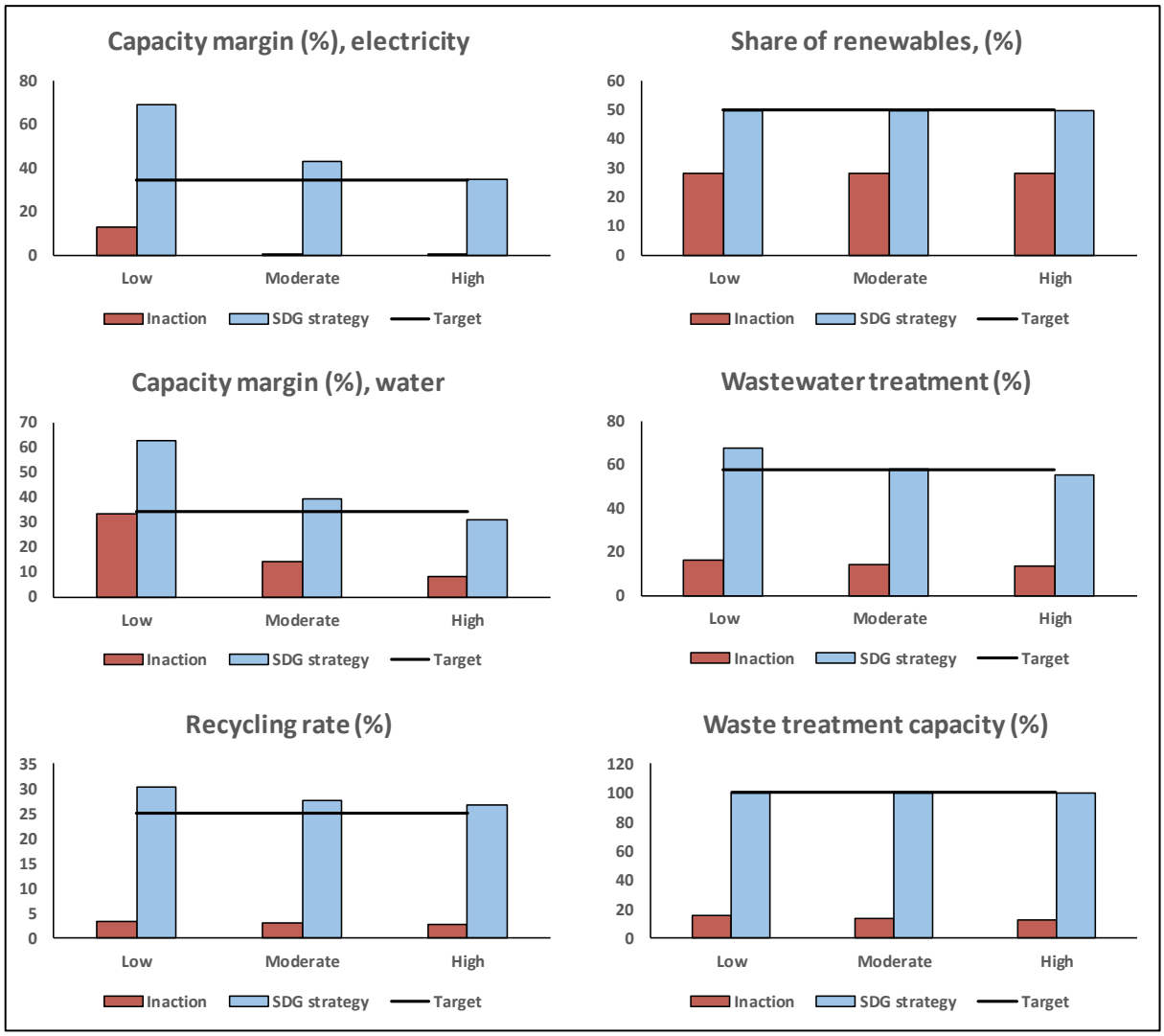


Figure 10: Indicator performance of SDG strategy in relation to stakeholder-defined targets under three scenarios of infrastructure demand for 2030: low, medium, high

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.

3.6. 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.

Chapter 4: Infrastructure strategies for achieving the global development agendas in small islands

Daniel Adshead[a], Orlando Román García[b], Scott Thacker[a,c], Jim W. Hall[a]

a Environmental Change Institute (University of Oxford), South Parks Road OX1 3QY, Oxford, United Kingdom.
b Centre for Sustainable Development, University of Cambridge. Trumpington Street, Cambridge CB2 1PZ.
c United Nations Office for Project Services (UNOPS), Marmorvej 51, Copenhagen, Denmark.

This chapter addresses Research Question 2: *How can the broad range of infrastructure policy and investment options available to decision-makers be organised into implementation strategies that align with global development and climate change targets?* The chapter develops a systematic analysis framework for developing infrastructure strategies that align with targets of the global agendas – specifically, the SDGs and the Paris Agreement. The methods are demonstrated in small-island case study to assist integrated sector planning in Saint Lucia.

Daniel Adshead designed the study, drafted the paper, and performed most of the analysis. Orlando Román García contributed to the analysis. Scott Thacker and Jim W. Hall provided comments and edits to the text and figures. The study was supported by the United Nations Office for Project Services (UNOPS) and the UK Infrastructure Transitions Research Consortium (ITRC). The data collection and verification in Saint Lucia was facilitated by the National Integrated Planning and Programme Unit (NIPP) in the Ministry of Finance.

This study was submitted to ***Earth's Future*** on 10 July 2019.

4.1. Abstract

Small island developing states face particular challenges to ensure their infrastructure promotes social, economic, and environmental well-being. Yet a systematic and robust process for making decisions about infrastructure across multiple sectors that aligns with development commitments has thus far proved to be illusive. With an application to the country of Saint Lucia, this paper develops a stakeholder-driven analysis framework integrating four interdependent sectors (electricity, water, wastewater, solid waste). Drawing on extensive consultation with decision-makers in-country – 134 stakeholders from 18 government ministries, agencies, academia, or the private sector – the analysis identifies specific interventions that could be implemented over the next decades to meet future needs for sustainable infrastructure services. These interventions are congruent with the government's development plans. Long-term, cross-sectoral portfolios of investments and policies ('strategies') are developed which demonstrably reach the targets of the Sustainable Development Goals and Saint Lucia's emissions reduction commitments under the Paris Agreement. The sequencing of these investments or policies is designed to optimise their efficiency and impact over time, identifying "quick wins" while ensuring that there is sufficient action to provide services in the long term sustainably. A comparison of costs associated with each strategy suggests that accounting for interdependencies and taking a long-term perspective can save costs over the life of infrastructure investments. This process of infrastructure assessment is applicable beyond the small island context, allowing practitioners a means to undertake systematic assessment of a country's future infrastructure needs and to develop appropriate solutions aligned with its national objectives and international commitments.

4.2. Introduction

Infrastructure systems, including energy, transport, telecommunications, water and waste management, provide essential services for the well-being of people, the economy, and the planet. Infrastructure will play a central role in nations' ability to meet the sustainability targets they aspire to (Bhattacharya et al. 2016; Thacker et al. 2018). In order to do so, decision-makers at all levels require improved methods and frameworks within which to assess the suitability of their current infrastructure systems, plan for future needs, and implement investment and policy actions that enhance the sustainability of the national infrastructure system within the technical, financial, and political confines of their national contexts. This study demonstrates a systematic application of such an assessment to a particular national context, guided by the global development and climate commitments defined in the 2030 Agenda for Sustainable Development and the Paris Agreement, respectively.

The 17 Sustainable Development Goals represent the objectives at the heart of the 2030 Agenda for Sustainable Development, which are now widely used as a means of shaping sustainability initiatives in government or the private sector (UNDP 2016; OECD 2017b; Prakash et al., 2017). Recent studies have used scenario and integrated assessment modelling to determine the broader social, economic, and governance transformations required to ensure successful achievement of the SDGs (Riahi et al. 2017; TWI2050 2018; Moyer & Bohl 2019) and to set out an agenda for their design, implementation, and monitoring (Sachs et al. 2019a). Of the 169 targets contained within the UN Sustainable Development Goals, 72% can be directly or indirectly influenced by actions targeting one or more infrastructure sectors

(Thacker et al. 2019). The SDGs are now increasingly addressed within objectives for infrastructure development; however, so far this has been limited to a focus on individual sectors, projects, or types of infrastructure. While systems approaches are widely called for and there have been successful cross-sectoral approaches, notably integrating energy and water (Yillia 2016; Fader et al. 2018) and water and waste (Hülsmann & Ardakanian 2018; Dilekli & Cazcarro 2019), methods for infrastructure planning that spans multiple interdependent infrastructure sectors are still in their infancy (Adshead et al. 2019).

The Paris Agreement committed signatory nations to work to keep the global temperature rise within this century to below two degrees above pre-industrial levels and to pursue efforts to limit it further to 1.5 degrees (UNFCCC 2015). The agreement requires each Party to define their individual commitments in terms of emissions reductions, or Nationally-Determined Contributions (NDCs), in addition to strengthening their abilities to deal with climate change impacts through adaptation measures. Naturally, infrastructure decisions are central to meeting these reductions, particularly those around clean energy transitions (Iyer et al. 2017; Cui et al. 2019), transport (ITF 2018), and waste management (Powell et al. 2018), and complement actions in other sectors such as forestry, agriculture, and industry. Decisions made within the policymaking domain of climate mitigation can have implications, both positive and negative, for achieving various SDG targets (Fuso Nerini et al. 2019). While each country party to the agreement has communicated its individual mitigation commitments, often with clear reference to related and prioritised SDG targets, the structure of these vary widely in terms of sectoral focus, degree of quantification, and baselines used.

Recent calls to more closely align the infrastructure agenda with the SDGs and the Paris Agreement recognise that major investment gaps will need to be filled in the coming decades (Bhattacharya et al. 2019). This creates an opportunity for new methodologies and novel modelling approaches to allocate investment where potential impacts are greatest, shaping better infrastructure investments and policies in key sectors (Rozenberg & Fay 2019). In the development context, cross-sectoral infrastructure investment portfolios have been used to compare approaches to meeting projected infrastructure needs across a range of futures (Ives et al. 2019), though were not linked to a holistic national plan, such as one aligned with the Sustainable Development Goals. On the other hand, cross-sectoral infrastructure planning has loosely linked in national development targets without attempting a methodological approach to strategy development (Adshead et al. 2018). This paper builds on these previous studies to systematically develop infrastructure strategies aligned with the objectives and targets of both global development agendas, applying the approach to the small island country of Saint Lucia.

4.2.1. Saint Lucia's infrastructure challenges

Infrastructure forms the backbone of Saint Lucia's society, delivering services that provide the daily needs of its citizens while supporting a tourism-based economy that brings hundreds of thousands of visitors to the island each year. As a small island developing state, Saint Lucia faces a particular set of challenges to ensure its infrastructure promotes social, economic, and environmental well-being for its residents and visitors, a reality that forces it to address its current and future predicament. In fact, in three of the four sectors addressed in this analysis, Saint Lucia is, or will soon be, vastly undersupplied with the infrastructure it needs. As shown

in Figure 11, electricity is the only infrastructure service (of the four considered in this study) which currently meets the population's needs, though the capacity margin will be eroded in future unless further action is taken. Water supply, wastewater treatment and solid waste management capacity are all below current needs.

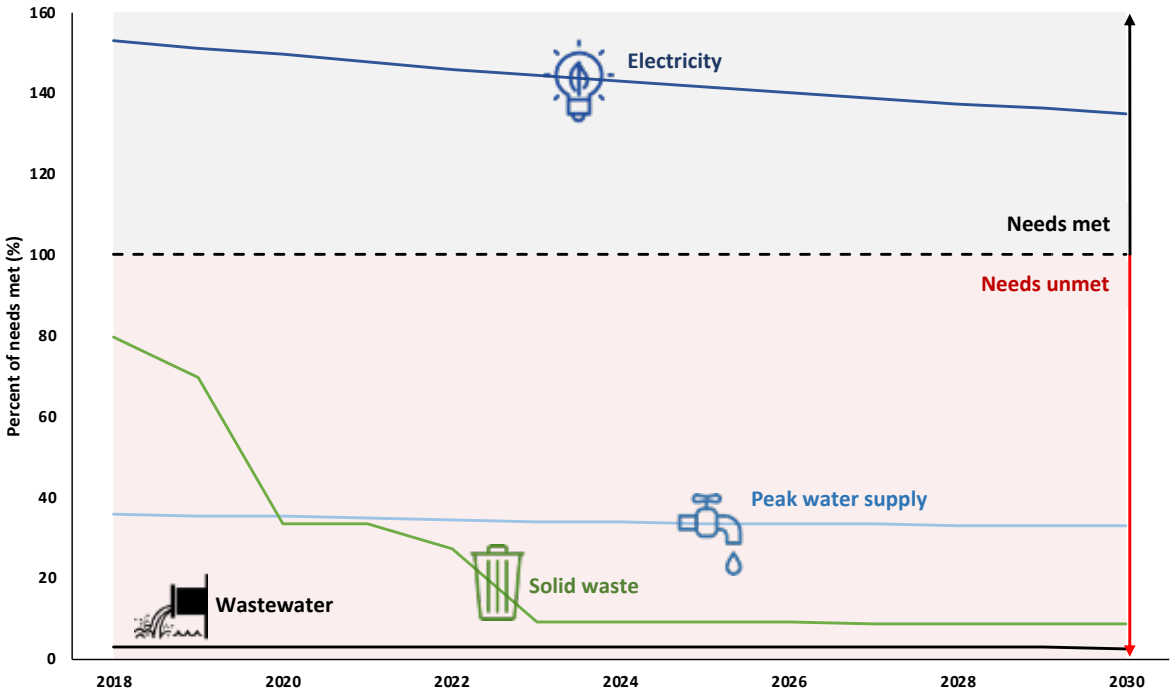


Figure 11: Current and projected infrastructure capacity in relation to needs to 2030 across four key sectors in Saint Lucia

Saint Lucia relies on diesel-based generation for its *electricity* supply, which supplies 99 percent of the island's electricity needs. While supply levels are currently adequate, this implies the need for fuel imports, which have a cost to the government of around 10% of GDP annually and affect consumers through high residential electricity tariffs. In the *water supply* sector, Saint Lucia faces large water security challenges in the dry season due to reduced river flows, low volumes of storage, and high demand from tourists, meaning that only around 40 percent of peak demand may be met during these periods. Siltation of the island's main dam has led to a reduction in reservoir and storage capacity, reducing supply to treatment plants.

Non-revenue water losses are a major concern of the island's water utility: approximately 30% of total water supply is lost through physical leaks in the transmission system and a further 26% from theft or metering inaccuracies. Only around 2% of *wastewater* is treated through secondary processes, with existing treatment infrastructure operating vastly under capacity. Untreated wastewater is associated with public health risks, including high levels of bacteria and the transmission of water-borne diseases. Untreated wastewater discharges threaten the safety of public and tourist beaches, as well as terrestrial and marine ecosystems that draw tourists to the island. As a small island, Saint Lucia's landfill capacity for *solid waste* is limited, with one dumpsite closed at the end of 2019 and the remaining site projected to reach the end of its lifespan by 2023. This creates the risk of increases in dumping and informal waste incineration or the need to export waste abroad at high cost. The increasing frequency and magnitude of climate hazards poses a threat to all infrastructure on the island, requiring that solutions be designed with resilience aspects in mind. Given the inter-connectedness of the infrastructure system, this implies considering the impacts of system failure across each of these sectors, as well as the housing, economic, and social facilities they serve.

There is already a wealth of infrastructure studies and appraisals for Saint Lucia undertaken by its various government ministries and agencies, as well as by external consultants and organisations, detailing potential development and policy options for the energy (IDB (2015); Torbert et al. (2016); CPI (2017); GoSL (2017); DSD (2019)), water supply, (Santander (2006); Stantec (2015); GoSL (2018)), wastewater (GEF-IWCAM (2011); Montoute & Cashman (2015); Ministry of Agriculture (2017)), and solid waste (Tsai (2013); CPI (2017)) sectors. Additionally, studies applied elsewhere in the region provide insight around the feasibility of a variety of

infrastructure solutions in the Caribbean context, e.g. UNEP/CAR-RCU (2009); UNEP-CEP (2010); Phillips & Thorne (2013); Amadio (2014); GIZ (2015); IDB (2018); Llanes & Kalogirou (2019). Together with the sector-specific analyses, these form a valuable resource of potential options for the country's future, which inform the integrated national infrastructure planning approach developed here.

Using a novel methodological process, this assessment integrates a complex range of data to underpin infrastructure investment and policy decision-making, and demonstrates it in a small island context. The next section outlines the steps in this process, describing the formulation of infrastructure strategies and justifying the assumptions used in the study. Comparative strategy results are shown at the level of individual infrastructure sectors. The cross-sectoral performance implications of each of these strategies is discussed with regard to the SDGs and greenhouse gas emissions. The results lead us to discussion of broader themes and transferable lessons for the future of national infrastructure planning in the context of sustainable development.

4.3. Methods

In order to conduct this study, a national infrastructure assessment process was developed, consisting of a series of analysis steps outlined in Figure 12. This process reconfigures prior methods designed to support sustainable infrastructure delivery through a formalised approach (Thacker et al. 2017). The participatory nature of this approach is well suited to infrastructure planning in small island contexts (Fuldauer et al. 2019), which, due to their small sizes, avoid constraints of stakeholder selection and participation faced in larger

countries (Cairns et al. 2013). As a result, a large proportion of Saint Lucia's key infrastructure stakeholders and experts could be consulted: data and feedback were obtained from 134 individual across 18 entities, including government ministries, departments, agencies, utilities, local consultancies, academia, and the private sector and used to populate the assessment framework.

This process is structured as follows. First, a series of infrastructure-relevant targets aligned with Saint Lucia's global development commitments or other international benchmarks are developed. Second, the current performance of the infrastructure system in relation to these targets is established. Third, the key factors driving the need for future infrastructure are considered and quantified. Fourth, the full range of confirmed, proposed, or potential investments or policies within each assessed sector is compiled from policy documents, datasets, and in-country consultation with the national government. These four steps feed into the fifth: the generation of a set of distinctive strategies composed of sets of investments and policies. These portfolios are designed to identify the type, size, and timing of various infrastructure interventions that can be implemented to meet the targets established in the first step, including the inaction route, which sets no performance targets.

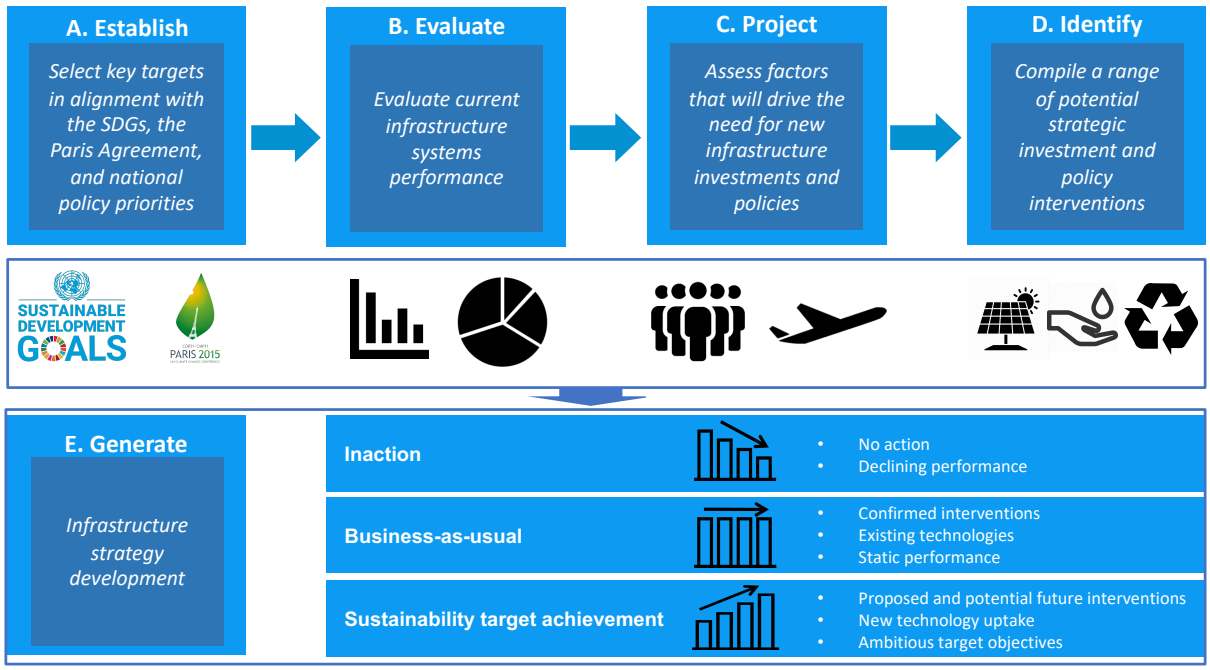


Figure 12: Structure of the methodological process for the infrastructure assessment

4.3.1. Select key targets in order to align infrastructure planning with the Sustainable Development Goals, the Paris Agreement, and national policy priorities

Infrastructure performance targets used in this assessment were arrived at after a collaborative process of engagement with decision-makers in the Government of Saint Lucia, which also served to highlight development challenges facing the country. Key indicators and targets (see Table 3) were identified through: (1) consultation with government entities to identify desired outcomes across strategic policy areas; (2) consultation of key national policy and strategy documents, such as the Third National Communication on Climate Change and the National Policy on Wastewater Management; (3) targets set according to quantifiable international commitments, specifically the Sustainable Development Goals and Saint Lucia's Nationally-Determined Contributions under the Paris Agreement; (4) the extension of these

targets to maintain ambitious development objectives post-2030; (5) targets based on international best-practice, such as outcomes achieved in the United States or the European Union.

4.3.2. Evaluate current performance of the infrastructure system

In order to assess current infrastructure performance, data on each of the four sectors addressed here – electricity, water supply, wastewater, and solid waste – was collected and verified, disaggregating the demand breakdown and current supply portfolios in each sector. Using this information, performance values for the targets in section 4.3.1 could be ascertained. Current gaps in infrastructure provision or performance were identified.

4.3.3. Assess the key factors that will drive the need for new infrastructure investments and policies

Future needs for infrastructure are driven by factors including changing demography and economic growth. Demand driver scenarios in Saint Lucia are formed of two components: residential population growth and tourism growth, which are combined to estimate peak number of infrastructure users on the island for any given day.

UN DESA (2019a) provides population projections underpinned by various assumptions around future fertility, mortality, and migration. Under the medium variant, Saint Lucia is expected to maintain its population at a similar level by 2050, while the Caribbean region as

a whole is projected to grow by a rate of 8.8%. Under alternative variants, changes in Saint Lucia's population range between nine percent decline and 15 percent growth by 2050.

Tourists have historically demonstrated a disproportionately larger demand for infrastructure services compared to residents, requiring greater amounts of energy and water per capita for luxury and leisure activities, and generating more waste per person than the average resident (Zorpas et al. 2014). Tourists can be divided into two types: stay-over tourists, who arrive by air for an average of 9 days (SLASPA 2019); and cruise ship tourists, who spend less than a day on the island, generally at beaches, restaurants, and tourist-oriented zones. Since cruises provide electricity, water, and waste disposal services for their guests, these types of tourists generally rely less on services provided on-island. However, the influx of cruise ships at certain times of the day and year put high stress on the island. A significant number of stay-over visitors also arrive by boat or yacht at the island's marinas, staying on average 2.4 days (SLASPA 2019).

Tourism growth will be driven in large part by major transport hub projects that will increase visitor numbers to the island: the planned expansion of Hewanorra International Airport and the recent agreement to construct and operate a new cruise port in Vieux-Fort. The current two-phase expansion of the airport will provide for up to 750,000 additional annual arrivals, more than tripling its current capacity (Airports Worldwide 2010). For the cruise terminal, three growth scenarios have been constructed based on SLASPA projections for increased passenger throughput (SLASPA 2019). However, the cruise ship trend is highly variable and there is a need to continually update these projections to provide an accurate assessment of the port's impact on Saint Lucia's future tourism numbers.

Estimates of combined residential and tourist population under a low, moderate, and high growth scenario for 2050 are shown in Figure 21. In this analysis, results are calculated using a 'moderate' scenario for both population and tourist growth components. Per capita assumptions around infrastructure use are derived from government-published statistics outlining the demand breakdown by sector – for example, electricity and water consumption (Central Bureau of Statistics 2018), and solid waste generated (SLUSWMA 2019). Stay-over and cruise ship tourist demand is derived from annual demand under the categories 'hotels', or 'boats', respectively, incorporating the average number of days each type of tourist spends on the island (SLASPA 2019). A portion of commercial demand is also attributed to the tourist sector.

4.3.4. Compile strategic options to outline the range of potential interventions that can be undertaken in the country

A strategic infrastructure plan is comprised of a sequence of investments and policies. As a first step, this study uses stakeholder input to catalogue the broad range of possible interventions that might be implemented as part of Saint Lucia's future infrastructure delivery in the addressed sectors. This step additionally classifies future interventions according to their likelihood of implementation: *confirmed, proposed, or potential*. Through consultation with decision-makers in government ministries and agencies, a list of projects or policies that have received *confirmed* funding by the government or other donors, or are currently in the implementation stage, is assembled. Next, a wide search of national policy documents identifies solutions considered feasible by experts and *proposed* in planning documents or

studies. This list is broadened by considering past studies from the wider Caribbean region, which allows the details of certain interventions to take shape. Finally, some interventions are classed as *potential* means of reaching ambitious long-term targets. These aspirational solutions tend to provide needed capacity not otherwise accounted for in existing studies and are implemented in the analysis if other solutions are still inadequate.

4.3.5. Generation of infrastructures strategies composed of selected and sequenced cross-sectoral infrastructure interventions

In prior studies, infrastructure strategies are developed and tested using simulation models to assess various combinations of interventions in relation to their performance across indicators (Hickford et al. 2014). These strategies have generally been organised by broader categories of infrastructure system transformation: behavioural change, system efficiencies, capacity investment, etc. (Otto et al. 2016). While addressing the direction of infrastructure policy across the system as a whole, they are useful in defining national policy alternatives in each sector (Hall et al. 2016). This assessment adopts a strategy generation method based on similar principles, but one organised around global development outcomes. By establishing quantified target objectives at the outset of the process, it provides a means by which to define an optimal implementation of investments and policies to achieve the given set of targets.

Strategy portfolio specification is run for each sector utilising the set of pre-defined interventions outlined in section 4.3.4. For each strategy, the selection of interventions is optimised to achieve its performance targets by specified dates. Where an investment or

policy straddles sectors, such as effluent reuse or water use efficiencies, the same magnitude of the chosen intervention is applied to each relevant sector.

The first case, *'Inaction'* implies that no further projects are implemented, while demand for infrastructure continues to increase according to per-capita growth assumptions. As such, this case is not strictly a strategy, but serves as a counterfactual to assess the extent of infrastructure performance decline linked to the selected demand growth scenario. The *'Business-as-usual'* strategy (BAU), incorporates short-term projects confirmed by the Government of Saint Lucia. Future projects or interventions are implemented only to maintain current infrastructure performance, and no ambitious efforts are undertaken to improve it. The *'National sustainability strategy*' is constructed to achieve specific user-defined targets for infrastructure performance aligned with specific SDG targets. The strategy also constrains maximum emissions levels in the electricity and waste sectors according to Saint Lucia's Nationally-Determined Contributions under the Paris Agreement. This strategy is thus aligned with all infrastructure-related targets for the analysed sectors set within both global agendas.

4.4. Results

The next sections summarise the components of an interdependent infrastructure analysis incorporating four of Saint Lucia's key sectors under a moderate demand projection. These results bring together infrastructure demand projections and supply options over time to address the country's pressing development challenges based on principles common to the global agendas. Sustainability targets derived from the SDGs and the Paris Agreement

underpin and inform the sequencing of these interventions across sectors. While an extensive list of options has been inputted into the model, similar intervention types are grouped here for simplification. Following the individual sector results, the cross-sectoral implications of the strategies are compared in relation to the global agendas, demonstrating the alignment of each strategy with key SDG and Paris targets.

4.4.1. Electricity

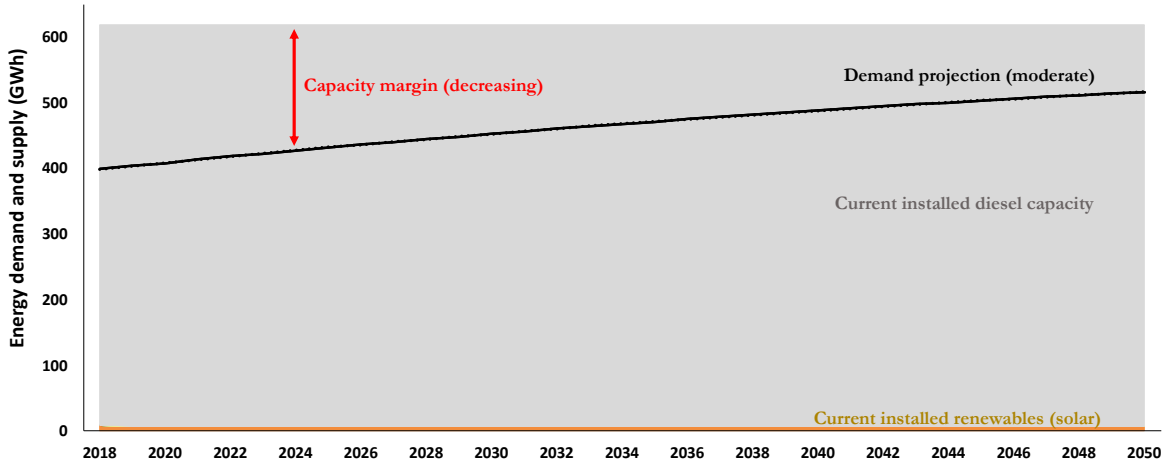
Saint Lucia's diesel capacity is sufficient to meet demand into the future, but increasing energy demand will narrow the margin with diesel capacity. As its population grows and it scales up its tourist capacity, its demand may increase by up to 30 percent by 2050 (Figure 13a). At the moment there is just one solar installation, providing for one percent of total electricity demand.

Favourable conditions for solar, wind, and geothermal energy on the island make these the prime supply-side components of a national sustainability strategy aiming to achieve the government's 2030 renewable generation target of 35 percent and subsequent scale-up to 50 percent. Saint Lucia has begun to tap this potential through confirmed solar and wind installations over the next five years (Figure 13b), which will increase its renewables share to 14 percent while maintaining strong reserve margins. However, additional solar generation in the short term is considered feasible before large investment in battery storage and upgrades are required (Torbert et al. 2016). An expansion of distributed solar generation is actively under assessment (DSD 2019). While contributions to national supply would be small, the resilience of the sector would stand to increase as other critical facilities such as schools,

health centres, desalination plants and water treatment facilities achieve self-sufficiency from the national grid. Saint Lucia's geothermal resources provide another untapped renewable energy source identified as a key component of the government's renewable energy strategy. Due to technical constraints on exploiting this resource economically, the majority of its projected capacity may not come online until after 2030 but can play a major role in achieving enhanced sustainability in the sector over the long-term.

Demand reductions and system efficiencies in the electricity network are considered relatively low-cost interventions that could be feasibly implemented by 2030 to reduce national energy demand by over five percent, including through LED street lighting, lighting and cooling efficiencies in new buildings, and a focus on energy use reductions in the tourism sector (Torbert et al. 2016; GoSL 2017). Due to their relative ease of implementation, these interventions provide "quick wins" for policymakers.

a



b

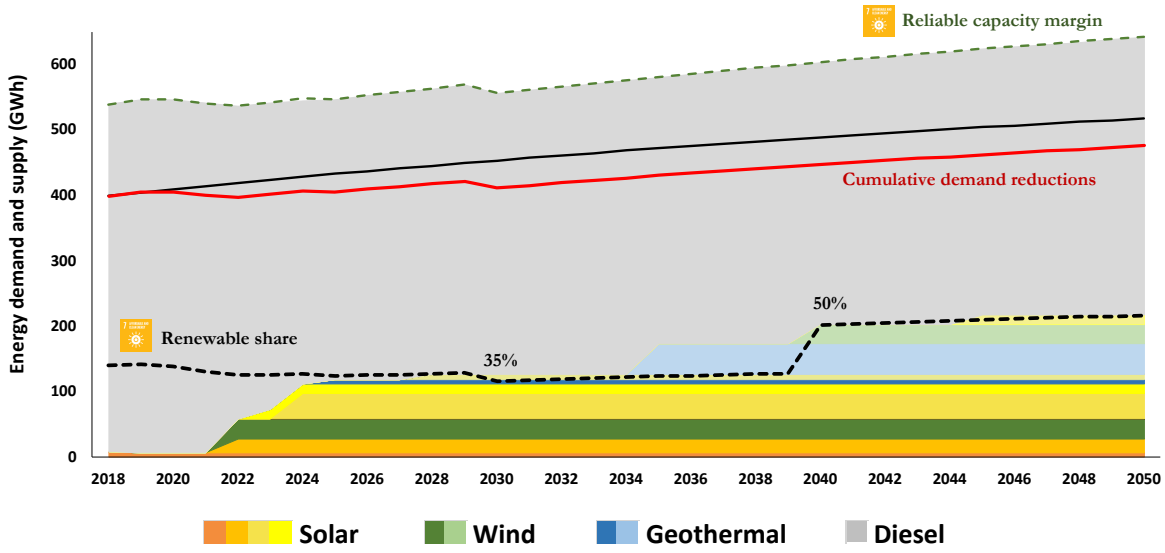


Figure 13: (a) Current electricity performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets. Supply interventions converted to estimated GWh using appropriate load factors for each technology.

4.4.2. Water supply

Water shortages in Saint Lucia are particularly acute during the dry season (Figure 14a) when river flows can decrease by up to 50 percent (Santander 2006). These often coincide with

high-demand periods, such as the tourist season. To account for the additional strain on water resources posed during these periods, and the higher daily margin required to ensure reliable supply, this analysis applies a peaking factor of 1.8 used in prior studies (Verma et al. 2015). These needs are projected to increase with additional tourist numbers. Meanwhile, the resilience of the water sector faces chronic and increasing pressures from (a) drier dry seasons linked to decreasing precipitation; and (b) a greater frequency of extreme weather events that reduce water storage capacity due to sediment run-off and embankment collapses (GoSL 2018b).

Given the geographical disparities between water availability on the island, achieving a resilient water sector will require distributed interventions beyond dependence on the island's main treatment plant. Eliminating the gap between reliable water supply and peak demand is directly linked to the achievement of several SDG targets in addition to its potential to influence those related to agriculture, health, and economic outcomes. Figure 14b shows a feasible pathway to a secure year-round water supply, combining a range of feasible solutions including additional water storage (dam capacity and storage tanks), desalination plants, and demand and loss reductions. The decentralised nature of these interventions, several of which have been confirmed by the government, allow for the targeting of communities where water shortages are most acute.

Crucially, more than 50 percent of water is lost in the transmission system as non-revenue water, roughly half through leakage. Large-scale loss reductions have precedent in similar contexts (IDB 2018) and can incorporate steps such as establishing metering zones for better monitoring of flows and pressure, establishing a comprehensive asset management strategy,

and undertaking pipe replacement to increase transmission efficiency up to 80-90 percent. With concurrent development of wastewater infrastructure, the potential to reuse effluent for irrigation or other uses provides additional water supply capacity in the longer term.

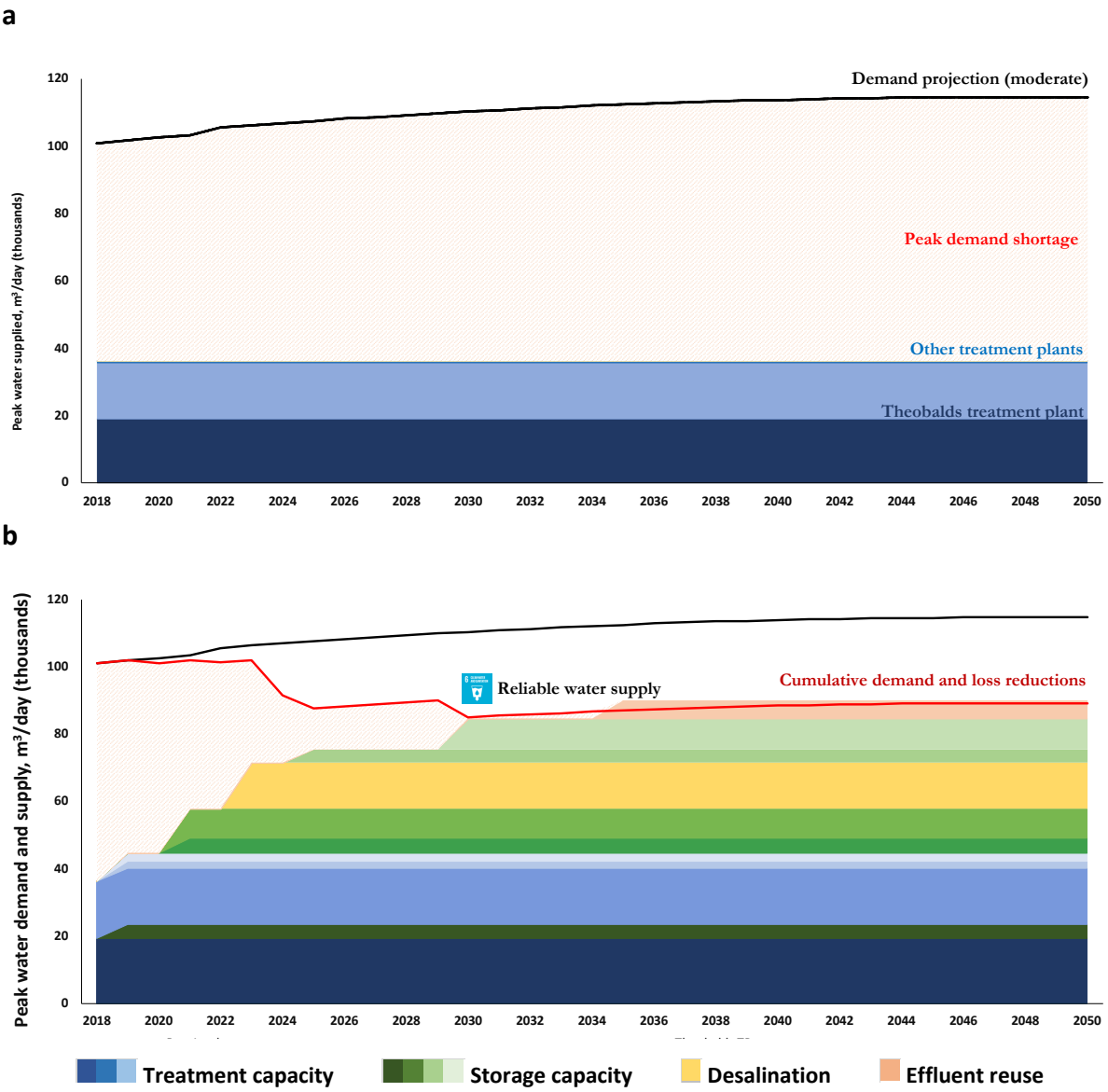


Figure 14: (a) Current water supply performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets.

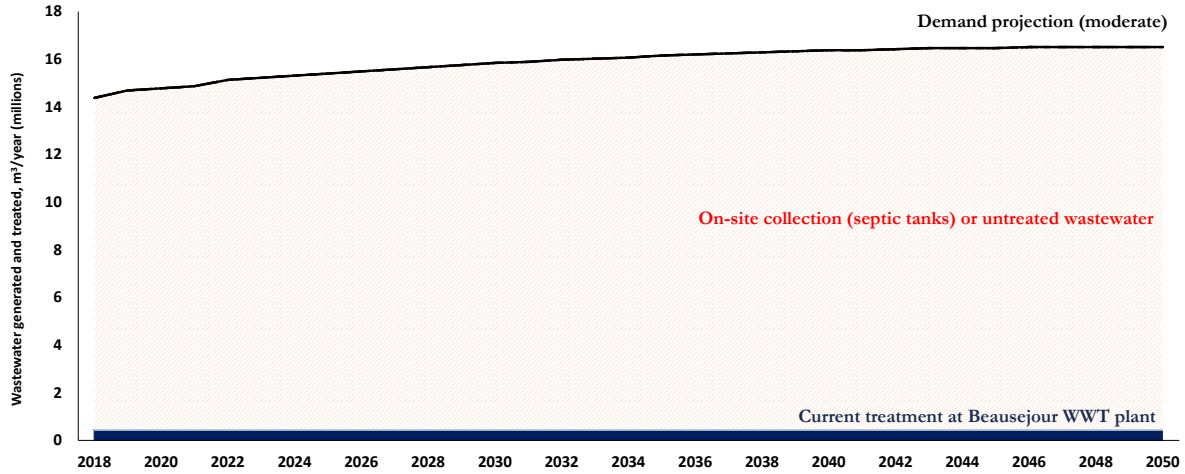
4.4.3. Wastewater

Only two percent of wastewater in Saint Lucia is currently treated. The majority is collected in septic tanks and/or discharged into the environment. The island's one operational wastewater treatment plant is utilised far below design capacity due to undersized sewer pipes unsuited to carrying larger volumes to the plant (Figure 15a). This status quo approach to wastewater treatment threatens the viability of Saint Lucia's main tourist attractions, namely pristine beaches and natural ecosystems, with associated health and economic consequences.

To improve the efficacy of Saint Lucia's wastewater treatment system a number of centralised and community-based treatment options are considered in a sustainability strategy, starting with measures to efficiently utilise the existing plant which can increase the treatment rate by over five times (Figure 15b). Halving the share of untreated wastewater by 2030 is a central performance target aligned with the SDGs which can set the stage for further improvements post-2030.

In smaller communities, decentralised treatment solutions may be more cost-effective. Wetlands are particularly appropriate for rural communities due to their simple design, operation and maintenance, and have already demonstrated improved and coordinated water resources management in the national context (GEF-IWCAM 2011). Furthermore, the strategy benefits substantially from synergies with the water supply sector: targeted interventions in hotels, new homes, and industrial facilities can provide relatively low-cost solutions that will reduce wastewater generation across the island.

a



b

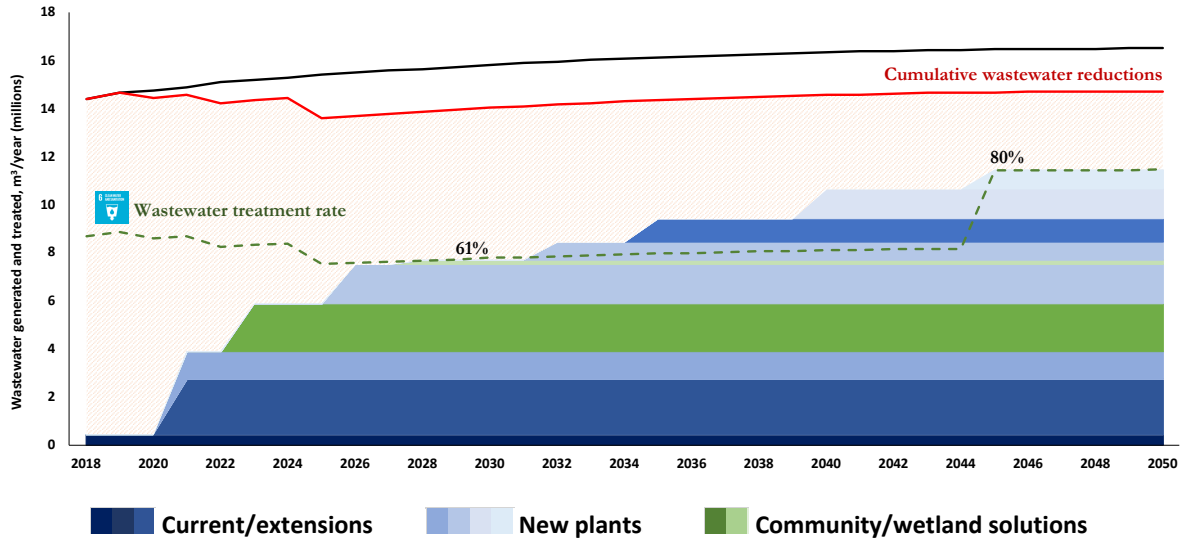


Figure 15: (a) Current wastewater performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets.

4.4.4. Solid waste

Solid waste management in Saint Lucia faces a looming capacity shortage as both landfills are due to close by 2023, when solutions must be in place to manage nearly 100 thousand tonnes

of waste annually. Common to small islands, space is extremely limited, and the government has committed to phase out new landfill requirements. There are no recycling facilities, waste transfer stations, or compost facilities on the island. Informal recycling operations, which collect recyclable materials for export, are increasingly squeezed as international markets such as China and India restrict their imports.

With unmoderated waste generation projected to increase by 12 percent to 2050 (Figure 16a), a strategic plan to develop and implement solutions must be prioritised to reduce the risk of illegal dumping and informal waste incineration. In addition to mobile incinerators which are being introduced to treat waste diverted from one of the island's dumpsites, harnessing waste through incentives in the recycling and compost industries can achieve ambitious targets in line with international best practice (Figure 16b). The diversion of waste from landfill can similarly help the country reduce methane emissions in line with its commitments under the Paris Agreement. Distributing waste management to smaller-scale facilities across the island will add redundancy, increasing the resilience of the system to climate hazards, which currently relies on functional road networks to collect and transport all waste to one centralised landfill site.

Nearly 50 percent of Saint Lucia's solid waste is organic (Tsai 2013), presenting an opportunity to divert compostable material from landfill for use in the agriculture sector. Although initiatives for backyard composting exist – such as in schools or hotels – they do not provide a significant contribution to the management of waste at a national scale. A recently opened facility in the neighbouring island of Saint Vincent suggests that large-scale commercial composting could play a part in Saint Lucia's national waste management strategy. Another

large component of the waste stream can be addressed with a renewed focus on recycling initiatives, with regional cooperation agreements providing a means to undertake Caribbean recycling initiatives in an economically viable way. A new recycling plant in neighbouring Martinique, currently operating under capacity, could serve as a destination for Saint Lucia's plastic, which comprises 22 percent of its waste. Paper (10%) and glass (7%) are other major waste components that could feasibly be separated from the landfill waste stream.

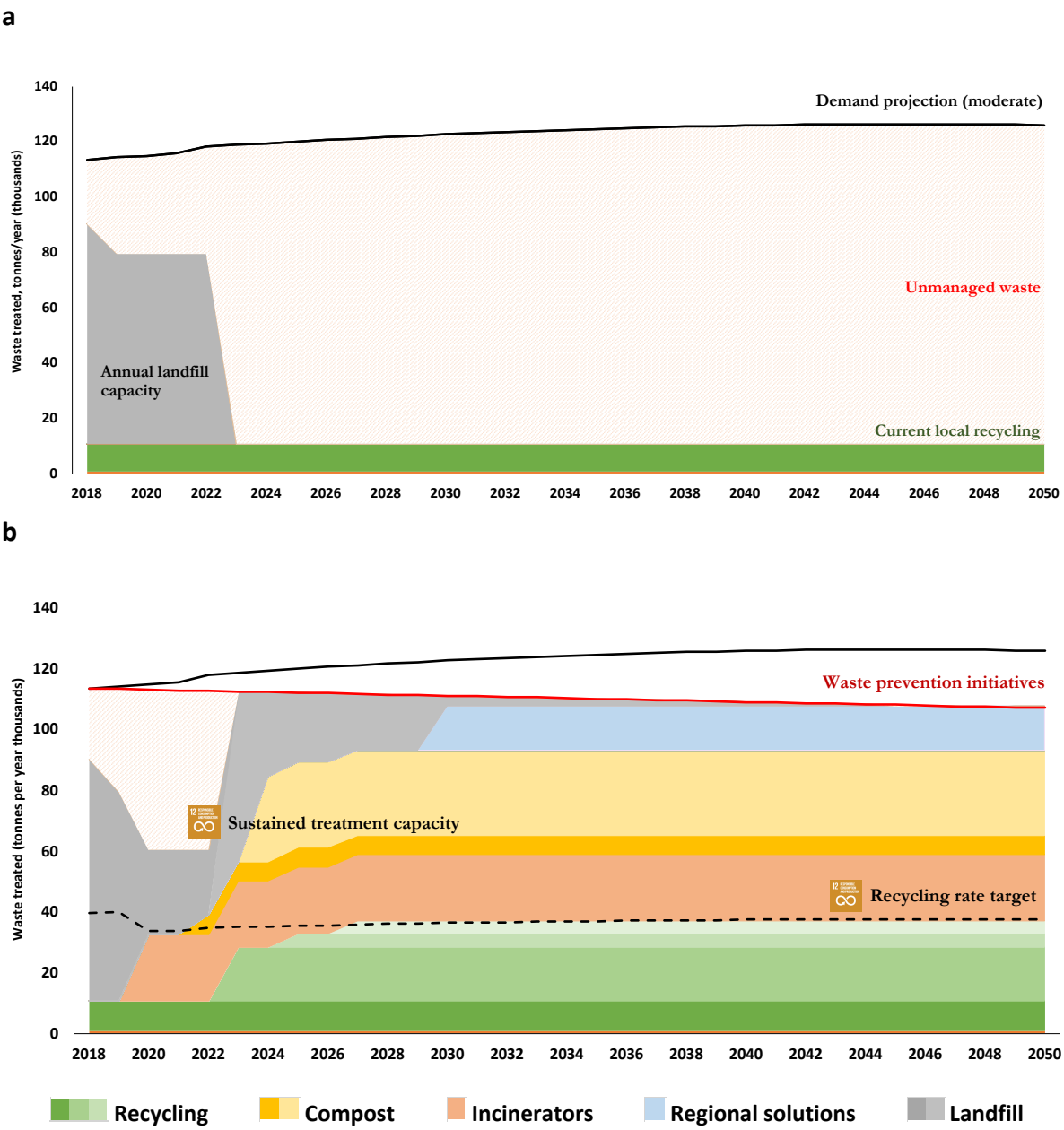


Figure 16: (a) Current solid waste performance and future needs driven by moderate demand projections; (b) Implementation and sequencing of a National Sustainability Strategy incorporating feasible investments and policies to meet relevant SDG and mitigation targets.

To summarise the results, Figure 17 shows the composition of each strategy in 2030 for each of the four sectors, corresponding with the end date of the SDG agenda.

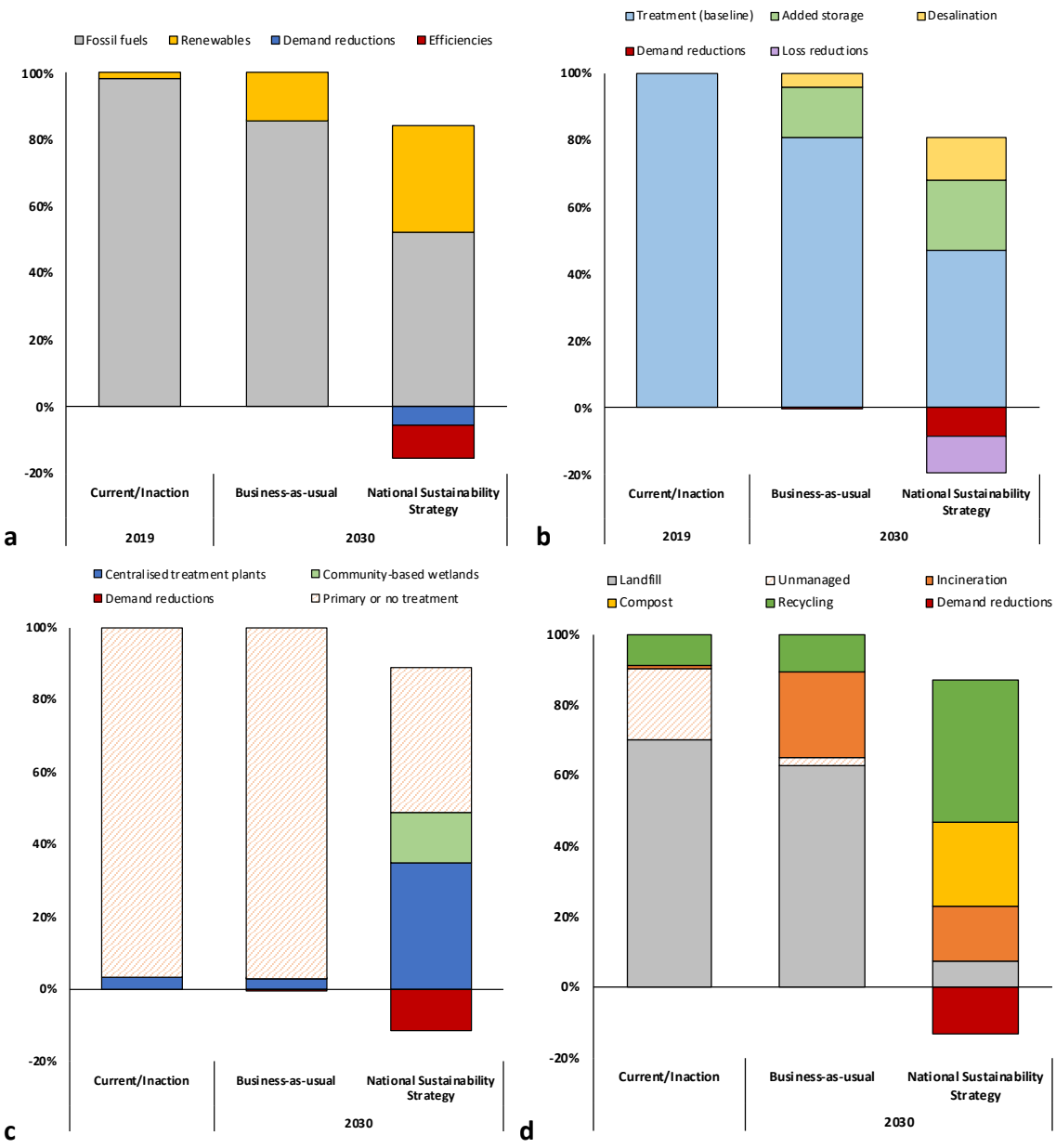


Figure 17: Comparison of infrastructure strategy portfolios for current/inaction, business-as-usual, and sustainability target achievement for (a) electricity; (b) water supply; (c) wastewater; (d) solid waste

4.4.5. Cross-sectoral implications for the Sustainable Development Goals

While these results demonstrate strategic pathways to align supply-side options with future demand for infrastructure, this study also sheds light on each strategy's cross-sectoral

performance in relation to global development outcomes. Previous work by Adshead et al. 2019 developed a means to illustrate the links between infrastructure implementation and specific development outcomes using a set of performance indicators defined in the national context. Applying this framework to Saint Lucia, we get a clearer sense of how different strategies may or may not lead to the achievement of key targets of the Sustainable Development Goals.

Using a sub-set of 18 SDG targets across six goals, Figure 18 shows how development outcomes most directly linked to electricity, water, wastewater, and solid waste infrastructure in Saint Lucia may fare under each strategy. Given a current estimated achievement level of 36 percent across these targets, based on measured indicators assigned to each target, a course of inaction sees this drop to 24 percent by 2030 as future demand growth outpaces current capacity. A business-as-usual approach makes slight gains in the short term due to the implementation of a handful of confirmed projects, but these improvements are halted and begin to marginally decline thereafter due to growing demands. In contrast, an infrastructure strategy based on sustainability objectives demonstrates a path to full achievement of these targets by 2030.

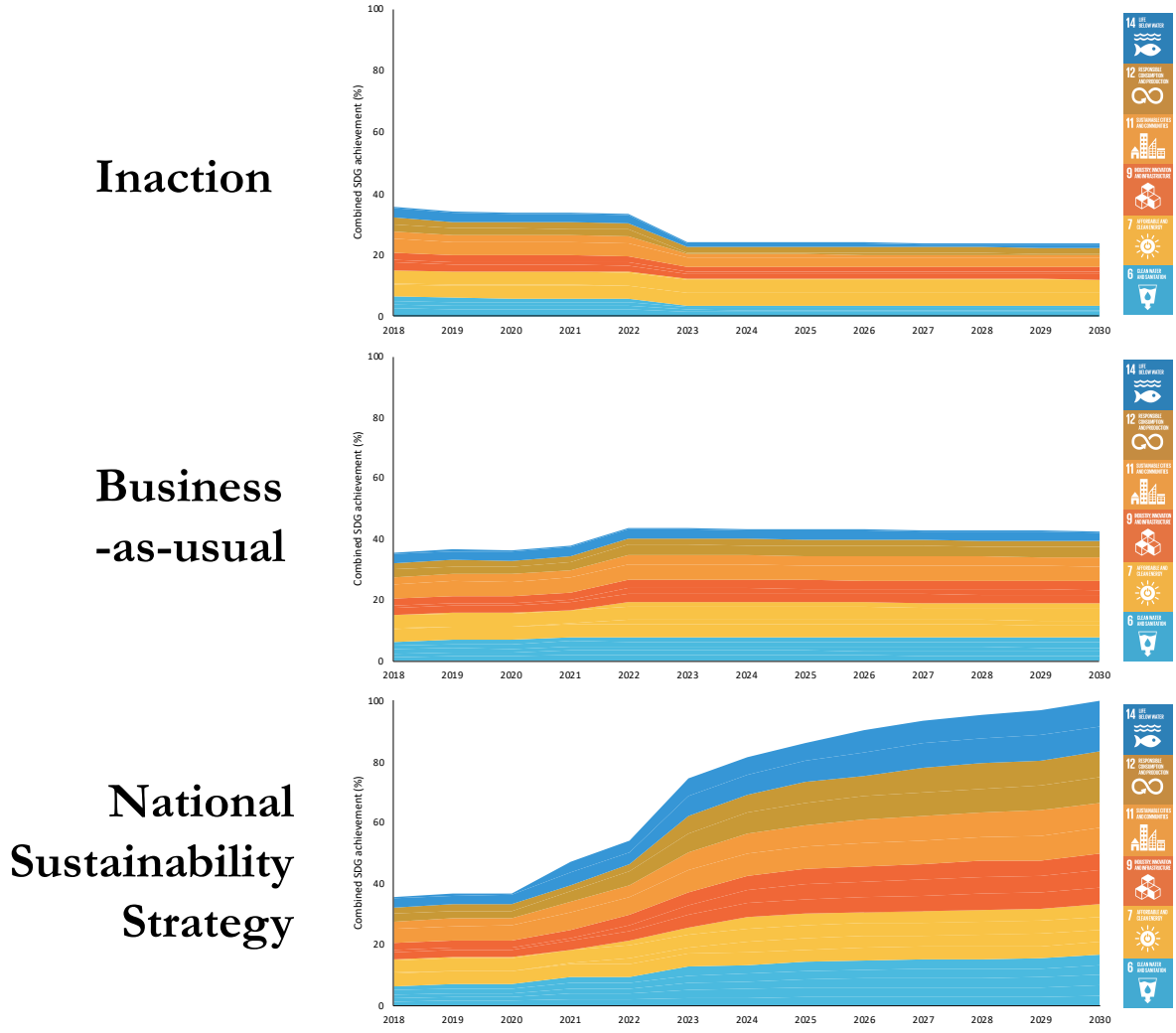


Figure 18: Combined SDG performance to 2030 by strategy, calculated across 18 targets directly linked to the provision of infrastructure using scoring method developed by Adshead (2019)

Sector-specific impacts unique to Saint Lucia's development challenges can be identified in these results. Sustainable Development targets that prioritise a secure energy supply (e.g. 7.1, 7.3, 11.1) fare relatively well in all strategies, due to Saint Lucia's implementation of strong reserve margins for diesel generation, which are entrenched in its Electricity Supply Act (GoSL 1994). Targets centred on environmentally sustainable energy and waste solutions (e.g. 7.2, 9.4, 12.5, 14.5) fare poorly and decline over time without strong interventions. The impact of sudden events such as the depletion of landfill capacity have immediate and visible effects

across numerous targets. In order to ensure that progress toward SDG achievement is sustained into the future, planned infrastructure interventions must also incorporate resilience to the threat of climate impacts and other external shocks.

4.4.6. Cross-sectoral implications for the Paris Agreement

Given that its contribution to global emissions is low, Saint Lucia – along with other small island countries – has generally prioritised adaptation measures to protect its people and infrastructure from the regular threat of climate change-related hazards, and to build resilience to their impacts. This adaptation focus forms a major component of its commitments under the Paris Agreement. Nevertheless, the country is also committed to reducing its greenhouse gas emissions to levels that will restrict global temperature increase to 1.5 degrees above pre-industrial levels and has used its NDCs as an opportunity to promote synergies between its climate commitments and other development priorities. Atypically for small island countries, Saint Lucia's mitigation NDCs extend beyond its energy sector plans to highlight sectoral strategies for a range of sectors, including transport, fisheries, waste, land use, environmental management, and coastal zone management (Atteridge et al. 2019).

To derive the results of the cross-sector infrastructure analysis outlined in the previous sections, the model introduced the government's mitigation targets as stated in the NDCs to help define the conditions for strategic investments and policies, which were assigned per-unit emissions values based on the type of fuel or technology used. Based on BAU emissions projections from 2010, these mitigation targets assume a 16% reduction in emissions by 2025 and a 23% reduction by 2030 (GoSL 2015a). In the electricity sector, energy efficiency

interventions proposed in the NDCs, such as buildings and appliances, were integrated into the strategy selection. While waste proposals were not quantified in the NDCs, overall reductions were achieved in this sector through a shift away from landfill toward lower emitting waste solutions. Although a high-emitting sector, transport interventions could not be integrated in the model; its emissions contributions are nevertheless shown here for comparison.

Figure 19 shows the baseline emissions, in tonnes of CO_2 equivalent, associated with Saint Lucia's main emitting sectors at the last reporting period in 2010 (GoSL 2015b). Over the next decade, meeting a rising demand for infrastructure services through a business-as-usual portfolio of diesel and landfill capacity, in addition to continued fossil fuel use in the transport sector, will result in a failure to meet its mitigation commitments. A national sustainability strategy can bring emissions in these two sectors to target levels, largely by shifting the country to a renewables-based energy portfolio, as well as by removing large quantities of methane-producing waste from landfill sites, to be treated instead through recycling and compost initiatives. In order to achieve its full greenhouse gas reduction commitments under the Paris Agreement, further emissions reductions in the transport sector, as well as industry and agriculture, are required.

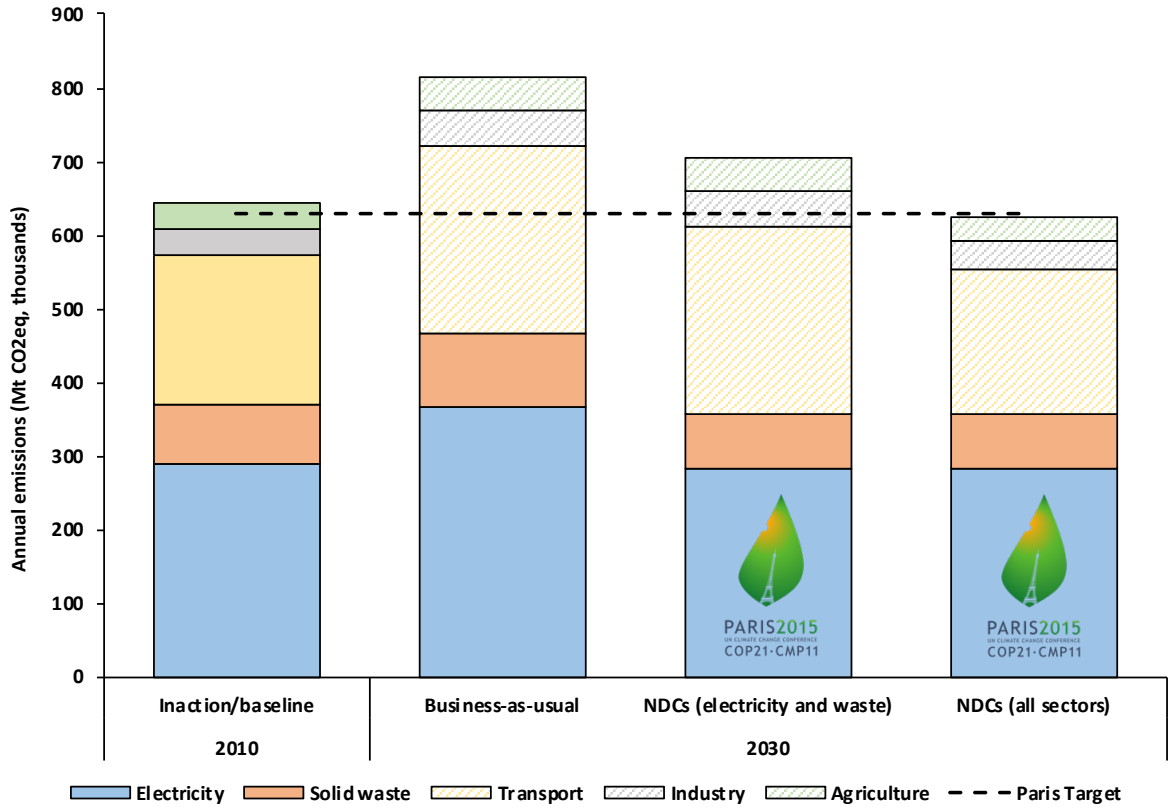


Figure 19: Emissions by sector compared to a 2010 baseline, showing a business-as-usual case and reductions attributed to emissions targets modelled in the electricity and waste sectors. Transport, industry and agriculture are not included in the modelling but required reductions are estimated here to give a full picture of Saint Lucia's commitments under the Paris Agreement.

4.5. Discussion

4.5.1. What have we learned from applying an integrated planning approach to a small island?

The methodological approach developed here provides a systematic process for infrastructure decision-makers, through stakeholder-driven participatory modelling, to formalise pathways to meeting global development targets. As suggested previously, the

small island context of Saint Lucia provides an illuminating study in which to apply this approach given the ability to access a wide and comprehensive range of the island's infrastructure decision-makers, planners, and practitioners.

Importantly, this study has demonstrated the benefits of infrastructure planning across sectors, suggesting that societal benefits can be amplified – and delivered more cost-effectively – when the infrastructure system is addressed in a holistic way. Often, silo-based planning of individual sectors fails to capture these benefits and may lead to sector-specific plans with conflicting outcomes or objectives. Infrastructure practitioners may envision monetary benefits associated with a particular project. In the case of a small island, where tourist revenue is the island's economic lifeline, plans for a new port, expanded airport, or resort development are often sought after for their expected income and employment benefits. But, with residential needs already vastly undersupplied by water, waste, and other infrastructure, how can these major new facilities be supported?

In Saint Lucia, the government's own projections indicate 101 and 57 percent increases in annual stay-over and cruise tourist arrivals, respectively, linked to planned expansions of its air and cruise transport hubs by 2050. This assessment has incorporated these projections to quantify the expected additional pressures on the island's existing infrastructure across other sectors. At the same time, on the solutions side, interdependent measures can address multiple sectors at once. Cumulative water efficiency measures integrated in a sustainable infrastructure strategy were shown to reduce wastewater generation by 12 percent. With the development of wastewater treatment technology, treated effluent may contribute an additional eight percent of water supply for uses such as irrigation. While not currently under

consideration, waste-to-energy and anaerobic digestion technologies may provide solutions that address challenges unique to Saint Lucia and other small islands, such as limited space for landfill and high amounts of organic waste. In Saint Lucia, proposals have shown that these could treat the majority of the island's non-organic and non-recyclable waste and would introduce energy self-sufficiency by generating electricity for the grid. If not feasible on the island, these technologies may also form part of a regional infrastructure strategy, whereby another island relies on waste inputs from its neighbours in order to maintain its investment operating at capacity.

Addressing interdependence has relevance both for meeting infrastructure demand in the long term and for increasing system resilience. Given its interconnectedness, the risks of service disruption posed by specific climate and weather hazards to Saint Lucia's infrastructure sectors can have much broader impacts across the island's social assets such as hospitals, schools, and government buildings.

Cost savings associated with cross-sectoral solutions can make them attractive to policymakers. National infrastructure systems designed in line with Saint Lucia's global commitments may require short-term investment in modern, high-tech facilities and networks – but long-term savings make these strategies most cost-effective. Incorporating demand- and efficiency-side measures in all sectors will bring total infrastructure requirements down – as well as the costs required to supply them. Similarly, investing in more sustainable technologies and solutions will cost governments less in the long-term as demand is more efficiently met and operating expenses decrease. Using per-unit generation costs for relevant technologies derived from national accounts and international energy statistics (NEA

2015; LUCELEC 2018), the total cumulative costs associated with the portfolios of investments and policies used in this analysis are shown for the country's electricity sector (Figure 20). Continuing along the current path to meet increased demand requires less short-term investment in capital expenditure but results in increased costs over time. Interdependent infrastructure sector modelling can identify strategies that lower operating costs in future years, leading to reduced financial commitments for national governments. Further, shifting away from a reliance on diesel-based energy generation will increase the country's energy independence by decreasing its vulnerability to fluctuations in international fuel prices. While data was insufficient to estimate costs across other sectors, these patterns of reduced costs are expected to apply in a similar manner.

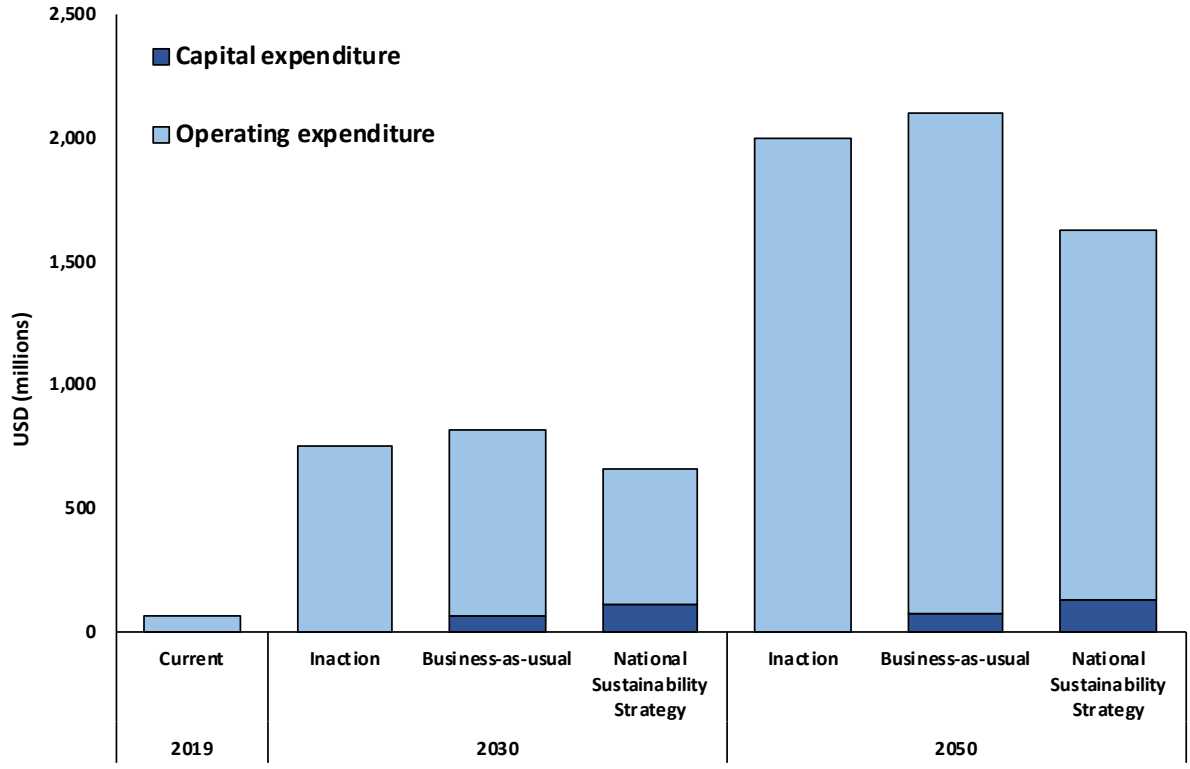


Figure 20: Long-term costs associated with inaction, business-as-usual, and a national sustainability strategy for Saint Lucia's electricity sector

4.5.2. Dynamic and adaptive infrastructure planning has transferable principles that can be applied to a wide range of countries of differing sizes, contexts, and stages of development

Finance and governance of infrastructure are major pieces of the development puzzle, and the adoption of robust and rigorous assessment methodologies allows decision-makers to make investments with a greater potential for impact. The development of tools and methods that decrease uncertainty, and thus mitigate risks, around sustainable infrastructure project delivery is key to attracting international investment necessary to fund ambitious infrastructure plans. A well justified infrastructure strategy helps to build confidence that investments will be used and will yield returns while being consistent with ESG (environmental, social and governance) commitments. Furthermore, infrastructure strategies directly linked to the likely achievement of specific global development targets, such as those included in the SDGs and the Paris Agreement, can provide justification for these large-scale financial commitments. Beyond what has been presented here, there is much scope to pursue scenario assessment of future changes in various aspects of the enabling environment in relation to infrastructure project implementation (Thekdi et al. 2014).

In order to avoid inappropriate infrastructure strategy selection – specifically, those that may face implementation barriers related to the enabling environment – this analysis has relied on stakeholders' opinions as to the potential success of investments and policies, and the timeframe for their implementation. For simplicity, the analysis has filtered out projects presently considered unfeasible in Saint Lucia, such as waste-to-energy. However, given the pace of technology change and shifting political winds, incorporating them alongside relevant risk indicators could provide a more thorough and adaptive assessment. These should

necessarily account for future political, financial, regulatory, and other barriers that may affect the projects' future implementation and may act as constraints or optimisation criteria in the modelling exercise.

A strong enabling environment is required to facilitate sustainable and resilient development across the infrastructure lifecycle. In Saint Lucia, the National Integrated Planning and Programme (NIPP) unit, embedded within the Department of Finance, is tasked with a major responsibility to drive forward this integrated approach to policymaking, coordinating aspects of regulation, finance, project delivery, operations and maintenance, and human capacity. Following a model that has been increasingly employed in other countries (PICC 2012; National Infrastructure Commission 2018; Treasury 2019), the unit provides a means to move away from a siloed approach to infrastructure. This governance model can ensure that national priorities and targets are established and pursued collectively with the input of all relevant stakeholders in the Government of Saint Lucia, research institutions, and the private sector, and regularly informed by the latest available data. Results from this assessment suggest that this will provide Saint Lucia with an infrastructure planning approach that will be cheaper, more efficient, and more closely aligned with national goals and international commitments in the long run. Providing decision-makers with evidence-based tools required to undertake strategic infrastructure assessment will better equip the government to make effective investments and policies in the future.

Infrastructure's ability to achieve development outcomes as encompassed by the SDGs additionally relies on the downstream components of its lifecycle. While the aspects addressed in this study are highly important, they address only the upstream planning

component of sustainable and resilient infrastructure. How infrastructure is then procured, built, operated, and eventually decommissioned is an important consideration for practitioners, in order to ensure that the development benefits of infrastructure are distributed to all stakeholders. In a small island context such as Saint Lucia, a centralised model of island-wide infrastructure planning may identify national-scale interventions aligned with development targets. However, the full range of indirect development impacts should be captured as much as possible throughout the rest of the infrastructure lifecycle by implementing fair employment practices, health and safety regulations, impact assessments, skills training, and other measures (UNOPS 2019). Ensuring that every project is delivered in such a way as to benefit the most vulnerable members of the population, with economic, social, or cultural aspects in mind, will magnify its potential contribution to achieving the Sustainable Development Goals.

4.6. Conclusion

This paper has developed and demonstrated the application of a systematic national infrastructure assessment to a small-island context, consisting of a stakeholder-driven analysis framework that aligns national infrastructure planning with the SDGs and the Paris Agreement. It provides the elements required to effectively assess current and future infrastructure performance, propose a range of strategic options, group these options into policy and investment portfolios, and compare their performance on development outcomes and emissions targets. The results demonstrate that Saint Lucia faces an ambitious, yet feasible, path to reaching relevant 2030 targets and addressing key development challenges through strategic interventions in the electricity, water, wastewater, and solid waste sectors.

The application of this methodology to Saint Lucia was limited in certain ways. First, island-wide data on the transport sector was insufficient to model current performance of the road network and to assess future transport options in relation to relevant SDGs and NDCs. As a result, the implications for emissions reductions in the sector, which will be crucial to meeting the country's NDCs, have been largely omitted from this analysis. A second limitation regards the costs associated with each strategy developed for this analysis, which have been shown only for the electricity sector, due to a lack of costed estimates for other infrastructure types in Saint Lucia. Nonetheless, cost-effectiveness and affordability are essential considerations and should be explored further in future infrastructure assessments.

In Saint Lucia, this study marks only the first step of a journey toward sustainable and resilient infrastructure planning. An iterative assessment process incorporating the methods demonstrated here may provide alternative results defined by the government's shifting priorities, feasibility of investment and policy implementation, and demand driver uncertainties at a given point in time. These principles can be used to inform more robust, coordinated planning and policy solutions, bringing together knowledge and insight from national and local government, the private sector, research and non-governmental organisations together in a central decision-making framework. This may aim to integrate other focus areas and development agendas, such as the Sendai Framework for Disaster Risk Reduction and the New Urban Agenda. A more expansive set of performance metrics using available data will allow infrastructure planning to be targeted to key challenges in each national context. Geospatial hazard and adaptation analysis can complement long-term infrastructure planning by assessing the long- and short-term threats to infrastructure assets posed by climate change and extreme weather events.

The challenges facing small islands in the coming decades are stark: demographic uncertainties, increased intensity of climate change, and the urgent need to ensure reliable, clean, and affordable infrastructure services for residents and visitors. With infrastructure so crucial to Saint Lucia's development, the consequences of inaction or a business-as-usual approach to infrastructure planning will limit the island's social and economic potential. This study demonstrates how a combination of infrastructure systems analysis and decision analysis, informed by quantified performance metrics, and help to create an actionable infrastructure strategy that maps out a pathway towards a more sustainable future for the island.

4.7. Appendix: supplementary figures and tables

Target	Date of target achievement	IN	BAU	NSS	Target source
Electricity capacity margin	2030	-	1.60	1.35	GoSL 1994 IEA/OBG 2020
Share of renewables	2030	-	0.14	0.35	GoSL 2015a SDG 7.2
Share of renewables	2040	-	0.14	0.50	GoSL 2015a
Water capacity margin, annual average	2030	-	1.55	1.40	WASCO 2019
Water capacity margin, peak demand	2030	-	0.56	1.00	WASCO 2019 SDG 6.1
Water capacity margin, peak demand	2045	-	0.56	1.00	SDG 6.1 extension
Wastewater treated	2030	-	0.03	0.61	SDG 6.3
Wastewater treated	2045	-	0.03	0.80	SDG 6.3 extension
Wastewater collected	2030	-	0.72	1.00	WASCO 2019
Recycling rate	2030	-	0.12	0.35	EPA 2017 SDG 12.4
Unmanaged waste (%)	2030	-	0.21	0.00	SLUSWMA 2019
Emissions - electricity sector (t CO2eq)	2025	-	329,079	286,808	
Emissions - waste sector (t CO2eq)	2025	-	88,605	77,223	GoSL 2015a
Emissions - electricity sector (t CO2eq)	2030	-	366,941	282,401	
Emissions - waste sector (t CO2eq)	2030	-	98,799	76,037	

Table 3: Key infrastructure targets aligned with Saint Lucia's national policy priorities and international development commitments

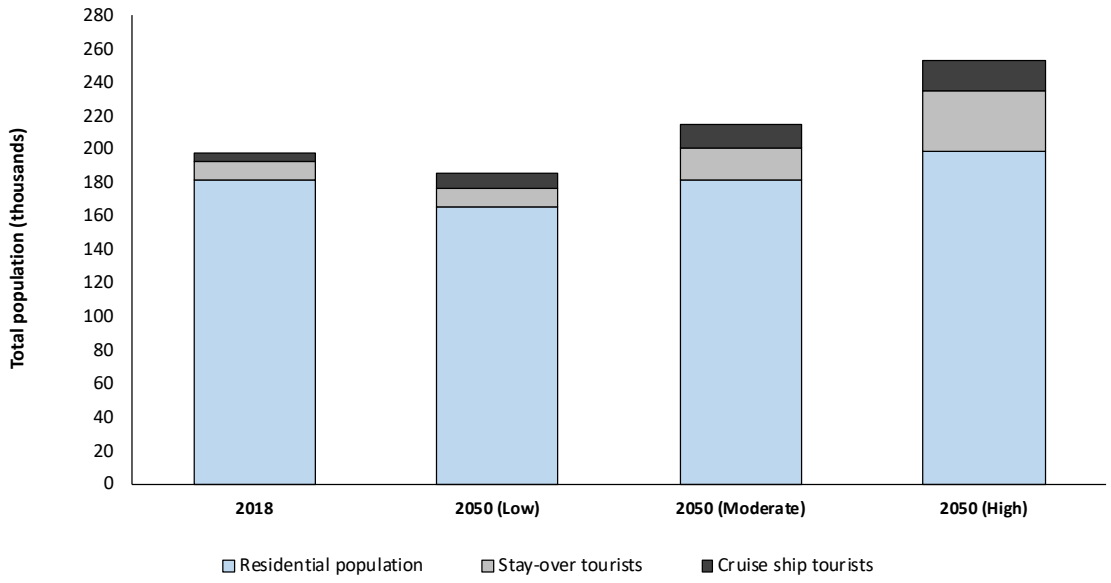


Figure 21: Combined residential and tourist population under a low, moderate, and high growth scenario, 2050

Chapter 5: Aligning mitigation actions with development challenges in updated Nationally Determined Contributions

Daniel Adshead[a], Scott Thacker[a,b], Jim W. Hall[a]

a Environmental Change Institute (University of Oxford), South Parks Road OX1 3QY, Oxford, United Kingdom.
b United Nations Office for Project Services (UNOPS), Marmorvej 51, Copenhagen, Denmark.

This chapter addresses Research Question 3: *How can synergies between development and climate objectives be utilised to define appropriate cross-sectoral actions in national mitigation strategies?* This chapter explores the range of mitigation targets and actions across the major infrastructure and land use sectors in the Nationally-Determined Contributions (NDCs) of 195 countries. Combining an established indicator framework for the SDGs with greenhouse gas inventory data from the UNFCCC, the chapter assesses the alignment of national NDC commitments with gaps in development and climate targets, at a country level and globally. The results suggest areas of consideration for stakeholders in the national policy domain and academic research in expectation of the revised set of NDCs.

Daniel Adshead designed the study, performed the analysis, and wrote the paper. Scott Thacker and Jim W. Hall provided feedback and edits to the text and figures.

This study was submitted to ***Global Environmental Change*** on 6 November 2020.

5.1. Abstract

The Nationally Determined Contributions, or NDCs, provide a formalised mechanism for countries to communicate their commitments to maintaining climate change to under two degrees, as specified in the Paris Agreement. Actions to mitigate greenhouse gas emissions can also contribute to a country's wider development targets, for example by promoting energy security, clean cooking, and afforestation. Aligning NDCs with country-specific targets for sustainable development provides greater motivation for mitigation policies. We have therefore systematically analysed the contribution that existing NDCs make to Sustainable Development Goal (SDG) performance for four of the most relevant indicators. From analysis of the NDCs of 195 countries we find that a large number of NDCs contain qualitative commitments only, and many NDCs contain no sectoral targets at all: energy (25% of NDCs), transport (48%), waste (62%), agriculture (68%) and forestry (48%). In most cases the relevant SDG targets will not be met through implementation of the NDCs. The study shows the extent to which mitigation commitments currently fall short of what is required to deliver on the selected SDG targets. Furthermore, the NDC formulation process lacks consistency in providing a mechanism for reporting that is measurable and comparable across contexts. When updating NDCs, countries have the opportunity to align them more explicitly with their sustainable development targets, which will leverage urgent action during the 'decade of delivery'.

5.2. Introduction

The year 2020 marks a crucial milestone in the enhancement of mitigation efforts under the Paris Agreement on Climate Change. As specified by the agreement's 'ambition mechanism', the 195 countries party to the agreement are expected to update and communicate their pledges (NDCs) to further reduce greenhouse gas emissions on a five-year basis and strengthen their mitigation and adaptation responses to climate change (UNFCCC 2015). At the same time, the 2030 Agenda for Sustainable Development (consisting of the 17 SDGs) necessitates continued commitment by national governments to address development challenges and improve upon performance across a range of social, economic, and environmental outcomes.

The 2030 Agenda recognises the alignment between climate change mitigation and other sustainable development objectives. Specifically, actions undertaken to reduce greenhouse gas emissions are known to have benefits across a range of development outcomes beyond climate change mitigation itself (Ürge-Vorsatz et al. 2014). A recognition of the development benefits of mitigation can help to motive and strengthen urgent action, when the benefits of mitigation may not be immediately evident, especially in the most resource-strapped countries.

Higher national carbon emissions have traditionally been associated with economic growth and development, largely through a country's increased energy consumption (Ang 2007), although the nature of the causal relationship between these two variables is debated (e.g. Mutascu 2016; Acheampong 2018). When considering aggregate measures of development

achievement, the negative environmental impacts of fossil fuel use that have always accompanied development tend to get outweighed by progress on economic and social indicators. For example, Figure 22 plots per capita greenhouse gas emissions against the average development score across the 17 SDGs for non-Annex parties to the United Nations Framework Convention on Climate Change, demonstrating a positive relationship between emissions and development score. The majority of these non-Annex parties are developing countries and are recognised as being especially vulnerable to the adverse impacts of climate change or to the potential economic impacts of climate change responses (Allwood et al. 2014). Crucially, these Parties are not legally bound to reduce emissions, so mitigation action needs to be driven by other motivations in order to decouple emissions from development progress.

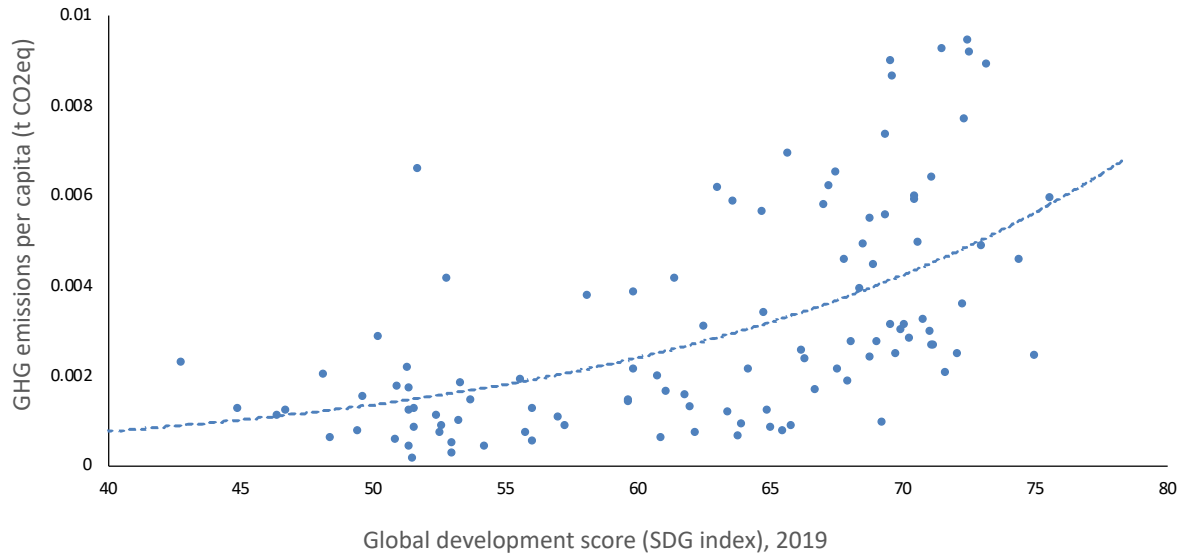


Figure 22: Per capita greenhouse gas emissions by global development score for Non-Annex countries (data from Sachs et al. 2019; UNFCCC 2020)

The need for emissions reductions is greatest amongst middle and high-income countries, as industrialised countries contribute a much higher proportion of current global emissions than

their less-developed counterparts. At the same time, high-income countries achieve only 76 percent on average across the 17 Sustainable Development Goals according to global indices (Sachs et al. 2019), due largely to disproportionate environmental degradation which is reflected through poor performance in SDGs 12 through 15. Higher per capita incomes are associated with more consumption and waste generation. Therefore, these countries also face important decisions, and potential trade-offs, around shifting their emissions trajectory while also addressing aspects of sustainable development in which they under-perform. Measures taken to reduce emissions can aim to target these outstanding gaps by accounting for specific co-benefits, such as air and water pollution.

During the years preceding the negotiation of the Paris Agreement at the 21st Conference of the Parties (COP21), research converged around the challenges of defining a framework for merging climate change mitigation and adaptation actions with development outcomes suited to a wide range of global contexts (Mitchell & Maxwell 2010). The *triple-win* potential provided by this 'climate-compatible' development landscape has provided an appealing framework for the assessment of development projects across multiple sectors (Suckall et al. 2015; England et al. 2018). It has, however, attracted scrutiny not least for its failure to address the commensurability and trade-offs inherent across its three dimensions, beyond economic measures (Ficklin et al. 2018). Furthermore, the often hierarchical structure of these dimensions – with development outcomes viewed only as *co-benefits* of climate stabilisation – has led to calls for reconceptualization of the framing and integration of climate and development goals (Janetos et al. 2012; Winkler et al. 2015).

By requiring each party to draft its commitments in the form of NDCs, the Paris Agreement has offered a formalised mechanism through which to assess and compare countries' approaches to integrating mitigation and national development goals, specifically those set according to the SDG framework. In response, studies have raised numerous inconsistencies in the *climate-compatible development* assessment environment: misalignment between mitigation pathways developed in response to the Agreement and non-climate dimensions of the SDG agenda such as energy (von Stechow et al. 2016) and poverty (Campagnolo & Davide 2019); missed synergies due to the separation of NDC planning from development policy (Scott et al. 2018); a lack of comparability with regard to mitigation impacts across contexts (Iyer et al. 2018); and the conflicting nature of the SDG and NDC policy instruments themselves (Shockley 2018).

In light of the expectation that countries increase the ambition of their NDC pledges, we focus on the interface of climate mitigation action and development to explore current commitments and propose ways in which their effectiveness might be increased. Due to limited guidance provided early in the submission process, there is extremely large variation in the content, form, scope and coverage of NDCs (Taibi & Konrad 2018; Roelfsema et al. 2020). Thus, there are numerous mechanisms available to decision-makers as a means to increase ambition levels, including strengthening or adding GHG targets, non-GHG sectoral targets, related policies and actions, and so on (Fransen et al. 2017). These targets, policies, and actions are distributed across various sectors, focusing on major infrastructure types (e.g. energy, transport and waste) as well as natural resource sectors and land uses, primarily forestry and agriculture. Updating these commitments through the SDG lens can lead to more targeted, comprehensive ambitions in the next NDC cycle (Brandi, Dzebo & Janetschek 2017).

Figure 23 depicts the relationship between greenhouse gas emissions and sustainable development, conceptualising three potential future trajectories for countries across income groups: (1) unmitigated development, where countries aim to increase their achievement across development indicators without prioritising their mitigation potential – this is the route that has been taken by high income countries; (2) measures to reduce emissions in line with ambitious targets, but which do not make much contribution to addressing SDG gaps in the country; (3) a well-aligned SDG and mitigation strategy to achieve maximum potential across both agendas.

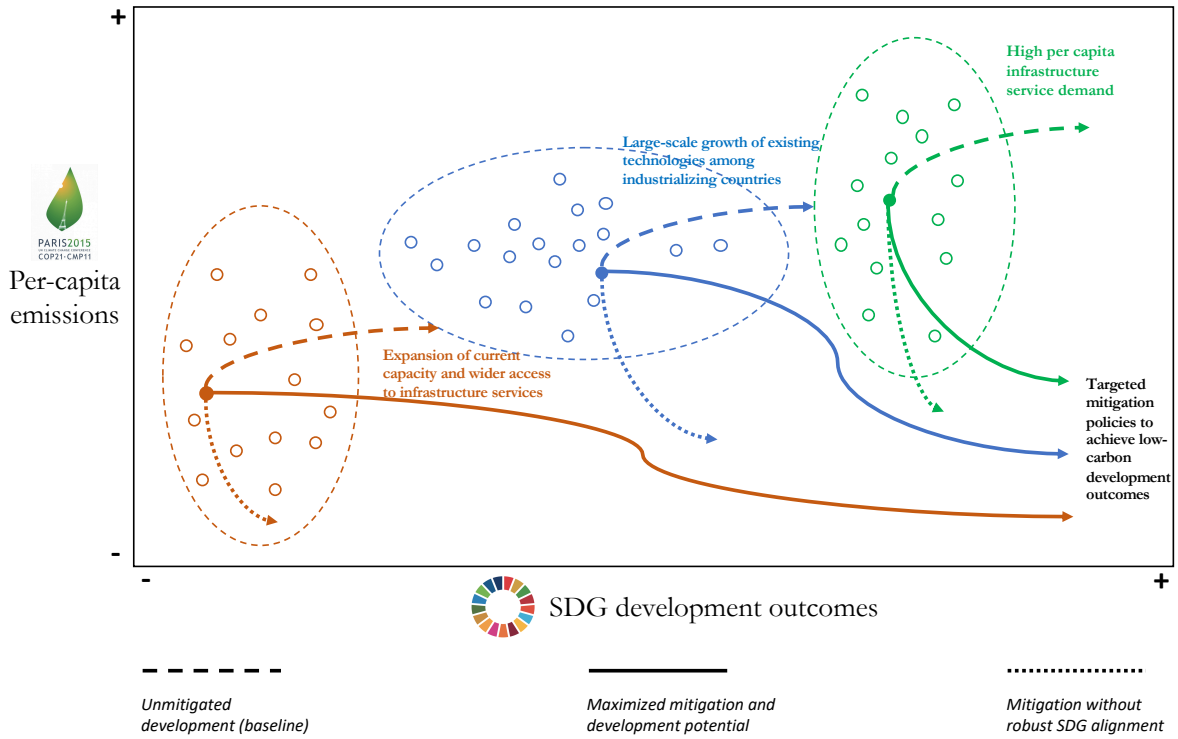


Figure 23: Potential country trajectories across the mitigation and development interface

The potential for infrastructure to influence sustainability outcomes is well-documented (e.g. Bhaduri et al. 2016; UNESCAP 2017; Fuso Nerini et al. 2018; Thacker et al. 2019), as are the

extensive SDG impacts of measures related to land use and restoration (FAO 2018; IRP 2019). However, the distribution of SDG achievement across goals varies by country (Sachs et al. 2019), necessitating targeted actions to address specific gaps and underperformance in certain themes or indicators. With a better understanding of these gaps, climate mitigation actions can be designed to deliver these targeted solutions.

Recent integrated modelling approaches used to assess the societal transformations required to achieve the Agreement's objectives (TWI2050 2018; Gidden et al. 2019) offer some insight into the advantages and trade-offs of certain sectoral contributions to mitigation. Not surprisingly, the development of renewable energy generation capacity has been identified as the most feasible direction to meet climate objectives (Gielen et al. 2019), although the early implementation of stringent demand reductions and efficiencies are also predicted to increase flexibility to meet emissions targets in the long run (Rogelj et al. 2015). While proportional contributions from the transport sector have been considered difficult to achieve (Pietzcker et al. 2014), a nuanced approach to identifying effective emissions reductions measures and policies can realise greater mitigation potential within the sector (Gota et al. 2019). In the waste sector, where the large role of methane in global warming is recognised (Du et al. 2017), a range of potential actions can come together as part of an effective management and mitigation strategy (Maria et al. 2020). However, the efficacy of such a strategy has been shown to be context-specific, based on factors such as the characteristics of the waste stream (Liu et al. 2017).

Among the land use sectors, large scale afforestation and reforestation are considered key components of carbon dioxide removal efforts (Rogelj et al. 2018). In agriculture, policy

options through which to increase mitigation ambition remain comparatively diverse (Richards, Wollenberg & van Vuuren 2018), and major challenges remain to integrate non-uniform mitigation targets into national policy frameworks (Fellmann et al. 2018). In addition to highlighting potential areas of focus for policymakers designing mitigation strategies, trade-offs between certain types of policies and development outcomes in key areas such as food security and energy access have been identified (Doelman et al. 2019; Fujimori et al. 2019; Dagnachew et al. 2018).

At the climate talks in Madrid (COP25), more than 100 countries signalled their intention to boost the ambition of their NDCs in the next NDC cycle. Despite this, doubts have been raised among stakeholders as to governments' commitments, citing the identification of appropriate policy options and balancing of political priorities as key barriers, in addition to financial considerations (van Tilburg et al. 2018). For less developed countries in particular, which arguably have the most to gain in terms of sustainable development benefits from a shift to a low carbon economy (Ryan-Collins, Ellis & Lemma 2011), these barriers can be daunting. Given this, and the lack of a consistent system for target-setting within NDCs, it seems that the commitments currently pledged by many countries do not fully align with their development needs. A greater understanding of mitigation's role in the achievement of sustainable development outcomes is critical to linking the two agendas and encouraging increased ambition in updated NDC pledges.

Previous initiatives have sought to examine the points of intersection between the mitigation and sustainable development agendas. These have largely focused on key word searches assessing the degree of alignment between actions communicated in countries' NDCs and

SDG target descriptions, with the majority of examples expressed in qualitative terms (Northrop et al. 2016; Dzebo et al. 2019). Using this approach, avenues for policy coherence have been identified at the country level (Nguyen et al. 2018), as have priority areas for thematic coherence between the two agendas, such as energy efficiency, sustainable forest management, and sustainable agriculture (Janetschek et al. 2020). Thematic areas found to be under-prioritised in NDC activities have similarly been identified (Dickin & Dzebo 2018). While these studies provide a basis for assessing general alignment between these two agendas, they do not go as far as to address countries' SDG achievement gaps and their potential elimination through specific sectoral actions or targets.

This study makes two important contributions to addressing these issues. First, it rationalises NDCs into several measurable metrics that can be used to evaluate achievement of mitigation and development outcomes. Second, it places development needs at the heart of climate policy and provides a framework for enhancing mitigation targets which is directly informed by the development challenges faced in a particular country or context. In doing so, it provides a means for policymakers to align their mitigation options to an overall development trajectory that can maximise achievement of the Sustainable Development Goals. This serves to dispel the common notion that increasing mitigation ambition could pose an insurmountable burden, financially or otherwise, by demonstrating how well-targeted mitigation can also deliver sustainable development benefits.

5.3. Methods

5.3.1. Mitigation commitments in Nationally Determined Contributions

In order to provide a means of comparison between current NDC ambition levels, we standardise several of the diverse measures included in the mitigation commitments within each NDC. To understand the range of mitigation mechanisms available to policymakers, we catalogue the full range and distribution of sectoral targets and actions across all country NDCs in the energy, transport, and waste sectors, as well as the major land use categories of forestry and agriculture. Where applicable, targets related to quantified levels (e.g. “30% renewable energy share in electricity production by 2030”) or actions (e.g. “Scale up access and adoption of 2 million efficient cook stoves up to 2030”) in each of these sectors were identified. Where no quantified targets exist for a sector, qualitative targets were noted (e.g. “Improving crop and livestock production practices for greater food security and higher farmer incomes while reducing emissions”). Where no quantitative or qualitative sectoral targets were identified in a country’s NDC, this was similarly recorded.

Figure 24 shows the geographical distribution of these types of commitments across each of the five sectors. While the sectoral focus of commitments varies country-to-country, some patterns emerge. Ambitious renewables targets are noted in small island countries where energy independence will be crucial to future economic security. A number of well-defined transport plans and targets exist in lower- to middle-income countries with rapidly urbanising populations. The need and potential for large-scale avoided deforestation and reforestation efforts is present in the tropics as well as some arid countries where desertification threatens

widespread environmental degradation. With agriculture accounting for a large share of national income in low-income countries, many countries in Africa and Asia emphasise mitigation measures in this sector. In terms of quantification, many high-income countries such as European Union members and the United States present their NDCs in the form of high-level emissions targets without detailing sectoral plans and sub-targets that support them.

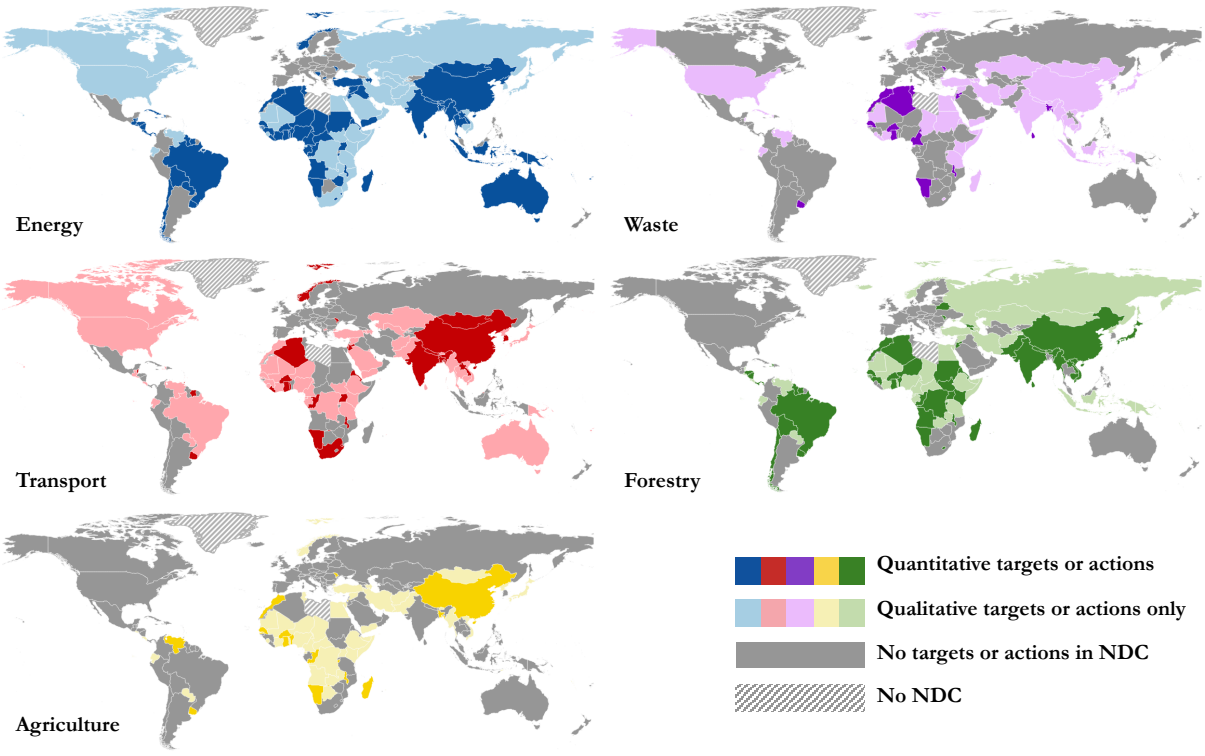


Figure 24: Geographical distribution of NDC commitment quantification across the energy, transport, waste, agriculture, and forestry sectors

Among the most commonly quantified targets, the various means of measurement used were standardised into metrics of change from current levels. Within the energy sector, mitigation commitments could be compared across the subcategories of renewable energy generation, consumption (demand and use reductions), supply efficiencies (transmission losses), and appliances (specifically, efficient cookstoves). **Renewable generation** is measured as a change

from the current level with a 2015 baseline derived from the IRENA (2020) global dataset. Where commitments are instead expressed in terms of individual projects or generation values (e.g. “Extension of National Wind Plan to 2,000 MW by 2030”), these values are incorporated in the current renewable capacity to estimate the NDC-based target. Similarly, **access to clean cooking** is measured as a percent shift from current levels (Sachs et al. 2019). Where commitments are made to implement a certain number of efficient cookstoves, the implications for access across the overall population are estimated using UN (2020) data on household size by country. Reductions in **energy consumption** (e.g. “Achieve 5% savings in overall electricity demand” and supply-side energy savings through reduced **transmission losses and efficiencies** (e.g. “50% decrease in losses through smart meters and net metering”) are quantified, as stated in the NDCs, as percent changes from the total demand.

In the forestry sector, **forest cover change** commitments were calculated as an increase from the 2015 baseline (World Bank 2020) for nationally stated targets (e.g. “Increase in the forest cover from 6 to 10 percent by the year 2030”). Where non-agricultural forest commitments are expressed in hectares (e.g. “100,000 ha reforestation by 2030”), these values are added to current coverage to estimate the national target, taking into account the annual or total nature of the forestation programme.

Targets related to the **transport** sector vary greatly and are thus not expressed in terms of a consistent metric, instead incorporating commitments related to public transport use, increase in fuel use efficiency, uptake of electric vehicles, expansion and uptake of rail transport, and others. However, since effective transport investments and policies are highly dependent on the national context, a general indicator of commitment to decarbonisation of

the sector could be derived (e.g. “20% shift from private transport to public transport” or “30% decrease in vehicle fuel consumption”). While these are not fully comparable, they give some indication of the country’s ambition given available resources and technologies. Similarly, actions and targets around municipal **solid waste** are expressed using diverse metrics such as reduced landfill, recycling and compost, or methane emissions capture, which can be used to proxy the NDC’s ambition to reduce emissions in the sector (e.g. “Reduce solid waste disposed in landfills to 60% from 80% by 2025” or “50% of the emissions from landfill methane are captured for flaring”).

While **agriculture** forms a significant component of many countries’ mitigation strategies, the range of targets used in NDCs, covering livestock, irrigation, fertilizer use, agroforestry, and other actions, makes sector commitments largely incomparable across countries in their current form.

5.3.2. Linking mitigation action in infrastructure and land use sectors to progress in key SDG targets

The varied NDC commitments outlined in the previous section each provide some means to contribute to a country’s development. However, there currently exists no framework to quantitatively link these targets to a definitive set of outcomes so as to assess the broader potential SDG contributions of a county’s NDC commitments. Using the SDG index indicators from the Sustainable Development Report (Sachs et al. 2019) we identify 17 indicators across 8 SDGs whose progress can be explicitly or directly measured by quantitative sectoral targets found in country NDCs. This includes the energy sector (7 indicators); transport sector (4);

waste sector (5); agriculture sector (4); and forestry sector (2), with three impacting more than one sector. For each of these indicators, outlined in Table 4, we can identify and justify several NDC targets across the five assessed sectors that can be used to measure direct progress toward it.

SDG	Indicator (from Sachs et al. 2019)	Related sectoral targets or actions from NDCs (mitigation component)	Mechanism of potential NDC impact on SDG indicator	Reference(s)	Number of NDCs
	**Cereal yield (t/ha)**	***Agriculture:*** • Area of increased soil fertility (ha or %) • Climate-smart agriculture targets (e.g. no-till, service crops) • Reclamation of degraded agricultural land (ha) • Committed areas of agroforestry or arboriculture (e.g. olive, citrus trees) (ha)	Improvement in crop yield due to mitigation action on soil, crops and land reclamation	Shang et al. 2014	16
	Sustainable Nitrogen Management Index	***Agriculture:*** • Fertilizer reduction or organic use • Reduction in N2O intensity of agriculture or livestock production • Climate-smart agriculture targets (e.g. no-till, service crops)	Mitigation actions to reduce nitrogen production associated with crop fertilization techniques improve sustainable nitrogen indicator, assuming yield does not decrease	Shibata et al. 2016	15
	**Age-standardised death rate attributable to household air pollution and ambient air pollution (per 100,000 population)**	***Energy:*** • Emissions reductions in the energy sector • Committed investments in renewable energy ***Transport:*** • Emissions reductions in the transport sector • Vehicle fuel use and efficiency • Electrification of transport ***Waste:*** • Landfill reduction targets	Emissions from the energy sector directly contribute to household air pollution (e.g. cooking fumes); emissions from the energy (including industry), transport, and waste (landfill) sectors directly contribute to ambient air pollution	Njoku et al. 2019 (waste)	100
	Traffic deaths rate (per 100,000 population)	***Transport:*** • Traffic decrease targets • Expansion of public transport networks	Decreased traffic associated with fewer accidents. Modern public transportation vehicles and networks reduce traffic deaths.	Lichtman-Sadot 2018; Cafiso et al. 2012	18
	**Population using at least basic sanitation services (%)**	***Waste:*** • Wastewater connection or treatment rate	Indicator directly measurable through action(s)	NA	1

	Freshwater withdrawal as % total renewable water resources	***Agriculture:*** • Share of crops using efficient irrigation technology • Construction of reservoirs	Specific mitigation actions in agriculture decrease share of national freshwater withdrawal used in sector	FAO 2016	3
	**Access to electricity (% population)**	***Energy:*** • Access to electricity at national scale or by population category (e.g. rural, urban, household) • Electrification or grid access • Committed investments in fossil fuels • Committed investments in renewable energy	Indicator directly measurable through action(s)	NA	100
	Access to clean fuels & technology for cooking (% population)	***Energy:*** • Share (or increase) in household access to clean cooking and fuels • Committed distribution of clean or efficient cookstoves	Indicator directly measurable through action(s)	NA	18
	CO2 emissions from fuel combustion / electricity output (MtCO2/TWh)	***Energy:*** • Emissions reductions in the energy sector • Committed investments in renewable energy	Indicator directly measurable through action(s)		
	Share of renewable energy in total final energy consumption (%)	***Energy:*** • Renewable energy target • Committed investments in renewable energy	Indicator directly measurable through action(s)	NA	85
	**Annual mean concentration of particulate matter of less than 2.5 microns of diameter (PM2.5) (µg/m3)**	***Energy:*** • Emissions reductions in the energy sector • Committed investments in renewable energy ***Transport:*** • Emissions reductions in the transport sector • Vehicle fuel use and efficiency • Electrification of transport ***Waste:*** • Landfill reduction targets	Emissions from the energy (including industry), transport, and waste (landfill) sectors directly contribute to ambient air pollution	Njoku et al. 2019 (waste)	100

	Satisfaction with public transport (%)	***Transport:*** • Traffic decrease targets • Expansion of public transport networks	Public transport and travel satisfaction linked to uptake and expansion of bus and rail networks	Currie & Wallis 2008; Abou-Zeid & Fujii 2015	18
	**Municipal Solid Waste (kg/day/capita)**	***Waste:*** • Solid waste management and landfill reduction • Recycling and compost targets • Waste incineration	Indicator directly measurable through action(s)	NA	13
	Nitrogen production footprint (kg/capita)	***Agriculture:*** • Reduction in N2O intensity of agriculture or livestock production ***Waste:*** • Compost targets	Composted food waste reduces overall nitrogen footprint as it reuses nitrogen	Shibata et al. 2016; Leary et al. 2017	15
	**Energy-related CO2 emissions per capita (tCO2/capita)**	***Energy:*** • Emissions reductions in the energy sector • Committed investments in renewable energy	Indicator directly measurable through action(s)	NA	97
	**Mean area that is protected in terrestrial sites important to biodiversity (%)**	***Forestry/land use:*** • Protected forest area (ha or %) • Protected, conserved, or restored terrestrial area - non-forest (e.g. grasslands, wetlands, rangelands) (ha or %) • Deforestation rate	Indicator directly measurable through action(s)	NA	35
	Permanent Deforestation (5 year average annual %)	***Forestry/land use:*** • Forest cover targets • Protected forest area (ha or %) • Deforestation rate • Planned afforestation or reforestation (ha)	Indicator directly measurable through action(s)	NA	48

Table 4: Sectoral actions or targets from the NDCs as a means to measure progress toward selected SDG index indicators (Sachs et al. 2019)

5.3.3. Tracking SDG progress and emissions changes linked to NDC commitments

Having comprehensively classified quantified NDC sectoral commitments (2.1) and linked specific NDC targets and progress to SDG target outcomes (2.2), we now estimate how a subset of these SDG outcomes across all countries are projected to change with the implementation of NDC targets as currently stated. We focus on a cross-sectoral subset of four indicators whose adjusted performance can be straightforwardly calculated using the targets established in the NDCs: (1) renewable energy generation; (2) access to clean cook stoves; (3) municipal solid waste generation; (4) afforestation / reforestation. For ease of analysis, slight adjustments to the latter two indicators, relative to their equivalents in Table 4, have been made:

- In order to focus on emissions from *landfilled* waste, recycled and composted material has been subtracted from per capita municipal solid waste generation using the appropriate rate for each country (Kaza et al. 2018);
- As target deforestation rates are not frequently cited in the NDCs, the current normalised deforestation score is adjusted using the projected change in forest cover as an estimate of its impact on mitigation in the forestry sector.

The impact of these targets on sectoral emissions was also assessed. Emissions data for each relevant sector was extracted from the UNFCCC emissions inventory. Sectoral totals of major emissions categories – energy (minus transport), waste, forestry/land use – were calculated from the latest reported year. A detailed list of the assumptions and methods used to track the impact of NDC commitments across these indicators is included in Table 5.

	Indicator	Assumptions used	Notes on metrics used
a. SDG-related indicator performance	*Renewable generation*	-	-Change in renewables derived from additional MW of generation committed in NDC or stated target (% of total). -Current renewables from IRENA (2020) renewable electricity statistics.
	Access to clean cook stoves	One cook stove minimum per household	-Change in access derived from number of additional cook stoves committed in NDC or stated access rate target. -Population and current clean fuel access rate by country from Sachs et al. (2019). -Household size by country from UN DESA (2019).
	MSW generation	-Indicator combines measures to reduce emissions from landfill -Recycled and composted waste subtracted from the waste stream.	-Municipal solid waste generation per capita from Sachs et al. (2019). -Country-level waste composition data (recycling and compost rates) taken from Kaza et al. (2018).
	Afforest/reforestation	-Change in target forest cover used to adjust normalised 5-year deforestation rate score from SDG index indicators. (Not enough targets related to specific deforestation rate included in NDCs).	-Change in forest cover derived from additional hectares of afforest/reforestation committed in NDC, or stated target (% of land area). -Forest cover data 2010-2015 from World Bank WDI (2020). -Deforestation rate (normalised) from Sachs et al. (2019).
b. Associated emissions reductions (all values shown per capita)	*Renewable generation*	Zero direct CO_2 emissions from renewable sources.	Not accounting for indirect (embodied) emissions which are insignificant in relation to savings (Pehl et al. 2017)
	Access to clean cook stoves	Savings of **4 kg CO_2 / efficient cookstove** per day	With conservative fuel savings of 35% observed in the laboratory, one BDS will save about 4 kg of CO2-e from entering the atmosphere per day (Wilson et al. 2016).
	MSW generation	**0.58 t CO_2/t MSW**	IPCC technical parameters and estimates for cost of conserved carbon of waste treatment practices (Schlömer et al. 2014)
	Afforest/reforestation	**5 t CO_2/ha** (most countries with forestry targets are in temperate or tropical regions)	Typical sequestration rates for afforestation / reforestation, in tonnes of carbon per hectare per year, are: 0.8 to 2.4 tonnes in boreal forests, 0.7 to 7.5 tonnes in temperate regions and 3.2 to 10 tonnes in the tropics (Brown 1996).

Table 5: Assumptions used to demonstrate changes in development outcomes and associated sectoral emissions reductions in four sectoral indicators

5.4. Results

5.4.1. Comparing mitigation ambition across 195 NDCs

Figure 25 shows the full breakdown of NDC targets across energy, transport, waste, agriculture, and forestry, highlighting the balance of quantitative, qualitative, or the lack of targets in each sector. Currently, a large number of NDCs contain qualitative commitments only, including in energy (20% of NDCs), transport (33%), waste (27%), agriculture (24%) and forestry (24%). Furthermore, many NDCs contain no sectoral targets at all: energy (25% of NDCs), transport (48%), waste (62%), agriculture (68%) and forestry (48%).

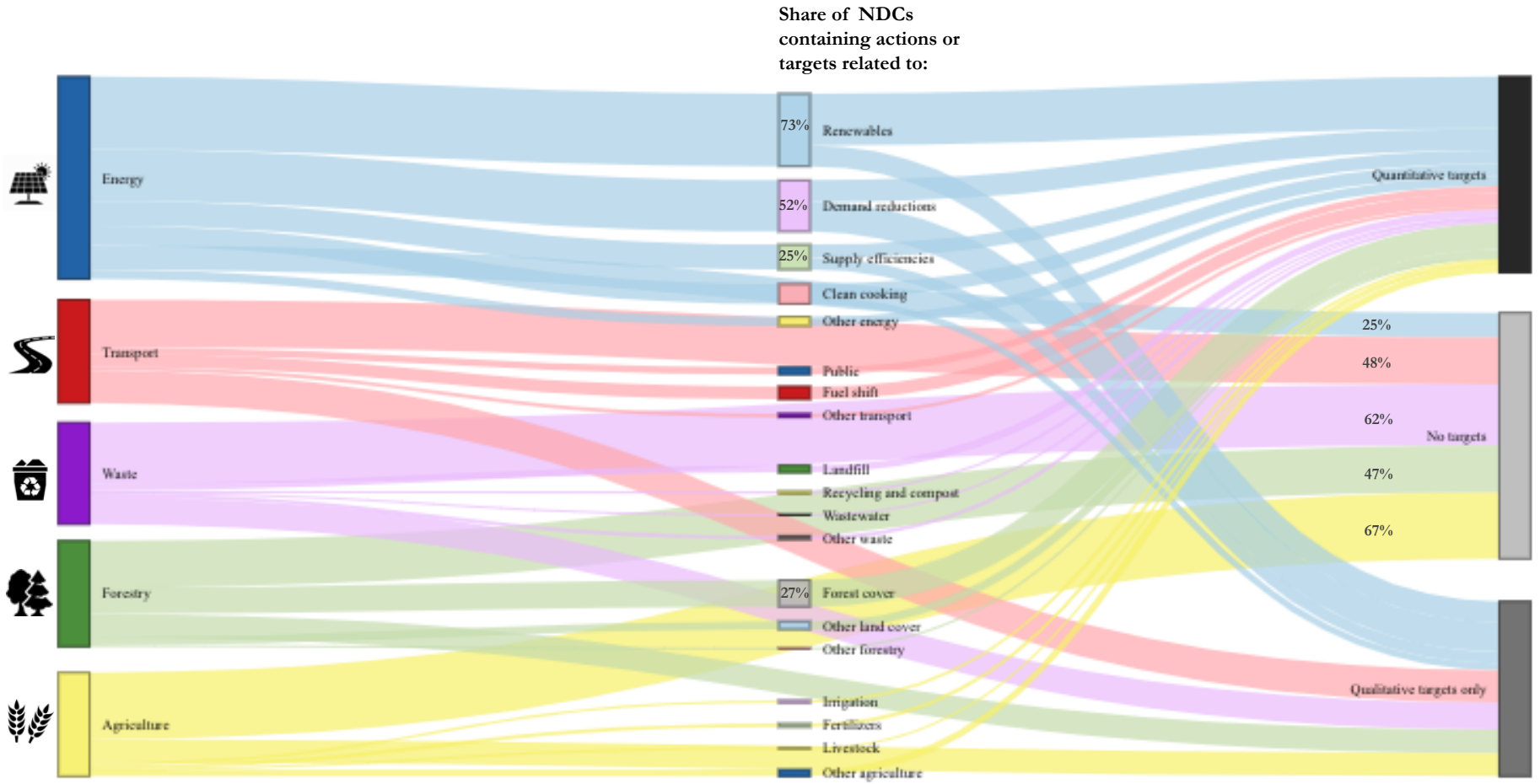


Figure 25: Breakdown of key sectoral targets and actions included in the mitigation component of first NDCs (2015) for 195 countries, grouped into five major infrastructure and land use sectors

Figure 26 demonstrates the range of the most common quantified measures in the NDCs. On average, energy targets seek to add approximately 25 percent of renewables to the generation mix while reducing energy consumption by roughly the same amount. Lower commitments are made on the supply efficiency side, with most NDCs aiming for transmission loss reductions between eight and 15 percent. Clean cookstove distribution varies widely with most committed parties aiming to provide access to up to an additional 50 percent of the population. Targets for the expansion of forest cover depend largely on the country context, with the most ambitious seeking to reforest up to 25 percent of the land area. Transport targets generally seek to decarbonise between 20 and 35 percent of the sector, while waste targets are more variable, with most aiming to reduce waste emissions by up to 50 percent, though very few overall are quantified.

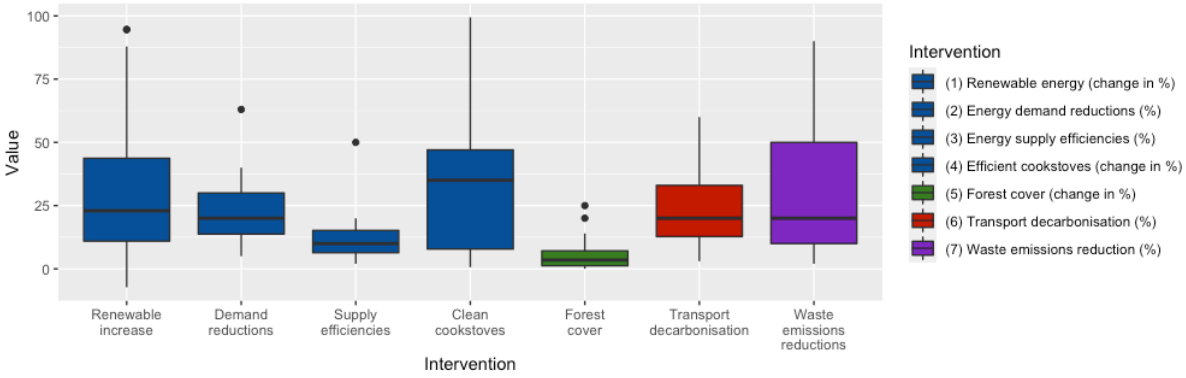


Figure 26: Range of most commonly quantified measures across the mitigation component of 195 NDCs as defined in Section 5.3.1

5.4.2. Aligning mitigation actions with sustainable development gaps

Using development index scores from the Sustainable Development Report dataset as a baseline, we can identify all targets and accompanying actions included in NDCs that are relevant to SDG achievement and endeavour to quantify the magnitude of their impact if

implemented as stated in the policy document. We quantify the impact of these NDC commitments on four of the most relevant SDG indicators: renewable energy; clean cooking; solid waste generation; and forest cover (Figure 27). Calculating changes in SDG target outcomes and emissions across these four indicators, we observe varying levels of sustainable development benefit from current NDC, as depicted in Figure 23.

Countries with renewable energy commitments – the most commonly quantified type of target in the NDCs – show high potential both to improve energy security as measured by SDG 7 and to achieve mitigation targets. There is no clear distinction in baseline performance by income group, though high-income countries make fewer commitments toward closing the gap between full renewable generation and current levels. Nevertheless, nearly half of all countries lack a quantified renewable energy target in their sectoral mitigation plan. In contrast, access to efficient cookstoves is strongly correlated to income group, with most low-income countries scoring poorly. An analysis of NDCs determines that most targets related to the implementation of efficient cookstoves focus on these low-income countries, with large gains in access expected as a consequence of these NDCs. While this provides a strong overall contribution to the achievement of SDG 7, the mitigation impact of replacing inefficient cookstoves is shown to be small on a national scale.

When current recycling and compost is accounted for, municipal solid waste generation is less clustered by income group, though higher income countries tend to score more poorly given their higher overall waste generation rates. Due to few countries quantifying waste targets, NDC commitments contribute to limited overall mitigation reductions, although differences in mitigation potential between countries suggest that waste stream content

plays a role. Afforestation and reforestation targets suggest moderate to large sectoral mitigation potential, with the ability to offset other emitting sectors of the economy. While high income countries generally score well as a baseline, the limited areas of existing or remaining forested land in many of these regions mean that reforestation potential is often greater.

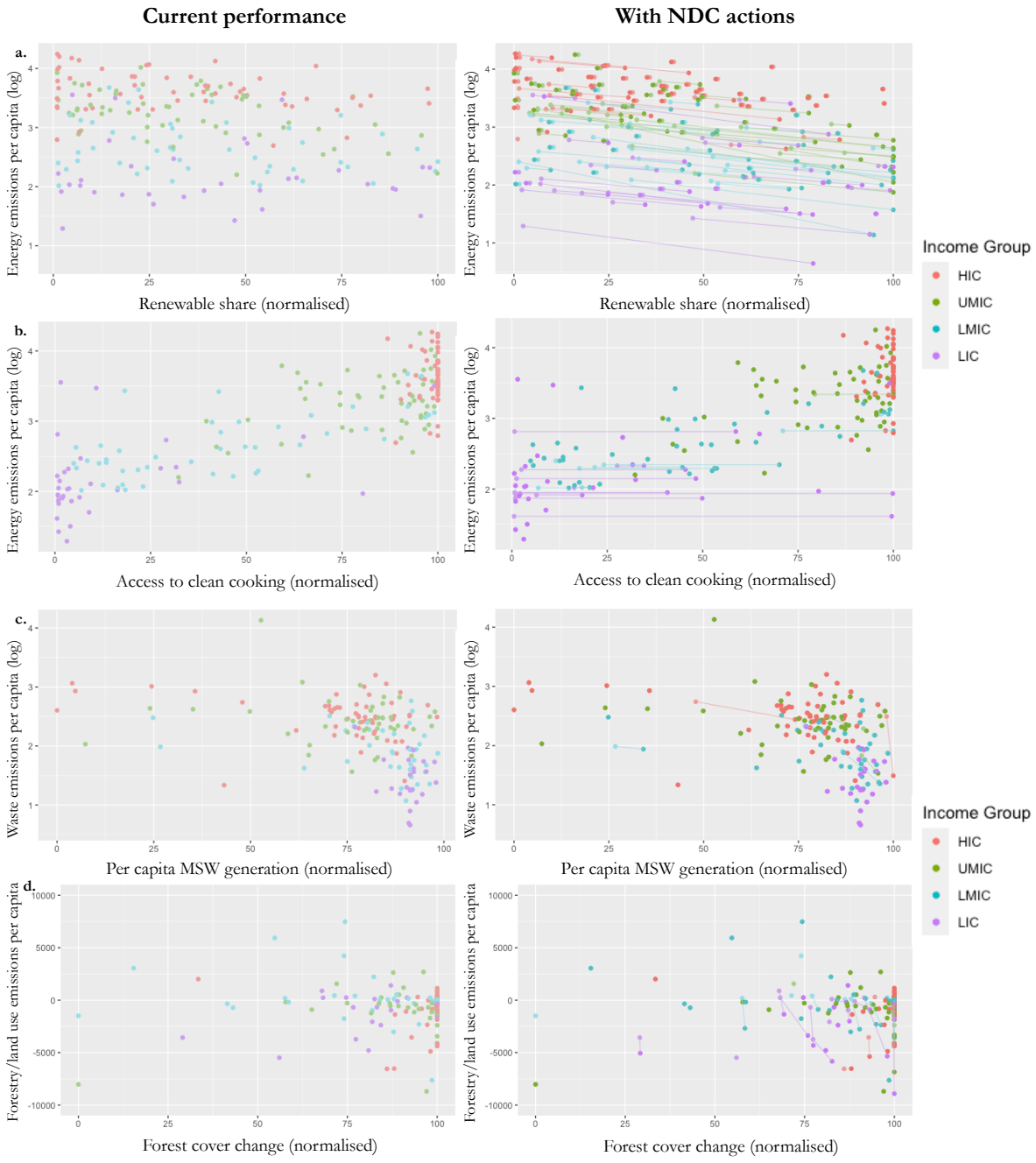


Figure 27: Projected change in selected mitigation (y-axis) and development (x-axis) outcomes as a result of current NDC commitments for: (a) Renewable generation; (b) Access to clean cooking; (c) MSW generation; (d) Forest cover change

In addition to tracking the progress of individual countries we can calculate the global proportion of countries, shown by income group, that have made sufficient target commitments to close their SDG achievement gap with respect to the four indicators studied (Figure 28). This accounts for the fact that a country may already have achieved, or is nearing achievement of, a given indicator (as defined in Table 4), and thus less ambitious commitments are needed to fulfil this objective. As previously noted, quantitative and qualitative renewable energy targets are widely cited throughout the NDCs. However, only seven percent of countries, mostly middle income, can achieve a transition to a fully renewable economy with current targets, while a further 12 percent narrow their current gap by at least 50 percent. The majority of countries with quantified targets make moderate commitments to add between 10 and 50 percent, as suggested in Figure 26.

With regard to clean cooking, most countries that have achieved or are projected to achieve these targets fall into the high-income category, accounting for 20 percent of the total. However, 62 percent of countries contain no related targets in their NDCs despite not having achieved full access to clean cooking. The reduction of landfill emissions follows a similar pattern albeit with no countries demonstrating the potential to eliminate landfill-based emissions. This is despite moderate to high recycling and compost rates in higher income countries that greatly reduce the quantities of municipal solid waste requiring landfill treatment. The reforestation indicator considers the extent to which forest cover commitments replace deforested land area from the previous five-year period, with 17 percent of countries meeting this criterion. This accounts for geographical considerations and the fact that not all countries have the potential for large-scale afforestation programmes, for example those in dry climates, placing the focus on maintaining existing cover. From an

emissions standpoint, the majority of countries achieving this outcome are from low or lower middle-income countries which are generally located in temperate or tropical regions, increasing the sequestration capacity per hectare of forest (Brown 1996).

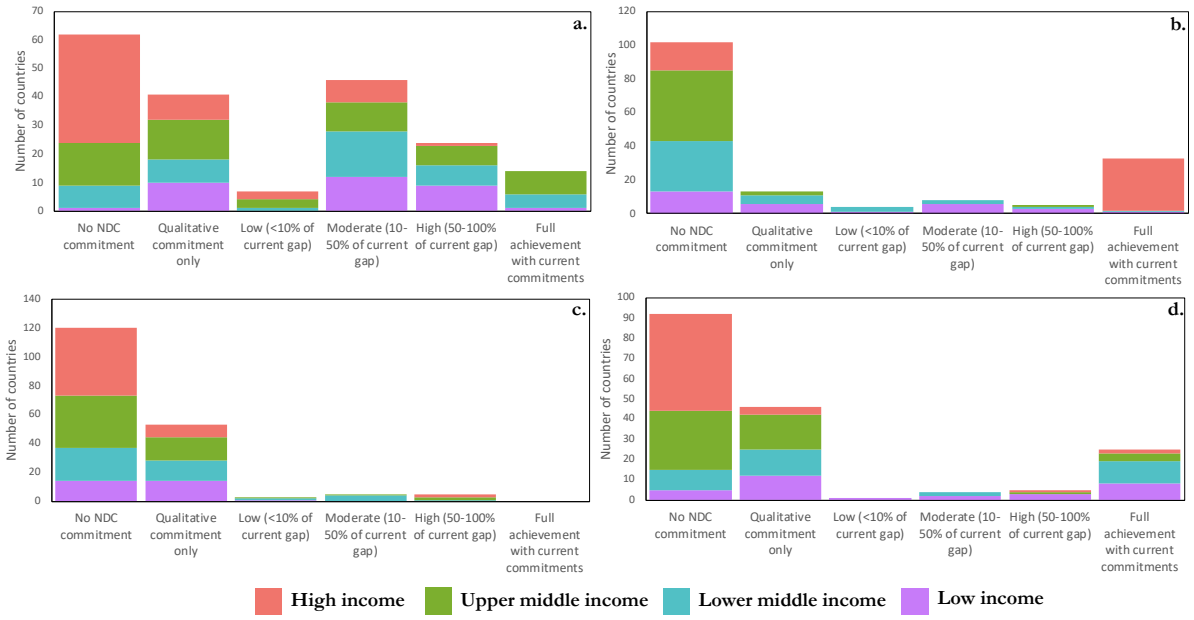


Figure 28: Global alignment of NDCs with selected SDG outcomes, by income group. Degree to which NDCs: (a) contribute toward renewables-based generation; (b) achieve full access to clean cooking; (c) reduce current emissions associated with MSW; (d) commit to replacing deforested land (5 years)

5.5. Discussion

How can we learn from the first round of NDCs in order to help countries upgrade their commitments to policies that will better meet climate and development targets? The results of this study highlight two main conclusions about the current round of NDCs. First, with regard to NDC content itself, current policy commitments and actions for most countries are not sufficient to achieve many related development outcomes. Second, from the perspective of the NDC formulation process, there is a need to be more specific and targeted in outlining

commitments in line with a consistent, measurable approach. This learning can be utilised to set the agenda for actors involved in the ongoing NDC revision process, specifically the stakeholders and decision-makers in national governments and academia tasked with ensuring the two-degree target is met.

5.5.1. Significance for national governments

The current NDC landscape lends itself to political and value positions regarding climate change response that differ between countries at varying stages of income, development, and historical emissions responsibility (Mills-Novoa & Liverman 2019). As a result, the focus for many countries risks becoming a justification of 'less ambition' rather than the pursuit of enhanced benefits through stronger commitments. We argue that these policy mechanisms can be set up using a more evidence-based approach that operationalises NDC commitments to deliver on development benefits tailored to each specific country context.

By taking into account the progress that has already been made toward development outcomes, and the potential contributions of different types of NDC actions, this analysis highlights major gaps in the commitment levels required to deliver on these outcomes. Examining only a subset of potential mitigation actions and indicators, we see that globally, most countries are under-committing with regard to the measures required to close these gaps. Ambitious NDC commitments may additionally provide a host of co-benefits across other development areas, as documented in recent academic and research studies (e.g. Deng et al. 2018). Given the importance of health, educational, economic and other outcomes to

future national prosperity, stronger mitigation action should be seen as a catalyst for delivering in these crucial domains.

Ultimately, NDC commitments must be accompanied by financial backing in order to be feasibly achieved. Development financing opportunities can be better justified if actions and targets are robustly linked to current and future performance. Greenhouse gas emissions reductions targets, which are reported at the economy-wide scale for the vast majority of countries, must be underpinned by actions – otherwise they are unlikely to be effectively implemented. This emphasises the need for a consistent and transparent target-setting and reporting process in order to direct resources to appropriate actions, to identify and to update them where targets are misaligned with desired impacts. This can create a policy environment where ambition levels and targets can be realistically set, which can provide momentum for the development of new policies, action plans, governance structures and capacities in the climate domain (Röser et al. 2020).

However, the current level of quantifiable commitment in the NDCs is limited as it relates to certain development challenges, with 23 percent of countries reporting no quantified sectoral targets, and a further 16 percent only defining qualitative targets. Without a detailed and transparent means of implementation, the success of proposed measures may be limited. The use of a widely accepted development agenda such as the SDGs through which to monitor and benchmark progress may accelerate buy-in from funders of large-scale infrastructure and land use projects and programmes. A consistent reporting process should also provide estimations of emissions reductions associated with proposed mitigation actions. While this exists to some extent in the current NDCs, many of these quantified GHG impacts are not

reported. This study has introduced broad assumptions around the mitigation impact of certain actions in order to develop a consistent global assessment framework. However, country-specific reporting can allow policymakers to capture differences at a more granular level between factors such as renewable generation technologies, types of cookstove, or forest categories.

This study emphasises that high-income countries must also continue to assess infrastructure system performance in relation to weakly-performing development indicators. This is important as large number of high and upper-middle income countries have not articulated sectoral actions to reduce emissions in their NDCs, despite not yet fully achieving most SDG outcomes.

5.5.2. Academic research and the NDC framework

Improvement of the NDC framework creates a role for academic research to develop more robust methods for assessing and tracking countries' progress toward climate and development goals. This also provides opportunities to address some of the methodological issues raised with the existing 'Climate-Compatible Development' framework. The methods outlined here makes several contributions to this end. By definition, the framework seeks alignment and synergies between climate pathways and development goals, including non-climate dimensions. While recognising the wide potential for development co-benefits, it defines the need for specific mitigation targets and actions based on existing outcomes and gaps. In addition, it allows policymakers to take a contextualised approach to assessing the impacts of specific NDC actions within their unique country contexts. Furthermore, it

produces more concrete proposals for action than existing studies that focus on discourse analysis of the policy documents.

Important academic contributions in this area will involve defining or establishing new measurable targets and indicators that can bring the climate science community behind standardised metrics used across countries within the global reporting system. Academics have a large role in proving the soundness and robustness of frameworks designed to create a consistent approach to policy at the interface of the climate and development domains.

5.6. Conclusion

The NDCs and SDGs can be brought together in a common framework that links the two agendas through quantitative assessment that has not been attempted elsewhere, with focus on the mitigation component of countries' commitments. Under a business-as-usual trajectory, low-income countries can be largely expected to move toward development outcomes with an accompanying rise in emissions. The NDCs under the Paris Agreement aim to shift countries toward lower-emissions development. However, a lot more can be done. The revision of NDCs poses a prime opportunity to align policy interventions related to climate change mitigation with a country's development trajectory, requiring an understanding of which specific SDG targets can be impacted and by how much.

Due largely to issues of scope, the study faced certain limitations. First, while NDC mitigation actions can have a broad range of impacts, selected indicators were chosen to demonstrate

how these impacts could be assessed and quantified. Increasing this selection of indicators will give decision-makers a greater ability to target mitigation strategies to desired outcomes. While these can draw on established indicator sets as done in this study, they should be justified in terms of the quantitative interactions included in the analysis; for example, examining the links between NDC transport targets and potential transportation outcomes such as road accidents; or between specific agricultural practices and water or food security. Second, to account for the fact that current variation in NDC content makes comparative assessment difficult, this paper has standardized target ambition as thoroughly as possible across major intervention types. However, some targets in sectors such as transport and waste were broadly aggregated to estimate the strength of commitment in the sector. Further research can provide a more granular assessment of sectoral actions and their proposed impacts on development targets. Third, this analysis has focused specifically on the mitigation component of the NDCs, although countries' adaptation commitments provide an equally extensive list of proposed sectoral targets and actions. These can be integrated in a more comprehensive analysis of NDC alignment with SDG targets.

This study provides a major step in moving toward a harmonised climate and development framework that is applicable across countries and contexts, and which can provide a clearer picture of what needs to be implemented, where, and by how much if we are to keep global temperature change to two degrees. With the NDC revisions under way in many countries, such a discussion is required to provide clarity and robustness to national climate policy for the 'decade of delivery' of these important global agendas.

Chapter 6: Conclusions and final remarks

6.1. Thesis summary and main contributions

The previous three chapters have developed and demonstrated research methods, analyses, and applications that address the overall objective of this thesis: to inform sustainable infrastructure planning in alignment with the global development and mitigation targets. Together, these studies weave together the narrative of this important work by assembling an assessment and planning framework centred around these major global agendas. The first study explicitly assesses the performance of diverse national infrastructure in the context of a globally accepted development framework, the SDGs. The second study developed a means to systematically select infrastructure investment and policy options by designing portfolios to meet both the SDGs and emissions reductions targets. The third enabled the Identification of development gaps and the subsequent definition of appropriate mitigation actions in infrastructure and land use to enhance the synergistic achievement of both the SDGs and Paris Agreement commitments.

The thesis has addressed the research questions outlined in Chapter 1, as follows:

With regard to Question 1, this thesis found that while numerous mechanisms to assess various aspects of infrastructure performance have been developed and demonstrated, there have been limited attempts to link performance assessment and development outcomes within an integrated framework. Chapter 3 outlined methods for defining this framework, which demonstrated a means to quantify progress across one or more SDG targets as the

result of a specific sectoral investment or policy at the national level. The application of this framework to a set of defined challenges in Curaçao highlighted the context-specific nature of infrastructure's contribution to SDG achievement, finding that SDG achievement across infrastructure-linked SDG targets may decline by 28 percent by 2030 in the case of no strategic investment or policy actions.

With regard to Question 2, the thesis developed and outlined a systematic process for infrastructure assessment across multiple sectors. The process brings together data on the core aspects of infrastructure planning: existing capacities, future demand scenarios, available investment and policy options, and, importantly, development and climate targets. Due to its use of participatory methods drawing on stakeholder preferences and knowledge to define desired outcomes, the assessment process is transferable to a range of international contexts. In this instance, its application to the small island developing state of Saint Lucia allowed nationally defined targets, as well as current mitigation commitments under the Paris Agreement, to inform a sustainable infrastructure strategy that would be cost-effective in the long-term.

With regard to Question 3, the thesis identified weaknesses in the current NDC reporting mechanism with regard to its ability to simultaneously address development needs in a particular national context and to define mitigation actions required to fill existing gaps. Using a comprehensive cataloguing of current NDC mitigation commitments across 195 countries, the study demonstrated a means to consider climate and development objectives synergistically so as to deliver on the SDGs and the Paris Agreement through targeted action across infrastructure and land use sectors. The alignment between these two agendas, in

terms of the goals they wish to achieve, is crucial for the long-term planning of national infrastructure strategies.

6.2. Contributions to research

6.2.1. Emphasising the role of infrastructure in sustainable development

This research has provided new insight into infrastructure's role in shaping a sustainable future. As detailed in Chapter 1, infrastructure has a profound impact on the achievement of development outcomes, potentially influencing up to 92 percent of SDG targets as well as serving as a key mechanism for climate mitigation action. This knowledge, however, requires further exploration and rigorous analysis if it is to be operationalised to deliver on sustainable outcomes. The studies in this thesis have furthered this knowledge, drawing directly on infrastructure's proven links to development targets to formulate a novel long-term planning approach directly aligned with the global agendas (the SDGs and Paris), while also formalising a means to assess, measure progress, and make policy recommendations across both of these agendas. The studies have also made progress in accounting for the multiple objectives of sustainable development and the multi-dimensional benefits that infrastructure can yield.

Bringing in real data and stakeholder preferences to generate results, the studies have rigorously defined and demonstrated the key components of a planning approach that can be transferred to range of global contexts. This type of approach may provide more meaningful findings for policymakers at a national scale than thematic studies that focus on specific goals, targets, or indicators.

6.2.2. Novel contributions to infrastructure systems modelling

The interdependence of the infrastructure system has been a major theme of this thesis. As noted in Chapter 2, many current infrastructure planning approaches rely on silo-based analyses that consider sectors in isolation. Each of the studies in this work has centred around an integrated analysis that brings in multiple key sectors – and accounts for ways in which these sectors may interact. The importance of land use sectors, while not included in the systems model itself, was emphasised as a means of complementing sustainability measures in the built environment. The methods and models used to link sectors in a holistic analysis serve as important research contributions which can be extended by integrating more complex interactions in future studies.

6.2.3. Planning for an uncertain future

Accounting for future uncertainties is essential when dealing with complex, interdependent systems. As with many studies before it, this work uses projections and scenarios to attempt to capture the future state of the world based on current information. The primary value of these studies, however, is not in providing static results that only address a current set of data and challenges. Rather, it is to develop methods that are adaptive and iterative, and which can provide updated recommendations for decision-makers as conditions change. At its core, each paper provides an adaptable framework for infrastructure assessment: in setting and updating infrastructure performance targets; in formulating portfolios of investments and policies based on current priorities and available technologies; and in prioritising mitigation actions based on a country's current development gaps. The research also emphasises the

importance of integrating dynamic government policies and proposals, such as new transport terminals, as key inputs into the uncertainty analysis.

In developing these methods, an emphasis has been put on establishing their efficacy and usefulness, directly addressing critiques that many flexible infrastructure planning approaches have seen little real-world application (e.g. Kwakkel & van der Pas 2010). The use of small island case studies may be also seen as a pilot approach that can test the process and frameworks, proving their efficacy before application to larger country contexts.

6.3. Reflections on practical applications of the work

In addition to its research and methodological contributions, this thesis was undertaken with the intention of demonstrating real-world applications of improved infrastructure planning for the benefit of practitioners and decision-makers, and to engage stakeholders in the assessment process. The case studies used in the thesis provided the opportunity to co-develop knowledge with stakeholders well-versed in the national context, and thus more invested in the data, methods, and results. This led to several practical applications and impacts of aspects of the work, related to both policy and national capacity building.

In Curaçao, the results of the long-term planning analysis formed the centrepiece of a Caribbean Resilient Infrastructure Conference, which demonstrated the island's regional leadership in sustainable and resilient infrastructure planning (News784 2018). As a result of the findings, certain policy initiatives were taken such as the use of a wastewater processing

station to eliminate uncontrolled discharge into the sea (Curaçao Chronicle 2018) and the development of an integrated water resources management task force (UNDP 2018).

In Saint Lucia, a new unit in the Department of Finance, the National Integrated Planning and Programme Unit, was created and tasked, among other responsibilities, with undertaking and continuously updating the long-term planning analysis developed here (GoSL 2019). The development of a national infrastructure systems modelling tool (NISMOD) for international contexts, which was used to perform some of the analysis in the thesis, was a practical outcome that has demonstrated uptake within the country, with stakeholders and government analysts trained on the innovative software for future use (St. Lucia Times 2020). A national infrastructure assessment report, which was endorsed by the country's Prime Minister, provided key data and analysis which is to be used to shape future policy and development (GoSL 2020).

With NDC revisions currently underway in most countries, there is now a strong need for methods to inform the selection of mitigation actions and targets. By demonstrating the ways in which a balanced mitigation strategy can close key development gaps, this work can be applied as a basis for decision-making by policymakers in a range of global contexts.

6.4. Future extensions and applications

While this this thesis has made contributions toward the design of a new infrastructure planning paradigm, there exist many opportunities to expand on its scope and methods. Potential future research directions are summarised here.

One extension involves the sectoral coverage of the analysis. While the methods developed a cross-sectoral approach to infrastructure planning, certain sectors, specifically the 'networked' sectors of transport and digital communications, were largely excluded due to a lack of data or the need for a more spatial approach to planning these sectors. Further studies may integrate and align these sectors with existing interdependent models using acquired data on flows (origin-destination), trip modes, and performance indicators that measure access to services. The scope can further be expanded to account for other infrastructure. As explained in Chapter 1, definitions of infrastructure range from the narrow (i.e. public works providing essential services) to the broad (i.e. publicly or privately owned components of the built – or occasionally, the natural – environment and the institutions, services, skills, and knowledge housed in or provided by them). Given the essential services provided by facilities such as schools and hospitals, these social components of the infrastructure system should also be integrated into planning models.

While demographic variables were primarily used in this study to demonstrate uncertainties with regard to future infrastructure, more comprehensive models can quantify the impacts of other drivers on future infrastructure needs. Economic growth scenarios at the national or regional scale can help shape infrastructure requirements at the household or industry level using a range of macroeconomic variables and assumptions. The chronic impacts of climate change similarly affect supply and demand for future infrastructure in key sectors. For example, potential water supply may decrease due to climatic drying trends; in countries where hydroelectric power is a dominant generation source, energy capacity may be similarly at risk due to lower dam levels. On the demand side, energy needs for cooling and air

conditioning may rise as the number of hot days increases. These considerations can be integrated in an interdependent planning model to better inform long-term projections under a range of scenarios.

Other opportunities to extend this research may utilise big data analysis to provide more comprehensive modelling of infrastructure systems interactions and their implications across a wider range of indicators. Geospatial analysis of climate hazards to infrastructure and land use may be used as a means to prioritise investments or policies within a long-term planning model, or to implement them in ways that are adaptive to the specific climate and weather events facing a country. Specific targets related to other global agendas, such as the Sendai Framework or the New Urban Agenda, can also be integrated. Land use and nature-based solutions should strongly complement built environment options in infrastructure system-of-systems modelling.

Finally, as we plan for better and more informed infrastructure decision-making, aspects of the enabling environment such as finance, governance, and capacity building must be accounted for to ensure its successful implementation. Efforts should be made to more efficiently link recommended projects and investments to finance opportunities based on detailed criteria, and to develop methods that can more accurately predict the future success of projects and investments based on a country's political orientation and governance metrics.

6.5. Implications for the SDGs and Paris: the 'decade of delivery'

We have now entered the final ten-year period of the global development agendas. This thesis highlights the urgency of action to achieve these transformations over the next decade, and the major infrastructural challenges that remain. However, it also paints an optimistic picture, suggesting that much progress can feasibly be made toward solving many of the world's most critical development issues. In doing so, it aims to shape the new generation of infrastructure thinking and planning to suit the needs of decision-makers balancing economic, social, and environmental concerns.

While financing remains a key barrier to the adoption of sustainable investments and technologies, this thesis suggests that embarking on an SDG-driven infrastructure plan will lead to more cost-effective outcomes in years to come. In addition, it stands to reduce environmental, health, and social externalities that will undoubtedly necessitate large amounts of spending to remedy in future years. By ambitiously striving toward desired SDG outcomes in the current planning paradigm, unnecessary future costs can be avoided.

Similarly, formalising mitigation commitments in national planning processes will be critical to making progress on climate targets. Despite the optimism generated by the near-universal signing of the Paris Agreement in 2015, continued iteration is required to update national mitigation policies if the two-degree target is to be met. By demonstrating improved social or economic outcomes linked to more ambitious climate commitments, this thesis looks to nudge decision-makers toward more forward-thinking outcomes.

6.6. Mobilising infrastructure for a sustainable future

The world's development challenges are complex, though not insurmountable. To confront them, we must seek out new and innovative ways to plan our cities, countries, and societies; infrastructure will be front-and-centre as we make the decisions that will shape the future sustainability of our planet for decades and centuries to come. This thesis emphasises some of the major shifts required in our current planning paradigm if we are to successfully achieve a sustainable future: accounting for the multiple objectives of sustainability; planning infrastructure as an interdependent system; and generating transferable and context-specific assessment methods aligned with globally recognised goals and targets. Mobilising this knowledge to develop sustainable infrastructure systems will require the involvement of decision-makers in all realms of infrastructure planning: researchers, policymakers, designers, practitioners, funders, and users themselves.

References

Abou-Zeid, M. and Fujii, S. (2015) Travel satisfaction effects of changes in public transport usage. Transportation 43, 301-314.

Acheampong, A.O. (2018) Economic growth, CO2 emissions and energy consumption: What causes what and where? Energy Economics 74: 677-692.

Adewumi, J.R., Ilemobade, A.A. and van Zyl, J.E. (2010) Treated wastewater reuse in South Africa: Overview, potential and challenges. Resources, Conservation and Recycling, 55(2): 221-231.

Adshead, D., et al. (2020) National Infrastructure Assessment: Saint Lucia. United Nations Office for Project Services (UNOPS): Copenhagen, Denmark.

Adshead, D., Fuldauer, L., Thacker, S., Hickford, A., Rouhet, G., Muller, W.S., Hall, J.W. and Nicholls, R. (2018) Evidence-based infrastructure: Curacao. National infrastructure systems modelling to support sustainable and resilient infrastructure development. United Nations Office for Project Services (UNOPS): Copenhagen, Denmark.

Adshead, D., Thacker, S., Fuldauer, L.I. and Hall, J.W. (2019) Delivering on the Sustainable Development Goals through long-term infrastructure planning. Global Environmental Change, 59.

Agyeman, J. and Evans, T. (2003) Toward Just Sustainability in Urban Communities: Building Equity Rights with Sustainable Solutions. The Annals of the American Academy of Political and Social Science 590: 35-53.

Airport tech (2017) Curaçao Airport Expansion [online]. Available from: http://www.airport-technology.com/projects/curacao-international-airport-terminal-expansion/.

Airports Worldwide (2010) Hewanorra International Airport. Airports Worldwide: Online.

Alawadi, K. and Dooling, S. (2015) Challenges and opportunities for participatory planning approaches within Dubai's urban context. Journal of Urbanism: International Research on Placemaking and Urban Sustainability, 9(3): 276-301.

Alinsato, A.S. (2015) Globalization, Poverty and Role of Infrastructures. Journal of Economics and Political Economy, 2(S1): 197-212.

Allen, C., Metternicht, G. and Wiedmann, T. (2017) An Iterative Framework for National Scenario Modelling for the Sustainable Development Goals (SDGs). Sustainable Development 25(5): 372-385.

Allwood J.M., Bosetti, V., Dubash, N.K., Gómez-Echeverri, L. and von Stechow, C. (2014) Glossary In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Edenhofer, O. et al.), pp. 1249–1279. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Amadio, M. (2014) Water Security Issue in the Caribbean Windward Islands. Review of Environment, Energy and Economics – Re3, Fondazione Eni Enrico Mattei, July.

Ang, J. (2007) CO2 Emissions, Energy Consumption, and Output in France. Energy Policy 35(10): 4772-4778.

Atkins, G., N. Davies & T.K. Bishop (2017) How to value infrastructure. Institute for Government. London, United Kingdom.

Atteridge, A., Verkuijl, C., and Dzebo, A. (2019) Nationally determined contributions (NDCs) as instruments for promoting national development agendas? An analysis of small island developing states (SIDS). Climate Policy, DOI: 10.1080/14693062.2019.1605331.

Awerbuch, S. (2006) Portfolio-based electricity generation planning: policy implications for renewables and energy security. Mitigation and Adaptation Strategies for Global Change 11: 693–710.

Baker, E., V. Bosetti, et al. (2015). Future costs of key low-carbon energy technologies: Harmonization and aggregation of energy technology expert elicitation data. Energy Policy 80: 219-232.

Baldwin, J. R. and J. Dixon (2008). Infrastructure Capital: What Is It? Where Is It? How Much of It Is There? The Canadian Productivity Review, 16.

Baruah, P.J. et al. (2014) Energy system impacts from heat and transport electrification. Proceedings of the Institution of Civil Engineers 167(3): 139-151.

Becchetti, L., Bruni, L. and Zamagni, S. (2020) The Microeconomics of Wellbeing and Sustainability. Giappichelli Editore. ISBN: 978-0-12-816027-5.

Beh, E. H. Y. et al. (2015) Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty. Water Resources Research 51: 1529-1551.

Ben Haim, Y. (2006) Info-Gap Decision Theory: Decisions Under Severe Uncertainty, 2nd edition. London, Academic Press.

Bertsch, V. and Fichtner, W. (2016) A participatory multi-criteria approach for power generation and transmission planning. Ann Oper Res 245: 177–207.

Bhaduri, A., et al. (2016) Achieving Sustainable Development Goals from a Water Perspective. Frontiers in Environmental Science, 4(64).

Bhattacharya, A.J., Oppenheim & Stern, N. (2015) Driving sustainable development through better infrastructure: key elements of a transformation program. Global Economy & Development Working Paper No. 91, July 2015.

Bhattacharya, A.J., Meltzer, J.P., Oppenheim, J., Qureshi, Z. and Stern, N. (2016) Delivering on sustainable infrastructure for better development and better climate. Brookings Institution. December 2016.

Bhattacharya, A.J., Gallagher, K.P., Muñoz Cabré, M., Jeong, M., & Ma, X. (2019) Aligning G20 Infrastructure Investment with Climate Goals and the 2030 Agenda, Foundations 20 Platform, a report to the G20.

Birkmann, J. et al. (2016) Extreme events, critical infrastructures, human vulnerability and strategic planning: emerging research issues. Journal of Extreme Events, Vol. 3, No. 4, 1650017.

Bisaga, I., Parikh, P., Mulugetta, Y. and Hailu, Y. (2018) The potential of performance targets (imihigo) as drivers of energy planning and extending access to off-grid energy in rural Rwanda. WIREs Energy Environ. 2019;8:e310.

Bollinger, L.A. and Dijkema, G.P.J. (2016) Evaluating infrastructure resilience to extreme weather – The case of the Dutch electricity transmission network. European Journal of Transport and Infrastructure Research 16(1): 214-239.

Bosetti, V., G. Marangoni, et al. (2015) Sensitivity to energy technology costs: A multi-model comparison analysis. Energy Policy 80: 244-263.

Brandi, C., Dzebo, A. and Janetschek, H. (2017) The Case for Connecting the Implementation of the Paris Climate Agreement and the 2030 Agenda for Sustainable Development. Deutsches Institut für Entwicklungspolitik. Briefing Paper 21/2017.

Briceño-Garmendia, C., Estache, A. and Shafik, N. (2004) Infrastructure Services in Developing Countries: Access, Quality, Costs and Policy Reform. World Bank Policy Research Working Paper 3468, December 2004.

Broto, V.C. et al. (2015) Participatory Planning for Climate Compatible Development in Maputo, Mozambique. UCL Press, London.

Brown, S. (1996) Tropical forests and the global carbon cycle: estimating state and change in biomass density. Pages 135-144 in M. Apps and D. Price (eds.), The role of forest ecosystems and forest management in the global carbon cycle. NATO Series. Springer Verlag. NY.

Brown, T., Beyeler, W. and Barton, D. (2004) Assessing infrastructure interdependencies: the challenge of risk analysis for complex adaptive systems. International Journal Of Critical Infrastructures 1(1): 108-117.

Brundtland, G. (1987) Report of the World Commission on Environment and Development: Our Common Future. United Nations General Assembly document A/42/427.

Bryce, J. M. et al. (2014) A multi criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. Transportation Research Part D 32: 435-445.

Busco, C. et al. (2017) Sustainable Development Goals: integrating sustainability initiatives with long-term value creation. Strategic Finance, September 2017.

Business Curaçao (2015) The development of an industry: the value proposition of Mega Pier 2.

Cabinet Office (2010) Sector resilience plan for critical infrastructure 2010. London, UK, Cabinet Office.

Cafiso, S., Di Graziano, A. and Pappalardo, G. (2012) Road Safety Issues for Bus Transport Management. Procedia - Social and Behavioral Sciences 48, 2251-2261.

Cairns, G., Ahmed, I., Mullett, J. and Wright, G. (2013) Scenario method and stakeholder engagement: Critical reflections on a climate change scenarios case study. Technological Forecasting and Social Change, 80, 1: 1-10.

Campagnolo, L. and Davide, M. (2019) Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. World Development 122: 96–109.

Carlsson, R., Otto, A. and Hall, J.W. (2013) The role of infrastructure in macroeconomic growth theories. Civil Engineering and Environmental Systems 30(3-4): 263-273.

Cassidy, M. (2014) Assessing gaps in indicator availability and coverage. Sustainable Development Solutions Network, June 23-24, 2014.

Central Bureau of Statistics (2018) Economic and Social Review. Government of Saint Lucia: Castries, Saint Lucia.

Centre for Process Innovation (CPI) (2017) Anaerobic Digestion Economic Feasibility Study: Generating energy from waste, sewage and sargassum seaweed in the OECS. CPI Report Number: CPI-SP-RP-141. CPI: Redcar, USA.

Cheng, J.J. et al. (2012) An ecological quantification of the relationships between water, sanitation and infant, child, and maternal mortality. Environmental Health, 11:4.

Cheng, C-T., Lo, S-L. and Lin, T.T. (2011) Applying real options analysis to assess cleaner energy development strategies. Energy Policy 39(10): 5929-5938.

Chester, M.V. (2019) Sustainability and infrastructure challenges. Nature Sustainability, 2(4): 265-266.

Chester, M.V. and Allenby, B. (2019) Toward adaptive infrastructure: flexibility and agility in a non-stationarity age. Sustainable and Resilient Infrastructure, 4(4): 173-191.

Chester, M.V., Markolf, S. and Allenby, B. (2019) Infrastructure and the environment in the Anthropocene. Journal of Industrial Ecology, 23: 1006-1015.

Chester, M.V., Underwood, B.S. and Samaras, C. (2020) Keeping infrastructure reliable under climate uncertainty. Nature Climate Change, 10: 482-490.

Cohen, F., Adlen, E., Coleoni, C., Hepburn, C. and Sperling, F. (2020) Can natural climate solutions resolve key trade-offs within the Sustainable Development Goals? Institute for New Economic Thinking, Oxford, UK.

COP25 (2019) Annex I: Enhanced ambition in national climate plans.

Covec and Beca (2013) Infrastructure Performance Indicator Framework Development, Prepared for National Infrastructure Unit, The Treasury.

Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y. and Seto, K.C. (2016) Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. Annual Review of Environment and Resources 41: 173–98.

Cui, R.Y., Hultman, N., Edwards, M.R., He, L., Sen, A., Surana, K., McJeon, H., Iyer, G., Patel, P., Yu, S., Nace, T. and Shearer, C. (2019) Quantifying operational lifetimes for coal power plants under the Paris goals. Nature Communications, 10:4759.

Cullen, J.M. and Allwood, J.M. (2010) The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy 38: 75-81.

Curaçao Central Bureau of Statistics (2015) Population Projections. Results and brief analysis of five projection variants. Willemstad, Curaçao.

Curaçao Chronicle (2018) Minister Promises Stop Uncontrolled Discharge Of Waste Water. https://curacaochronicle.com/politics/minister-promises-stop-uncontrolled-discharge-of-waste-water/.

Curaçao Ports Authority (2017) Our ports: Facts and Figures [online]. Available from: http://www.curports.com/our-ports/facts-and-figures/.

Curaçao Tourism Board (2016) Statistics and Data [online]. Available from: www.curacao.com.

Currie, G. and Wallis, I. (2008) Effective ways to grow urban bus markets – a synthesis of evidence. Journal of Transport Geography 16: 419-429.

Curaçao Tourism Board (2016b) Tourism Annual Report [online]. Available from: www.curacao.com.

D'Alessandro, S., Cieplinski, A., Distefano, T. and Dittmer, K. Feasible alternatives to green growth. Nature Sustainability 3: 329–335.

Dagnachew, A.G., Lucas, P.L., Hof, A.F. and van Vuuren, D.P. (2018) Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa. Energy Policy 114: 355-366.

Dasgupta, S. and Tam, E. K. L. (2005) Indicators and framework for assessing sustainable Infrastructure. Canadian Journal of Civil Engineering 32(1): 30-44.

Deng, H-M., Liang, Q-M., Liu, L-J. and Anadon, L.D. (2018) Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. Environmental Research Letters 12(12).

Department of Sustainable Development (2019) Saint Lucia's Nationally Determined Contribution Partnership Plan. Government of Saint Lucia: Castries, Saint Lucia.

Dewar, J.A. (2002) Assumption-Based Planning: A Tool for Reducing Avoidable Surprises. RAND Corporation. Cambridge University Press.

Dickin, S. and Dzebo, A. (2018) Missing in climate action: concrete health activities in nationally determined contributions. The Lancet, Volume 2, Issue 4, E144.

Dilekli, N. and Cazcarro, I. (2019) Testing the SDG targets on water and sanitation using the world trade model with a waste, wastewater, and recycling framework. Ecological Economics, 165.

Doelman, J.C., Stehfest, E., Tabeau, A. and van Meijl, H. (2019) Making the Paris agreement climate targets consistent with food security objectives. Global Food Security 23: 93-103.

Du, M. et al. (2017) Quantification of methane emissions from municipal solid waste landfills in China during the past decade. Renewable and Sustainable Energy Reviews 78: 272-279.

Dzebo, A., Janetschek, H., Brandi, C. and Iacobuta, G. (2019) Connections between the Paris Agreement and the 2030 Agenda: the case for policy coherence. SEI Working Paper. Stockholm Environment Institute, Stockholm.

Edelenbosch, O.Y. et al. Decomposing passenger transport futures: Comparing results of global integrated assessment models. Transportation Research Part D: Transport and Environment, 55:281-293.

England, M.I., Stringer, L.C., Dougill, A.J. and Afionis, S. (2018) How do sectoral policies support climate compatible development? An empirical analysis focusing on southern Africa. Environmental Science and Policy 79: 9-15.

Estache A. and Wodon Q. (2014) Infrastructure and the MDGs. In: Infrastructure and Poverty in Sub-Saharan Africa. Palgrave Macmillan, New York.

European Union (2015) Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020. Brussels, Belgium.

Fader, M., Cranmer, C., Lawford, R. and Engel-Cox, J. (2018) Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets. Frontiers in Environmental Science, 6, 112.

Fazey, I. et al. (2016) Past and future adaptation pathways. Climate and Development 8(1): 26-44.

Fellmann, T. et al. (2018) Major challenges of integrating agriculture into climate change mitigation policy frameworks. Mitigation and Adaptation Strategies for Global Change 23: 451–468.

Ficklin, L., Stringer, L.C., Dougill, A.J. and Sallu, S.M. (2018) Climate compatible development reconsidered: calling for a critical perspective. Climate and Development 10(3): 193-196.

Fong, M. W. L. (2009) Technology leapfrogging for developing countries. Encyclopedia of Information Science and Technology. M. Khosrow-Pour. Hershey, Pa, USA: 3707-3713.

Food and Agriculture Organization (FAO) (2016) Coping with water scarcity in agriculture a global framework for action in a changing climate. http://www.fao.org/3/a-i6459e.pdf.

Food and Agriculture Organization (FAO) (2018) Transforming Food and Agriculture to Achieve the SDGs. Food and Agriculture Organization of the United Nations. Rome, 2018.

Fordham, M. (1999) Participatory Planning for Flood Mitigation: Models and Approaches. Australian Journal of Emergency Management, 13(4): 27-34.

Franks, M., K. Lessmann, M. Jakob, J.C. Steckel and O. Edenhofer (2018) Mobilizing domestic resources for the Agenda 2030 via carbon pricing. Nature Sustainability, 1: 350-357.

Fransen, T., Northrop, E., Mogelgaard, K. and Levin, K. (2017) Enhancing NDCs by 2020: Achieving the Goals of the Paris Agreement. Working Paper. Washington, DC. World Resources Institute.

French, S., J. Maule & N. Papamichail (2009) Decision Behaviour, Analysis and Support. Cambridge, Cambridge University Press.

Frischmann, B. M. (2012). Infrastructure: The Social Value of Shared Resources. New York, Oxford University Press.

Fu, X. and Zhang, J. (2011) Technology transfer, indigenous innovation and leapfrogging in green technology: the solar-PV industry in China and India. Journal of Chinese Economic and Business Studies 9(4): 329-347.

Fujimori, S. et al. (2019) A multi-model assessment of food security implications of climate change mitigation. Nature Sustainability 2: 386-396.

Fuldauer, L.I., Adshead, D., Thacker, S., Hickford, A.J. (2018) Long-term strategic infrastructure model. Oxford University, Oxford, UK.

Fuldauer, L.I., Ives, M.C., Adshead, D., Thacker, S. and Hall, J.W. (2019) Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. Journal of Cleaner Production, 223: 147-162.

Fuso Nerini, F., et al. (2018) Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nature Energy, 3(1): p. 10-15.

Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H. and Milligan, B. (2019) Connecting climate action with other Sustainable Development Goals. Nature Sustainability, 2: 674–680.

G20 (2020) C20 Infrastructure Working Group Draft Policy Paper 2020. Second draft for consultation 29/04/20.

Gamper, C.D. and C. Turcanu (2007) On the governmental use of multi-criteria analysis. Ecological Economics, 62: 298-307.

Garrick, D.E. et al. (2017) Valuing water for sustainable development. Science 358(6366): 1003-1005.

GEF-IWCAM (2011) Wastewater Wetland Treatment System. Protecting watershed services and developing management incentives in the Fond D'or Watershed area of Saint Lucia. Project Experience Note #6. Caribbean Environmental Health Institute (CEHI): Castries, Saint Lucia.

Gersonius, B. et al. (2013) Climate change uncertainty: building flexibility into water and flood risk infrastructure. Climatic Change 116: 411-423.

Gidden, M.J. et al. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geoscientific Model Development 12(4): 1443–1475.

Gielen, D. et al. (2019) The role of renewable energy in the global energy transformation. Energy Strategy Reviews 24: 38-50.

GIZ (2015) Regional Waste-to-Energy Collaborative. Island Energy Transitions: Pathways for Accelerated Uptake of Renewables. CARICOM Energy Program: Greater Georgetown, Guyana.

Global Commission on the Economy and Climate (2016) The Sustainable Infrastructure Imperative: Financing for Better Growth and Development. The 2016 New Climate Economy Report.

Global Infrastructure Hub (GI Hub) (2017) Global Infrastructure Outlook: 2017.

Global Infrastructure Hub (GI Hub) (2019) "QII Principles endorsed by G20 Leaders". 1 July 2019.

Global Infrastructure Hub (GI Hub) (2020) Forecasting infrastructure investment needs and gaps. https://outlook.gihub.org/.

Goluža, M. (2019) Planning Major Transport Infrastructure: Benefits and Limitations of the Participatory Decision-Making Processes. In J. Nared and D. Bole (eds.), *Participatory Research and Planning in Practice*, The Urban Book Series, pp. 185-205.

Gota, S., Huizenga, C., Peet, K., Medimorec, N. and Bakker, S. (2019) Decarbonising transport to achieve Paris Agreement targets. Energy Efficiency 12: 363–386.

Government of India (GoI) (2019) National Infrastructure Pipeline, Volume I. Report of the Task Force, Department of Economic Affairs, Ministry of Finance.

Government of Saint Lucia (GoSL) (1994) Electricity Supply Act. Government of Saint Lucia: Castries, Saint Lucia.

Government of Saint Lucia (GoSL) (2015a) Intended Nationally Determined Contribution under the United Nations Framework Convention on Climate Change (UNFCCC).

Government of Saint Lucia (GoSL) (2015b) Saint Lucia National Greenhouse Gas Inventory Report 2010.

Government of Saint Lucia (GoSL) (2017) Third National Communication on Climate Change for Saint Lucia. Government of Saint Lucia: Castries, Saint Lucia.

Government of Saint Lucia (GoSL) (2018a) Saint Lucia's Sectoral Adaptation Strategy and Action Plan for the Water Sector (Water SASAP) 2018–2028 under the National Adaptation Planning Process. Government of Saint Lucia: Castries, Saint Lucia.

Government of Saint Lucia (GoSL) (2018b) National Adaptation Plan. Government of Saint Lucia: Castries, Saint Lucia.

Government of Saint Lucia (GoSL) (2019) NIPP Unit Launched. http://www.govt.lc/news/nipp-unit-launched.

Government of Saint Lucia (GoSL) (2020) National Infrastructure Assessment completed. http://www.govt.lc/news/national-infrastructure-assessment-completed.

Grafakos, S., A. Flamos, V. Oikonomou & D. Zevgolis (2010) Multi-criteria analysis weighting methodology to incorporate stakeholders' preferences in energy and climate policy interactions. International Journal of Energy Sector Management, 4, 3: 434-461.

Griscom, B.W. et al. (2017) Natural climate solutions. Proceedings of the National Academy of Sciences 114(4): 11645-11650.

Haasnoot, M. et al. (2013) Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 23: 485-498.

Haasnoot, M. et al. (2012) Exploring pathways for sustainable water management in river deltas in a changing environment. Climatic Change 115: 795-819.

Hall, J. W. et al. (2012) Robust Climate Policies Under Uncertainty: A Comparison of Robust Decision Making and Info-Gap Methods. Risk Analysis 32(10).

Hall, J.W., Tran, M., et al. (2016) The Future of National Infrastructure: A System-of- Systems Approach. Cambridge University Press, Cambridge.

Hall, J.W., Thacker, S., Ives, M.C., Cao, Y., Chaudry, M., Blainey, S.P. and Oughton, E.J. (2017) Strategic analysis of the future of national infrastructure. Proceedings of the Institution of Civil Engineers - Civil Engineering, 170(1): 39-47.

Hall, R.E. and Jones, C.I. (1999) Why Do Some Countries Produce So Much More Output Per Worker Than Others? The Quarterly Journal of Economics, Vol. 114, No. 1, pp. 83-116.

Hamilton, K., Brahmbhatt, M. and Liu, J. (2017) Multiple benefits from climate change mitigation: assessing the evidence. Grantham Research Institute on Climate Change and the Environment. November 2017.

Harkes, I.H.T. et al. (2015) Shrimp aquaculture as a vehicle for Climate Compatible Development in Sri Lanka. The case of Puttalam Lagoon. Marine Policy, 61: 273-283.

Helmrich, A. and Chester, M.V. (2020) Reconciling complexity and deep uncertainty in infrastructure design for climate adaptation. Sustainable and Resilient Infrastructure, DOI: 10.1080/23789689.2019.1708179.

Hendricks, M.D et al. (2018) The development of a participatory assessment technique for infrastructure: Neighborhood-level monitoring towards sustainable infrastructure systems. Sustainable Cities and Society, 38: 265-274.

Hickford, A.J., Nicholls, R.J., Otto, A., Hall, J.W., Blainey, S.P., Tran, M. and Baruah, P. (2014) Creating an ensemble of future strategies for national infrastructure provision. Futures, 66: 13-24.

Hickford, A., Blainey, S., Ortego, H. and Pant, R. (2017) A Review of Resilience in Interdependent Transport, Energy and Water Systems. Agenda setting scoping studies summary report. ARUP, UK.

Hong, P. (2016) Jointly building the "Belt and Road" towards the Sustainable Development Goals. United Nations Department of Economic and Social Affairs (DESA). Preliminary draft.

Howell, S., Lee, H. et al. (2014) Leapfrogging or Stalling Out? Electric Vehicles in China. HKS Faculty Research Working Paper Series, July 2014.

Hülsmann, S. and Ardakanian, R. (eds). (2018) Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals. United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES).

Huxham, D. et al. (2015) Applying Climate Compatible Development and economic valuation to coastal management: A case study of Kenya's mangrove forests. Journal of Environmental Management, 157: 168-181.

ICIF and iBuild (2015) A Critique of Current Infrastructure Performance Indicators: Towards Best Practice.

Inter-American Development Bank (IDB) (2015) Challenges and Opportunities for the Energy Sector in the Eastern Caribbean. Saint Lucia Energy Dossier. Technical note No. IDB-TN-852. IDB: Washington D.C., USA.

Inter-American Development Bank (IDB) (2018) Case Study: Performance-based Contract for NRW Reduction and Control – New Providence, Bahamas. Technical note No. IDBTN-813. IDB: Washington D.C., USA.

Inter-American Development Bank (2018) What is Sustainable Infrastructure? A Framework to Guide Sustainability Across the Project Cycle. IDB-TN-1388, March 2018.

International Renewable Energy Agency (IRENA) (2020) Data & Statistics. Available online: https://www.irena.org/Statistics.

International Resource Panel (IRP) (2019) Land Restoration for Achieving the Sustainable Development Goals: An International Resource Panel Think Piece. United Nations Environment Programme, Nairobi, Kenya.

International Transport Forum (ITF) (2017) Strategic infrastructure planning: international best practice. OECD Publishing.

International Transport Forum (ITF) (2018) Transport CO2 and the Paris Climate Agreement: Reviewing the Impact of Nationally Determined Contributions. International Transport Forum Policy Papers 50, OECD Publishing.

Ives, M.C., M. Simpson & J.W. Hall (2018) Navigating the water trilemma: a strategic assessment of long-term national water resource management options for Great Britain. Water and Environment Journal. Print ISSN 1747-6585.

Ives, M.C. et al. (2018) A Fast Track Analysis of Infrastructure Provision in Palestine. Outcomes from the ITRC/UNOPS collaboration. 2 March 2018.

Ives, M.C., Hickford, A.J., Adshead, D., Thacker, S., Hall, J.W., Nicholls, R.J., Sway, T., Abu Ayyash, M., Jones, R. and O'Reagan, N. (2019) A systems-based assessment of Palestine's current and future infrastructure requirements. Journal of Environmental Management, 234: 200-213.

Iyer, G., Ledna, C., Clarke, L., Edmonds, J., McJeon, H., Kyle, P. and Williams, J.H. (2017) Measuring progress from nationally determined contributions to mid-century strategies. Nature Climate Change, 7:871-874.

Iyer, G. et al. (2018) Implications of sustainable development considerations for comparability across nationally determined contributions. Nature Climate Change 8: 124-129.

Janetos, A.C. et al. (2012) Linking climate change and development goals: framing, integrating, and measuring. Climate and Development 4(2): 141-156.

Janetschek, H., Brandi, C., Dzebo, A. & Hackmann, B. (2020) The 2030 Agenda and the Paris Agreement: voluntary contributions towards thematic policy coherence. Climate Policy 20(4): 430-442.

Janoušková et al. (2018) Global SDGs Assessments: Helping or Confusing Indicators? Sustainability, 10, 1540; doi:10.3390/su10051540.

Jeon, C. M., A. A. Amekudze, et al. (2013) Sustainability assessment at the transportation planning level: Performance measures and indexes. Transport Policy 25: 10-21.

Jowitt, P. (2009) Water infrastructure, the UN MDGs and sustainable development. Desalination 248: 510-516.

Kahn Ribeiro, S., Figueroa, M. J., Creutzig, F., Dubeux, C., Hupe J. and Kobayashi, S. (2012) Chapter 9 - Energy End-Use: Transport. In Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 575-648.

Kaur, M., Hewage, K. and Sadiq, R. (2020) Investigating the impacts of urban densification on buried water infrastructure through DPSIR framework. Journal of Cleaner Production, 259, 120897.

Kaza, S., Yao, L.C., Bhada-Tata, P. and Van Woerden, F. (2018) What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development. Washington, DC: World Bank.

Kinder, T. (2002) Introducing an infrastructure for joined-up-government in local public administration: a West Lothian case study. Research Policy 31: 329-355.

Kingsborough, A. (2016) Urban climate change adaptation pathways for long-term adaptation decision-making. Doctoral thesis, University of Oxford.

Knoeri, C., Steinberger, J.K. and Roelich, K. (2016) End-user centred infrastructure operation: towards integrated end-use service delivery. Journal of Cleaner Production 132: 229-239.

Koks, E., Pant, R., Thacker, S. and Hall, J.W. (2019) Understanding business disruption and economic losses due to electricity failures and flooding. International Journal of Disaster Risk Science: 1-18.

Kopperoinen, L., Itkonen, P. and Niemelä, J. (2014) Using expert knowledge in combining green infrastructure and ecosystem services in land use planning: an insight into a new place-based methodology. Landscape Ecology 29: 1361–1375.

Kriegler, E. et al. (2010) Socio-economic Scenario Development for Climate Change Analysis. CIRED Working Paper DT/WP No 2010-23, October 2010.

Kwakkel, J.H. & van der Pas, J.W.G.M. (2011) Evaluation of infrastructure planning approaches: An analogy with medicine. Futures 43(9): 934-946.

Kwakkel, J. H. et al. (2010) Adaptive Airport Strategic Planning. European Journal of Transport and Infrastructure Research 10(3): 249-273.

Le Blanc, D. (2015) Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sust. Dev.* 23, 176-187.

Leary, N., de la Reguera, E., Fitzpatrick, S. and Boggiano-Peterson, O. (2017) Reducing the Nitrogen Footprint of a Small Residential College. Sustainability (New Rochelle) 10(2): 96-104.

Leipziger, D., Fay, M., Wodon, Q. and Yepes, T. (2003) Achieving the Millennium Development Goals: The Role of Infrastructure. World Bank Policy Research Working Paper 3163, November 2003.

Lempert, R. J., S. W. Popper, et al. (2003) Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. Santa Monica, CA, RAND Corporation.

Li, S. and Li, R. (2019) Evaluating Energy Sustainability Using the Pressure-State-Response and Improved Matter-Element Extension Models: Case Study of China. Sustainability 11, 290.

Lichtman-Sadot, S. (2019) Can public transportation reduce accidents? Evidence from the introduction of late-night buses in Israeli cities. Regional Science and Urban Economics 74, 99-117.

Lienert, J., Schnetzer, F. and Ingold, K. (2013) Stakeholder analysis combined with social network analysis provides fine-grained insights into water infrastructure planning processes. Journal of Environmental Management, 125: 134-148.

Liu, Y., Xing, P. and Liu, J. (2017) Environmental performance evaluation of different municipal solid waste management scenarios in China. Resources Conservation and Recycling 125: 98-106.

Llanes, J.L. and Kalogirou, E. (2019) Waste-to-Energy Conversion in Havana: Technical and Economic Analysis. Social Sciences, 8, 119.
LUCELEC. 2018. Transforming the Electricity Sector (2018) Annual Report. Castries, Saint Lucia.

Majid, A. et al. (2020) An Analysis of Electricity Consumption Patterns in the Water and Wastewater Sectors in South East England, UK. Water 12, 225.

Mäkinen, J. (2020) Linking Energy Planning with the Sustainable Development Goals: The Case of Ghana. Master's thesis, KTH Royal Institute of Technology.

Marchau, V. A. W. J. (2010) Dynamic adaptive transport policies for handling deep uncertainty. Technological Forecasting & Social Change 77: 940-950.

Maria, C., Góis, J. and Leitão, A. (2020) Challenges and perspectives of greenhouse gases emissions from municipal solid waste management in Angola. Energy Reports 6(1): 364-369.

Martin, J.-L. (2002) Relationship between crash rate and hourly traffic flow on interurban motorways. Accident Analysis & Prevention 34(5): 619-629.

Marvin, S. and Graham, S. (1993) Utility Networks and Urban Planning: An Issue Agenda. Planning Practice and Research 8(4): 6-14.

Masterton, G. et al. (2017) Infrastructure performance indicators – a new approach based on the Sustainable Development Goals.

McCollum, D.L. et al. (2018a) Connecting the sustainable development goals by their energy inter-linkages. Environmental Research Letters 13(3).

McCollum, D.L. et al. (2018b) Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nature Energy 3: 589-599.

Merven, B., Stone, A. Hughes, A. and Cohen, B. Quantifying the energy needs of the transport sector for South Africa: A bottom up model. Energy Research Centre, June 2012.

Mills-Novoa, M. and Liverman, D. (2019) Nationally Determined Contributions: Material climate commitments and discursive positioning in the NDCs. WIREs Climate Change 10(5).

Ministry of Agriculture, Fisheries, Physical Planning, Natural Resources and Co-operatives Saint Lucia. (2017) National Policy on Wastewater Management. Government of Saint Lucia: Castries, Saint Lucia.

Mitchell, T. and Maxwell, S. (2010) Defining climate compatible development. CDKN ODI Policy Brief November 2010/A.

Modi, V. et al. (2012) Infrastructure from the Bottom Up. The Earth Institute, Columbia University. New York.

Montoute, M.C. and Cashman, A. (2015) A knowledge, attitudes and practices study on water, sanitation and hygiene in Anse La Raye Village, Saint Lucia. CERMES Technical Report No 78. Centre for Resource Management and Environmental Studies (CERMES): Barbados.

Morley, J., Widdicks, K. and Hazas, M. (2018) Digitalisation, energy and data demand: The impact of Internet traffic on overall and peak electricity consumption. Energy Research & Social Science 38: 128-137.

Moss, R.H. et al. (2010) The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Moya, D. et al. (2017) Waste-To-Energy Technologies: an opportunity of energy recovery from Municipal Solid Waste, using Quito - Ecuador as case study. Energy Procedia 134: 327–336.

Moyer, J.D. and Bohl, D.K. (2019) Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals. Futures 105: 199-210.

Mulugetta, Y., Ben Hagan, E. and Kammen, D. (2019) Energy access for sustainable development. Environmental Research Letters 14 (2019) 020201.

Murray, S. (2019) The critical role of infrastructure for the Sustainable Development Goals. The Economist Intelligence Unit Limited.

Mutascu, M. (2016) A bootstrap panel Granger causality analysis of energy consumption and economic growth in the G7 countries. Renewable and Sustainable Energy Reviews 63: 166-171.

Natarajan, L., Lock, S.J., Rydin, Y. Lee, M. (2019) Participatory planning and major infrastructure: experiences in REI NSIP regulation. TPR, 90 (2) 2019.

National Infrastructure Commission (2016) The impact of technological change on future infrastructure supply and demand. London, United Kingdom.

National Infrastructure Commission (2018) National Infrastructure Assessment. London, United Kingdom.

National Research Council (1996) Measuring and Improving Infrastructure Performance. Washington, DC: The National Academies Press. https://doi.org/10.17226/4929.

NEA/IEA/OECD (2015) Projected Costs of Generating Electricity (2015) OECD Publishing, Paris, https://doi.org/10.1787/cost_electricity-2015-en.

de Neufville, R. (2003) Real Options: Dealing with Uncertainty In Systems Planning and Design. Integrated Assessment 4(1): 26-34.

de Neufville, R. (2009) Identifying Real Options to Improve the Design of Engineering Systems. 10.1201/9781420071702.ch8.

Newig, J. and Koontz, T.M. (2014) Multi-level governance, policy implementation and participation: the EU's mandated participatory planning approach to implementing environmental policy. Journal of European Public Policy, 21(2): 248-267.

News784 (2018) Caribbean Resilient Infrastructure Conference, Curacao 8 – 9 May. https://news784.com/feature/caribbean-resilient-infrastructure-conference-curacao-8-9-may/.

Nguyen, Q., Janetscheck, H., Iacobuta, G. and Dzebo, A. (2018) pathways for policy coherence in implementation of NDC and SDGs in Viet Nam and the role of civil society. Hanoi, Vietnam: Friedrich Ebert Stiftung.

Nilsson, M., Griggs, D. and Visbeck, M. (2016) Map the interactions between sustainable development goals. Nature 534:320–322.

Nilsson, M., Lucas, P. and Yoshida, T. (2013) Towards an Integrated Framework for SDGs: Ultimate and Enabling Goals for the Case of Energy. Sustainability, 5: 4124-4151.

Njoku, P.O., Edokpayi, J.N. and Odiyo, J.O. (2019) Health and Environmental Risks of Residents Living Close to a Landfill: A Case Study of Thohoyandou Landfill, Limpopo Province, South Africa. International Journal of Environmental Research and Public Health 16(12): 2125.

Norlander, R.J. (2013) The contributions of digital communications technology to human rights education: A case study of Amnesty International. Doctoral thesis, Saybrook University.

Northrop, E., Biru, H., Lima, S., Bouye, M. and Song, R. (2016) Examining the Alignment Between the Intended Nationally Determined Contributions and Sustainable Development Goals. Working Paper. Washington, DC: World Resources Institute.

Nunes, A.R., Lee, K. & O'Riordan, T. (2016) The importance of an integrating framework for achieving the Sustainable Development Goals: the example of health and well-being. BMJ Global Health 2016; 1:e000068. doi: 10.1136/bmjgh-2016-000068.

O'Rourke, T.D. (2007) Critical infrastructure, interdependencies, and resilience. 'The Bridge' National Academy of Engineering, 37(1), pp.22-29.

O'Sullivan, T.L., Kuziemsky, C.E., Toal-Sullivan, D. and Corneil, W. (2013) Unraveling the complexities of disaster management: A framework for critical social infrastructure to promote population health and resilience. Social Science & Medicine, 93: 238-246.

Ockwell, D. G., Watson, J. et al. (2008) Key policy considerations for facilitating low carbon technology transfer to developing countries. Energy Policy 36: 4104-4115.

OECD (2003) OECD Environmental Indicators: Development, Measurement and Use. Paris, France.

OECD (2007) Infrastructure to 2030 (Volume 2): Mapping Policy for Electricity, Water and Transport. International Futures Programme. OECD: Paris.

OECD (2015) Towards a Framework for the Governance of Infrastructure. Paris, France.

OECD (2017a) "Infrastructure for climate and growth", in Investing in Climate, Investing in Growth, OECD Publishing, Paris.

OECD (2017b) Measuring distance to the SDG targets. OECD: Paris.

OECD (2018) Financing Climate Futures: Rethinking Infrastructure. Policy Highlights. OECD: Paris.

Otto, A., Hall, J.W., Hickford, A.J., Nicholls, R.J., Alderson, D., Barr, S. and Tran, M. (2016) A Quantified System-of-Systems Modeling Framework for Robust National Infrastructure Planning. IEEE Systems Journal, 10, 2: 385-396.

Oxford Business Group (2020) Indonesia to see increased energy generation capacity under a new plan. https://oxfordbusinessgroup.com/analysis/generation-game-under-new-plan-country-will-see-increased-capacity.

Pakzad, P. and Osmond, P. (2016) Developing a sustainability indicator set for measuring green infrastructure performance. Procedia - Social and Behavioral Sciences 216: 68-79.

Pakzad, P., Osmond, P. and Corkery, L. (2017) Developing key sustainability indicators for assessing green infrastructure performance. Procedia Engineering 180: 146-156.

Pant, R., Zorn, C., Thacker, S. and Hall, J.W. (2018) Systemic Resilience Metrics for Interdependent Infrastructure Networks. Proceedings of the 6th International Symposium on Reliability Engineering and Risk Management (6ISRERM) 31 May - 1 June 2018, Singapore.

Pant, R., Russell, T., Zorn, C., Oughton, E. and Hall, J.W. (2020) Resilience study research for NIC - Systems analysis of interdependent network vulnerabilities. Environmental Change Institute, Oxford University, UK.

Pauliuk, S. and Müller, D.B. (2014) The role of in-use stocks in the social metabolism and in climate change mitigation. Global Environmental Change 24: 132-142.

Pehl, M. et al. (2017) Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nature Energy 2: 939-945.

Phillips, W. and Thorne, E. (2013) Municipal solid waste management in the Caribbean. ECLAC – Studies and Perspectives series – The Caribbean – No. 22.

PICC (2012) A Summary of The South African National Infrastructure Plan. Presidential Infrastructure Coordinating Commission Report 2012.

Pietzcker R.C., Longden, T., Chen, W., Fu, S., Kriegler, E., Kyle, P. and Luderer, G. (2014) Long-term transport energy demand and climate policy: Alternative visions on Transport Decarbonization in Energy-Economy Models. Energy 64: 95–108.

Pizzutilo, F. and Venezia, E. (2016) Real Option Analysis Applied to Transport Investment Projects. Proceedings of the Third International Conference on Traffic and Transport Engineering.

Plappally, A.K. and Lienhard, J.H. (2012) Energy requirements for water production, treatment, end use, reclamation, and disposal. Renewable and Sustainable Energy Reviews 16(7): 4818-4848.

Powell, J.T., Chertow, M.R. and Esty, D.C. (2018) Where is global waste management heading? An analysis of solid waste sector commitments from nationally-determined contributions. Waste Management, 80: 137-143.

Pradhan, P. et al. (2017) A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earth's Future, 5(11): 1169-1179.

Prakash, M., Teksoz, K., Espey, J., Sachs, J., Shank, M. and Schmidt-Traub, G. (2017) Achieving A Sustainable Urban America. The US Cities Sustainable Development Goals Index 2017. Sustainable Development Solutions Network.

Presidencia de la República de Colombia (2020) COMPROMISO POR COLOMBIA EMPLEO / Los proyectos de Quinta Generación (5G) tendrán como eje central la sostenibilidad, el empleo y los temas sociales. Bogotá, 07/08/2020.

President's Commission on Critical Infrastructure Protection (1997) Critical Foundations – Protecting America's Infrastructures. Report of the President's Commission on Critical Infrastructure Protection, October 1997.

Ramaswami, A. et al. (2016) Meta-principles for developing smart, sustainable, and healthy cities. Science, Vol 352, Issue 6288: 940-943.

Raworth, K. (2017). Doughnut economics: seven ways to think like a 21st-century economist. London: Random House.

Retallack, A.E. and Ostendorf, B. (2019) Current Understanding of the Effects of Congestion on Traffic Accidents. International Journal of Environmental Research and Public Health 16(18): 3400.

Reusser, D. et al. (2013) Relating climate compatible development and human livelihood. Energy Procedia 40: 192-201.

Riahi, K. et al. (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42: 153-168.

Richards, M.B., Wollenberg, E. and van Vuuren, D. (2018) National contributions to climate change mitigation from agriculture: allocating a global target. Climate Policy 18(10): 1271-1285.

Rinaldi, S.M., Peerenboom, J.P. and Kelly, T. K. (2001) Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Systems Magazine, 21(6): 11-25.

Robinson, J., Burch, S., Talwar, S., O'Shea, M. and Walsh, M. (2011) Envisioning sustainability: Recent progress in the use of participatory backcasting approaches for sustainability research. Technological Forecasting and Social Change, 78(5): 756-768.

Roelfsema, M. et al. (2020) Taking stock of national climate policies to evaluate implementation of the Paris Agreement. Nature Communications 11.

Rogelj, J. et al. (2015) Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Climate Change 5: 519-527.

Rogelj, J. et al. (2018) Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change 8: 325-332.

Rozenberg, J., and Fay, M., eds. (2019) Beyond the Gap: How Countries Can Afford the Infrastructure They Need while Protecting the Planet. Sustainable Infrastructure Series. Washington, DC: World Bank. doi:10.1596/978-1-4648-1363-4. License: Creative Commons Attribution CC BY 3.0 IGO.

Röser, F., Widerberg, O., Höhne, N. and Day, T. (2020) Ambition in the making: analysing the preparation and implementation process of the Nationally Determined Contributions under the Paris Agreement. Climate Policy 20(4): 415-429.

Ryan-Collins, L., Ellis, K. & Lemma, A. (2011) Climate Compatible Development in the Infrastructure Sector. An overview of the opportunities and challenges at the nexus of climate change, infrastructure and development. June 2011.

Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nackicenovic, N. and Rockström, J. (2019a) Six Transformations to achieve the Sustainable Development Goals. Nature Sustainability, 2:805-814.

Sachs, J.D., Schmidt-Traub, G., Kroll, C., Lafortune, G., Fuller, G. (2019b) Sustainable Development Report 2019. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).

Saint Lucia Air and Sea Ports Authority (SLASPA) (2019) Personal communication.

Saint Lucia Solid Waste Management Authority (SLUSWMA) (2019) Personal communication.

Saint Lucia Water and Sewerage Company (WASCO) (2019) Personal communication.

Santander Investment Services (2006) Project for the Private Sector Participation Transaction in St. Lucia's Water Utility. Diagnostic of the Utility.

Schlömer S. et al. (2014) Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Schmale, J., von Schneidemesser, E. and Dörrie, A. (2015) An Integrated Assessment Method for Sustainable Transport System Planning in a Middle-Sized German City. Sustainability, 7: 1329-1354.

Scholten, L. et al. (2015) Tackling uncertainty in multi-criteria decision analysis – An application to water supply infrastructure planning. European Journal of Operational Research 242: 243-260.

Schmidt-Traub, G. et al. (2017) National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards. Nature Geoscience, 10: 547-555.

Scott, A., Worrall, L. and Patel, S. (2018) Aligning energy development and climate objectives in Nationally Determined Contributions. CDKN Working Paper, January 2018.

van Soest, H.L. et al. (2019) Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. Global Transitions 1: 210-225.

Shang, Q. et al. (2014) Soil fertility and its significance to crop productivity and sustainability in typical agroecosystem: a summary of long-term fertilizer experiments in China. Plant and Soil 381, 13-23.

Shen, L. et al. (2011) Key Assessment Indicators for the Sustainability of Infrastructure Projects." Journal of Construction Engineering and Management 137(6): 441-451.

Shibata, H. et al. (2016) Nitrogen footprints: Regional realities and options to reduce nitrogen loss to the environment. Ambio 46, 129-142.

Shockley, K. (2018) Sustainable development goals and nationally determined contributions: the poor fit between agent-dependent and agent-independent policy instruments. Journal of Global Ethics 14(3): 369-386.

SIDSSA (2020) Sustainable Infrastructure Development Symposium South Africa. https://sidssa.org.za/.

Smith, K.R. et al. (2013) Energy and human health. Annual Review of Public Health 34: 159-188.

Soares, H. et al. (2018) Social infrastructure and the preservation of physical capital: Equilibria and transitional dynamics. Applied Mathematics and Computation, 321: 614-632.

Spanò, M., Gentile, F., Davies, C. and Lafortezza, R. (2017) The DPSIR framework in support of green infrastructure planning: A case study in Southern Italy. Land Use Policy, 61: 242-250.

Srivastava, P. and Mostafavi, A. (2018) Challenges and Opportunities of Crowdsourcing and Participatory Planning in Developing Infrastructure Systems of Smart Cities. Infrastructures, 3, 51.

St. Lucia Times (2020) New Tools To Help Saint Lucia Build Resilient Infrastructure. https://stluciatimes.com/new-tools-to-help-saint-lucia-build-resilient-infrastructure/.

Stantec (2015) Dennery Water Supply Redevelopment Plan. Revised Final Report.

von Stechow, C. et al. (2016) 2 °C and SDGs: united they stand, divided they fall? Environmental Research Letters 11(3).

Steinberger, J.K. and Roberts, J.T. (2010) From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. Ecological Economics, 70(2): 425-433.

Suckall, N., Stringer, L.C. and Tompkins, E.L. (2015) Presenting Triple-Wins? Assessing Projects That Deliver Adaptation, Mitigation and Development Co-benefits in Rural Sub-Saharan Africa. AMBIO 44: 34–41.

Suleiman, L. and Cars, G. (2010) Water supply governance in Accra: "authentic" or "symbolic". Water Policy 12: 272-289.

Sultana, P. and Abeyasekera, S. (2008) Effectiveness of participatory planning for community management of fisheries in Bangladesh. Journal of Environmental Management, 86(1): 201-213.

Sun, J., Li, T., Li, F. and Chen, F. (2016) Analysis of safety factors for urban expressways considering the effect of congestion in Shanghai, China. Accident Analysis & Prevention 95(B): 503-511.

Taibi, F-Z. and Konrad, S. (2018) Pocket Guide to NDCs under the UNFCCC.

Tanner, T. et al. (2014) Political Economy of Climate Compatible Development: Artisanal Fisheries and Climate Change in Ghana. IDS Working Paper, Volume 2014, No 446.

Thacker, S., Hall, J.W., Russell, T., Pant, R., Leung, J. and Koks, E. (2017) System-of-systems infrastructure modelling to support national sustainable development outcomes. Proceedings of the 2017 International Symposium of Next Generation Infrastructure, London, UK.

Thacker, S., Pant, R. and Hall, J.W. (2017) System-of-systems formulation and disruption analysis for multi-scale critical national infrastructures. Reliability Engineering & System Safety 167: 30-41.

Thacker S, Adshead D, Morgan G, Crosskey S, Bajpai A, Ceppi P, Hall JW & O'Regan N. (2018) Infrastructure: Underpinning Sustainable Development. United Nations Office for Project Services, Copenhagen, Denmark.

Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., and Hall, J.W. (2019) Infrastructure for sustainable development. Nature Sustainability, 2(4): 324-331.

Thekdi, S.A and Lambert, J.H. (2014) Quantification of Scenarios and Stakeholders Influencing Priorities for Risk Mitigation in Infrastructure Systems. Journal of Management in Engineering, 30(1): 32-40.

van Tilburg, X., Luijten, J., Röser, F., Lütkehermöller, K. and Minderhout, S. (2018) NDC update report – Ambition: Taking a long-term perspective. ECN Policy Studies and New Climate Institute.

Torbert, R., Bunker, K., Doig, S., Locke, J., Mushegan, S. and Teelucksingh, S. (2016) Developing the Saint Lucia Energy Roadmap. Rocky Mountain Institute, Basalt, USA.

Tortajada, C. and van Rensburg, P. (2020) Drink more recycled water. Nature 577, 26-28.

Treasury (2019) Establishing a New Independent Infrastructure Body Cabinet Paper. Government of New Zealand (2019).

Tsai, T. (2013) A study of recycling in Saint Lucia. Taiwan ICDF Overseas programme: Taipei, Taiwan.

TWI2050 (2018) Transformations to Achieve the Sustainable Development Goals. Report prepared by The World in 2050 initiative. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. www.twi2050.org.

UN DESA (2019a) Revision of World Population Prospects. Available online: https://population.un.org/wpp/.

UN DESA (2019b) Household Size & Composition. Available online: https://population.un.org/Household/#/countries/.

UN DESA (2020) The 17 Goals. https://sdgs.un.org/goals.

UNDP (2016) Scaling up Climate Action to Achieve the Sustainable Development Goals. UNDP, New York.

UNDP (2018) A Roadmap for SDG Implementation in Curaçao. December 2018.

UNEP/CAR-RCU (2009) Financial Assessment for Wastewater Treatment and Disposal (WWTD) in the Caribbean Report. Caribbean Institute for Environmental Health (CEHI), St. Lucia.

UNEP-CEP (2010) International Overview of Best Practices in Wastewater Management. International Best Practices. CEP Technical Report 65. UNEP CAR/RCU: Kingston, Jamaica.
UNFCCC (2015) The Paris Agreement. Available online: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

UNESCAP (2017) Transport and the Sustainable Development Goals, in Transport and Communications Bulletin for Asia and the Pacific. United Nations Economic and Social Commission for Asia and the Pacific: Thailand.

UNISDR (2015) Sendai Framework for Disaster Risk Reduction. UNISDR/GE/2015 – ICLUX EN5000 1st edition.

United Nations (2017) New Urban Agenda. United Nations Conference on Housing and Sustainable Urban Development.

United Nations Development Programme (2016) Scaling up climate action to achieve the Sustainable Development Goals. UNDP, New York.

United Nations Framework Convention on Climate Change (2015) The Paris Agreement.

United Nations Framework Convention on Climate Change (UNFCCC) (2020) Greenhouse Gas Inventory Data - Detailed data by Party. https://di.unfccc.int/detailed_data_by_party.

United Nations Framework Convention on Climate Change (UNFCCC) (2020) NDC Registry. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx.

UNOPS (2020) “Infrastructure”. Available online: https://www.unops.org/expertise/infrastructure.

UNOPS/ECI/University of Oxford (2019) ‘Sustainable’ tool. sustainable.unops.org.

Ürge-Vorsatz, D., Tirado Herrero, S., Dubash, N.K. and Lecoq, F. (2014) Measuring the Co-Benefits of Climate Change Mitigation. Annual Review of Environment and Resources 39: 549-582.

Verma, S., Kanwar, V., and John, S. (2015) Water Supply Engineering. Vikas Publishing House Pvt Ltd. ISBN: 978-93259-8425-7.

Vladimirova & Le Blanc (2016) Exploring Links Between Education and Sustainable Development Goals Through the Lens of UN Flagship Reports. Sustainable Development, 24: 254-271.

van Vuuren, D.P. et al. (2015) Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. Technological Forecasting & Social Change 98 (2015) 303–323.

Wang, T. and de Neufville, R. (2005) Real options “in” projects. Prepared for the 9th Real Options Annual International Conference in Paris, France. June 2005.

Watson, J. and Sauter, R. (2011) Sustainable innovation through leapfrogging: a review of the evidence. International Journal of Technology and Globalisation 5(3/4): 170-189.

Watson, J., et al. (2015) Lessons from China: building technological capabilities for low carbon technology transfer and development. Climatic Change 131: 387-399.

Weitz, N., M. Nilsson & M. Davis (2014) A Nexus Approach to the Post-2015 Agenda: Formulating Integrated Water, Energy, and Food SDGs. SAIS Review vol. XXXIV no. 2 (Summer–Fall 2014).

Weitz, N., et al. (2018) Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustainability Science, 13(2): p. 531-548.

White House (1998) Presidential Decision Directive/NSC-63 – May 22, 1998.

Willows, R. I. and R. K. Connell, Eds. (2003) Climate adaptation: Risk, uncertainty and decision making, UKCIP Technical Report. UKCIP, Oxford.

Wilson, D.L., Talancon, D.R., Winslow, R.L., Linares, X. and Gadgil, A.J. (2016) Avoided emissions of a fuel-efficient biomass cookstove dwarf embodied emissions. Development Engineering 1: 45-52.

Winkler, H., Boyd, A., Gunfaus, M.T. and Raubenheimer, S. (2015) Reconsidering development by reflecting on climate change. International Environmental Agreements: Politics, Law and Economics 15: 369–385.

Wise, R. M., I. Fazey, et al. (2014) Reconceptualising adaptation to climate change as part of pathways of change and response. Global Environmental Change 28: 325-336.

Woetzel, J. et al. (2017) Bridging infrastructure gaps: has the world made progress? Discussion paper in collaboration with McKinsey's capital projects and infrastructure practice, October 2017.

World Bank (2020) World Development Indicators. Available online: https://databank.worldbank.org/home.aspx.

World Economic Forum (2019) Bridging the Infrastructure Gap: Tools for Creating Investable Infrastructure Project Pipelines. Community Paper, November 2019.

World Energy Council (2017) World Energy Trilemma 2017: Changing dynamics using distributed energy resources to meet the Trilemma Challenge.

Yillia, P.T. (2016) Water-Energy-Food nexus: framing the opportunities, challenges and synergies for implementing the SDGs. Österr Wasser- und Abfallw, 68: 86–98.

Yin, W. (2019) Integrating Sustainable Development Goals into the Belt and Road Initiative: Would It Be a New Model for Green and Sustainable Investment? Sustainability, 11(24), 6991.

Young, K. (2015) Strategic Appraisal of Interdependent Infrastructure Provision. Doctoral thesis, University of Oxford.

Young, K. and J.W. Hall (2015) Introducing system interdependency into infrastructure appraisal: from projects to portfolios to pathways. Infrastructure Complexity 2(2).

Zegras, C. (2006) Sustainable Transport Indicators and Assessment Methodologies. Background Paper for Plenary Session 4 at the Biannual Conference and Exhibit of the Clean Air Initiative for Latin American Cities: Sustainable Transport: Linkages to Mitigate Climate Change and Improve Air Quality. São Paulo, Brazil.

Zhou, X. & Moinuddin, M. (2017) Sustainable Development Goals Interlinkages and Network Analysis: A practical tool for SDG integration and policy coherence. IGES Research Report No. RR1602.

Zorn, C., Koks, E. and Eggimann, S. (2020) Demand side management impacts on electricity network vulnerability.

Zorn, C., Pant, R., Thacker, S. and Shamseldin, A.Y. (2020) Evaluating the magnitude and spatial extent of disruptions across interdependent national infrastructure networks. ASME J. Risk Uncertainty Part B, 6(2). 020904.

Zorpas, A., Voukkai, I. and Loizia, P. (2014) The impact of tourist sector in the waste management plans. Desalination and Water Treatment, 56, 5:1141-1149.

Statements of authorship

SCHOOL OF GEOGRAPHY AND THE ENVIRONMENT
ENVIRONMENTAL CHANGE INSTITUTE

South Parks Road, Oxford OX1 3QY
+44 1865 285070

I, Jim W. Hall, certify that Daniel Adshead completed the majority of the work in the three journal articles below, which form part of his DPhil thesis:

- *Delivering on the Sustainable Development Goals through long-term infrastructure planning*
- *Infrastructure strategies for achieving the global development agendas in small islands*
- *Aligning mitigation actions with development challenges in updated Nationally Determined Contributions*

Signature:

Date: 29 October 2020

SCHOOL OF GEOGRAPHY AND THE ENVIRONMENT
ENVIRONMENTAL CHANGE INSTITUTE

South Parks Road, Oxford OX1 3QY
+44 1865 285070

I, Scott Thacker, certify that Daniel Adshead completed the majority of the work in the three journal articles below, which form part of his DPhil thesis:

Delivering on the Sustainable Development Goals through long-term infrastructure planning

Infrastructure strategies for achieving the global development agendas in small islands

Aligning mitigation actions with development challenges in updated Nationally Determined Contributions

Signature

Date: 27.10.2020

SCHOOL OF GEOGRAPHY AND THE ENVIRONMENT
ENVIRONMENTAL CHANGE INSTITUTE

South Parks Road, Oxford OX1 3QY
+44 1865 285070



I, Lena I. Fuldauer, certify that Daniel Adshead completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- *Delivering on the Sustainable Development Goals through long-term infrastructure planning*

Signature:
Lena Fuldauer

Date:
12/10/2020

CENTRE FOR SUSTAINABLE DEVELOPMENT
DEPARTMENT OF ENGINEERING

Trumpington Street
Cambridge CB2 1PZ

UNIVERSITY OF CAMBRIDGE

I, Orlando Román García, certify that Daniel Adshead completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- *Infrastructure strategies for achieving the global development agendas in small islands*

Signature:

Date: 14/10/2020