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A Macroeconomic Framework for Long-Term Resilience and Growth

David Bartolini, Andrew Ceber, Valerie Cerra, Pedro Juarros, Yujin Kim, Junko Mochizuki, and Christine Richmond

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ABSTRACT: This paper describes a macroeconomic framework integrating disasters in the analysis of growth and long-term economic resilience. The framework is a dynamic growth model incorporating endogenous human and physical capital accumulation, fiscal policy interventions, and public debt dynamics. The model allows for flexible analyses of slow and fast onset climate impacts and fiscal policy reforms to foster sustainable long-term growth and adaptation, including enhanced spending on resilient investment and non-structural adaptation options. Focusing on adaptation policies, specifically on investing in resilient infrastructure, we present the country cases of Benin and Jamaica, examining tradeoffs and synergies in macro-fiscal policies for addressing sustainable long-term growth and the impacts of disasters.*

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* Disasters here refer to extreme events and the analysis includes heightened frequency of such shocks as a result of climate change.

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I. Introduction

Achieving long-term growth and resilience will require substantial public and private investment in the coming years. Established as "a plan of action for people, planet, and prosperity,"[1] the sustainable development goals (SDGs) encompass 17 goals and 169 targets aimed at global transformation, founded on the vision of long-term growth and resilience Among the goals are human rights and human dignity and the rule of law, sustainable economic growth and decent work, together with access to education and healthcare, clean water and sanitation, reliable energy and transport, and actions to combat climate change. The estimates of funding needs attest to the "supremely ambitious and transformational"[2] nature of the global goals, exacerbated by the COVID-19 pandemic (Benedek et al., 2021; Olusegun et al., 2021).[3] Gaspar et al. (2019) and Carapella et al. (2023), focused on health, education, water and sanitation, electricity, and road alone, estimate that additional spending in 2030 of approximately US$0.5 trillion and US$ 2.35 trillion will be needed for low-income (LICs) and emerging market (EM) countries. This represents an average incremental spending of 16 and 5 percentage points of GDP for LICs and EMs respectively.[4]

Managing this scale of public and private investment requires sound macro-fiscal planning, along with effective reforms to foster an enabling environment. The incremental spending on investments needed for longer-term growth and resilience could be financed through a combination of means including domestic resource mobilization, improvement in spending efficiency, public debt-financing, official development assistance, and private sector engagement (IMF, 2015).[5] Additional scope to mobilize each source depends on a country's circumstances, as does the effectiveness of the resource mobilization strategy. Global experiences show, for example, an effective combination of tax policy reforms, with administrative capacity building, can achieve a substantial increase in the tax-to-GDP ratio, such as those demonstrated in China between 1995-2002 (5 percentage point increase) and Georgia between 2004-2009 (12 percentage point increase).[6] Decision-makers in LICs and EMs likewise can benefit from expert policy guidance to navigate reforms and an integrative analytical tool is essential, which allows for an articulation of inter-temporal macro-fiscal trade-offs and synergies. In this vein, the medium-term revenue strategy (MTRS) approach, an instrument underpinning cohesive tax reforms and supported by the IMF, is also increasingly adopted as a good practice to plan for SDG spending (Benitez et. al, 2023).[7]

Climate change adds critical new dimensions to global achievement of the SDGs. According to the Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report (AR6) in 2022, an estimated 3.3 to 3.6 billion people globally are living in settings that are "highly vulnerable" to climate change, particularly in small island states and regions in Africa, South America, and Asia. Climate change is already posing increasing threats to sustainable development from an increase in average temperatures, to sea level rise, and increased frequency and intensity of climate shocks, which damage infrastructure and thwart economic activities in affected areas. As has been estimated by studies including Aligishiev et al. (2022), Aggarwal et al.

[1] Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs (un.org)

[2] Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs (un.org)

[3] For more details about the SDGs financing challenges, please see the IMF SDG Financing Tool, an interactive scenario builder to assess the macroeconomic coherence of countries' SDG financing plans. It helps stakeholders develop long-term plans, evaluate policy impacts, and compare financing options.

[4] Please see, Fiscal Policy and Development: Human, Social, and Physical Investments for the SDGs (imf.org), and How to Assess Spending Needs of the Sustainable Development Goals: The Third Edition of the IMF SDG Costing Tool.

[5] *Ibid*

[6] *Ibid.* Staff Discussion Notes Volume 2023 Issue 006: Building Tax Capacity in Developing Countries (2023) (imf.org)

[7] Concept Note for PCT Workshops on MTRS.pdf (tax-platform.org)

(2024), and Zdzienicka et al. (2021), and well as published national adaptation plans (NAP), the coming years will require significant climate adaptation investment to attenuate the adverse impacts of climate change, prompting the need for sound ex-ante macro-fiscal assessments.

Achieving sustainable and inclusive economic development, while responding to the challenges of climate change, requires holistic policy actions guided by an integrated conceptual framework (Amar et al., 2022; Cerra et al., 2022; Bellon and Massetti, 2022a and 2022b). A key component of such framework is a coherent macroeconomic model to assess the impact of climate change and climate policies within the broader context of a country's development policies, along with other economic shocks.

This paper describes a macroeconomic model (C-SDG) integrating the analysis of climate change and sustainable development. The C-SDG, built on the model initially developed for the analysis of SDG financing options (SDG-FiT) (Benedek et al., 2021), is a dynamic growth model incorporating endogenous human and physical capital accumulation, fiscal policy interventions, and public debt dynamics. The model allows for flexible analyses of multiple climate shocks and slow-onset climate impacts as well as policy reforms to foster adaptation and SDGs, including enhanced public and private spending on standard versus resilient investment along with non-structural adaptation options. It facilitates the examination of tradeoffs and synergies in macro-fiscal policies for addressing growth, climate change[8] and the SDGs. The C-SDG model is especially suited to evaluate the macro-fiscal aspects of SDGs needs and financing among countries facing significant climate change risks (from disasters and slow-onset drivers). It is especially relevant for countries exposed to hurricanes and tropical storms, such as those in Central America and the Pacific, as well as countries prone to flooding, including Bangladesh, India, Vietnam, Indonesia, Iraq, Pakistan, Cambodia, and various West and Central African nations. In these regions, such climate shocks frequently destroy public infrastructure (i.e., roads, bridges, health and education buildings).[9] As a first step in demonstrating the model's applicability, we apply it to analyze adaptation policies, focusing on investments in resilient public infrastructure in response to major natural disaster shocks and its impact on SDG needs.

The rest of the paper is structured as follows: Section II elaborates on the macroeconomic impact of climate change and policies to address it. Section III and IV describe the model and its calibration, respectively. Section V applies the model to two country applications, Benin and Jamaica, and Section VI concludes.

[8] Disasters here refer to extreme events and the analysis includes heightened frequency of such shocks as a result of climate change.
[9] While the framework is designed to account for the effects of slow-onset climate events, our current analysis focuses on the macroeconomic impacts of specific climate disasters, reserving the examination of slow-onset effects for future research.

II. Climate Change Impacts and Policies

A. Socio-Economic Impacts

Climate change is a global phenomenon, and its effects are generally distinguished as slow-onset versus extreme (including fast-onset) events. According to the IPCC, slow-onset events refer to "risks and impacts associated with increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization"[10], and extreme events are defined as "the occurrence of a value of a weather or climate variable above (or below) a threshold value"[11] and include fast-onset phenomena such as floods, storms, and cyclones.

Both slow- and fast-onset events can cause considerable costs to an economy. The immediate channel through which climate change affects an economy is its impact on the real sector. In many regions, climate change is already affecting productivity, while extreme events have caused substantial destruction of capital (physical, natural, and human capital). As per the IPCC AR6 report, there is *high confidence* that adverse climate impacts on economic damages are already happening in climate-sensitive sectors including agriculture, forestry, fishery, energy, and tourism (Mendelsohn et al., 1994). Climate change is projected to continue to adversely affect real sector production. Based on the latest multi-model simulations, Jägermeyr (2021), for example, projects that global maize yields by the end-of-century (2069–2099) could decline as much as 10 percent (low emissions scenario[12]) and 20 percent (high emissions scenario[13]). Lam et al. (2016) estimates that global maximum catch potential of fishers is projected to decrease almost 8 percent by 2050 under the high emissions scenario, leading to revenue decline of approximately 10 percent. According to the 2019 World Bank's *Lifelines* report, disasters currently cost low- and middle-income countries US$ 390 billion a year in infrastructure damages while investing in resilient infrastructure, which costs 3 percent more, will yield a total net benefit of US$ 4.2 trillion.[14]

Climate change impacts are further exacerbated through transmission channels in the fiscal, external, and monetary sectors. When climate change, including extreme events, leads to the destruction of productive capital along with loss of productivity and output, households and firms employ a variety of coping mechanisms, decreasing consumption/savings (or increasing dis-savings, Khan et al., 2024). Faced with increased response and reconstruction spending, along with a decline in tax revenue, the fiscal balance tends to worsen. Disasters also generally increase the need for capital imports, with loss of export outputs hurting the balance of trade. Governments also take a variety of monetary policy responses to manage pressures on inflation and exchange rates.[15] The recent years have seen an increase in empirical and theoretical studies clarifying the interactions of climate and macro-fiscal variables. Using a combination of macroeconomic data and ground and satellite disaster indicators across 164 countries, Fuje et al. 2023, for example, find that

[10] https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

[11] https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf

[12] The low emissions scenario refers to SSP126, which is in line with the Paris goal to keep global mean temperature increase below 2 ºC with respect to pre-industrial times.

[13] The high emissions scenario refers to SSP585. which projects a median temperature increase of 4.4°C above the pre-industrial time, while representing the upper bound of SSP scenario combination, SSP585 is increasingly considered implausible given the extreme assumptions made on growth and emissions trajectories.

[14] Lifelines: The Resilient Infrastructure Opportunity

[15] Monetary Policy in Disaster Prone Developing Countries, IMF Working Paper.

droughts lead to the deterioration of the primary balance and public debt of EMDEs by as much as 1.4 and 1.5 percent of GDP, respectively. Using monthly data for 177 countries, Nguyen and Nguyen (forthcoming) identify that under non-pegged exchange rate regimes, disasters, on average, lead to nominal and real exchange rates depreciation of up to 6 percent two years following the disaster. Akyapi et al. (2022) using high-frequency and high-resolution weather variables show that more frequent high temperatures, severe droughts, and fewer mild temperature days reduce GDP per capita by 0.2 percentage points, and fiscal policy helps mitigate these shocks. Lastly, using high frequency data for seven Central American countries, Kim et al. (2022) find that climate events resulted in a decline of monthly (year-on-year) economic activity by around 0.5-1 percentage point, while increasing remittances by more than 3 percentage points. Understanding how these alternative transmission channels interact to determine outputs are important in order to allow for effective ex-ante planning of macro-fiscal policy considerations under climate change.

B. Adaptation Policy

Adaptation policies entail enhancing physical, financial, and economic resilience, and alleviating the socioeconomic impacts of residual damages to both fast and slow-onset events. Adaptation refers to a country's measures to limit and respond to local damages caused by global climate change. Public investment to build and maintain resilient public infrastructure can reduce the damage imposed by climate shocks, as well as increase the capacity of private sector to produce and distribute its output (Rozenberg and Fay, 2019). The government can invest in early warning and other information systems and support research and development into new crops and technologies that help households and firms adapt to new climate conditions. Adaptation policies can alleviate residual climate damages by strengthening social safety nets and providing relief to households and communities most affected by climate shocks, particularly the poor who have limited savings and access to finance. It can also support financial inclusion and promote ex-ante disaster risk financing against climate-related losses.

A country's ability to implement climate change adaptation policies depends on financial capacity and accessibility. Adaptation investment can be costly but can limit the need for post-disaster debt financing by improving resilience ex-ante, which can be more cost effective than frequent disaster relief (Hallegatte et al., 2020; OECD, 2018; Marto et al., 2018). Annual adaptation costs vary significantly across countries; they can exceed 1 percent of GDP for some developing countries and be above 10 percent of GDP for some island states (Aligishiev et al., 2022). Aggarwal et al. (2024) estimate that accounting for mitigation and adaptation needs of the SDG sectors related to human and physical capital development will require an additional 0.4 percent of global GDP to achieve strong performance in these SDGs by 2030. The financial sector can help support investment, provide post-disaster liquidity, and manage other physical, transition, and liability risks of climate change (Carney, 2015). However, to date, the private sector has mobilized considerably less resources for adaptation compared with mitigation (OECD, 2015, Deepali et al., 2024). Domestic resource mobilization and international support through grants and loans will be critical to finance the costs of adaptation, particularly given the increase in debt and debt distress that many countries experienced following the global COVID-19 pandemic.

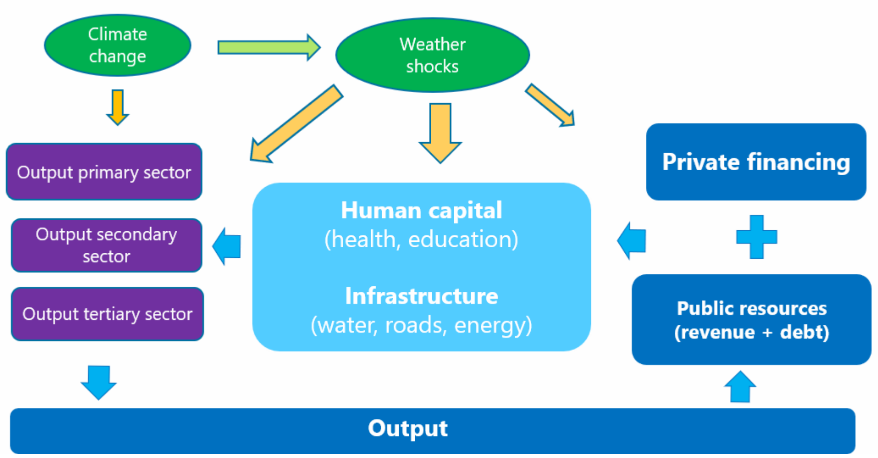
III. Model Description

A. Model Overview

This section describes the key features of C-SDG model developed to study the impacts of climate change on economic growth, public finances, financing needs, as well as public policy options and their links to sustainable development.

The model analyzes long-term macroeconomic consequences of climate change impact in the context of endogenous growth. It is built on the dynamic macroeconomic model initially developed for the analysis of SDG financing options – SDG-FiT (Benedek et al., 2021) including full macroeconomic linkages and consistency in the real, fiscal, and external sectors. The SDG-FiT model is extended to include channels of climate change impacts – namely fast and slow-onset impacts – and the government's adaptation policies, which impact the production function and main fiscal indicators (Figure 1).

Figure 1. C-SDG Model Structure



Source: The Authors

Investment in human and physical capital is the core component of the model. Growth depends on private and public investment decisions and demographic trends. Investment in human capital, public infrastructure, and private capital follows the Debt and Investment Growth (DIG) model and related extensions (Atolia et al., 2017). Spending in these areas builds up human capital, private capital, and two types of public capital: namely standard and resilient capital, which have different susceptibility to the impact of climate change, as in the DIGNAD model from Marto, Papageorgiou, and Klyuev (2018).[16] Human, public, and private physical capital are considered complementary. Hence, investment in one type of capital raises the returns to investment in the remainder of capital. The stock of public and private capital increases with investment and

[16] While the C-SDG framework, with its production function approach, offers greater flexibility in terms of sectoral damages, inclusion of SDG financing needs, fiscal decomposition, and steady-state convergence, the DIGNAD model captures general equilibrium effects with a unique steady state in which agents optimize, and both prices and quantities adjust to natural disaster shocks. In principle, the C-SDG framework requires more intensive data calibration than DIGNAD, where macro-fiscal variables can be obtained from countries' WEO and DSA projections, and the relative price of resilient public infrastructure and damage reduction is modeled similarly. However, the calibration of the disaster shock is crucial for the C-SDG framework. A full review of the C-SDG framework vis-à-vis other macroeconomic models are beyond the scope of this WP, but an interested reader may refer to available reviews such as: NGFS (2024) Climate macroeconomic modelling handbook, Fernández-Villaverde et al (2014)..

declines with depreciation. The accumulation of human capital is financed from current spending on health and education, and it diffuses into the economy as new cohorts enter the labor force.

Climate change reduces output growth through lower physical and human capital and lower productivity. Climate change impacts refer to (a) climate-related events, like hurricanes, flooding, etc., which can disrupt economic activity and destroy physical infrastructure and capital, as well as (b) slow-onset impact of climate change (i.e., increasing average temperatures, increasing sea level, etc.) through a reduction of TFP growth. The model allows for various intensities and frequency of these shocks and trends.[17] The climate shock deteriorates the stock of physical capital, potentially private and public, thus resulting in a reduction in real GDP, which will also result in lower tax revenue. Output is also affected by a reduction in the accumulation of human capital as the shock hinders education spending efficiency – for instance, a hurricane may destroy roads and school facilities, making it impossible for students to attend in-person classes until the infrastructure is reconstructed. Climate shocks may result in a deterioration of the budget balance because tax revenues fall due to lower economic activity and possible tax relief measures implemented to support household and firms, and also because of additional spending in the form of transfers. The slow onset impacts of climate change also led to gradual productive losses, which permeate through an economy.

The impact of fast and slow-onset climate change can be mitigated by (a) increasing the share of (climate) resilient capital and (b) investment in other adaptation options. Climate resilient public infrastructure refers to capital goods or infrastructure systems that are designed, built, and maintained to withstand, adapt to, and recover from climate shocks and the long-term impacts of climate change. These systems are essential for reducing vulnerabilities, protecting communities, and ensuring the continued delivery of essential services in the face of extreme weather events, rising temperatures, sea-level rise, and changing precipitation patterns.[18] One of the main economic trade-offs the government faces is how much to invest among standard versus resilient infrastructure, other adaptation, and productive investment. The two types of capital represented in the C-SDG are substitutes in the production function, but resilient infrastructure is more costly than standard capital. For many developing countries where the know-how and experience of investment in resilient capital is low, effective institutional building – including the strengthening of public investment management, regulatory environments on infrastructure standards and capacity building of relevant sectors – will be crucial. These efforts will generally take years, if not decades, to materialize and proactive and forward-looking macro-fiscal planning will be needed. The model allows for the quantification of the various inter-temporal trade-offs, allowing a decision-maker to simulate alternative policy options to invest in adaptation.

The model includes three economic sectors and three types of SDG-related infrastructure. The economy consists of three sectors namely: primary, secondary, and tertiary. Public physical capital is divided into key SDG-relevant sectors namely power, roads, and water and sanitation infrastructure (Hutton and Varughese, 2016). The production function may be calibrated specifically for each economic sector and type of public capital, along with private physical capital, human capital, and labor. The inclusion of three separate economic sectors allows for tailoring the impact of climate change to the specific economic activity. For instance, a drought mainly hinders agricultural production, while a hurricane that damages the electricity grid

[17] The determination of frequencies and impacts should be country (or region) specific and could draw on historical frequencies and impacts as reported in databases such as EM-DAT, Standardized Precipitation Index (SPI) and assumptions from the literature on the impact of climate change.

[18] For example, with development's partners support Ethiopia has built climate-resilient roads using drainage systems, permeable surfaces, and elevated designs to withstand heavy rainfall and erosion. For more details, see "Resilience of the Ethiopian Roads Network" and "A 360 approach to building climate resilience into the road sector".

would mainly affect the manufacturing sector. The impact of climate change including extreme events may be calibrated using biophysical modeling outputs as will be demonstrated below.

Climate change affects financing needs for SDGs. The model builds on the macroeconomic structure of the SDG-FiT developed to analyze financing needs for reaching the SDG targets (Benedek et al., 2021). The current version can be used to assess the impact of climate change on financing needs, given that climate change reduces output growth and the accumulation of productive capital, thus reducing tax revenue and increasing spending (or crowding-out other SDG spending) and public debt. In the same vein, the model can provide indications of the benefits of adaptation policy in terms of mitigating the negative impact of climate change on financing needs for SDGs.

B. Model Specification

The macroeconomic model incorporates economic interdependencies between the real, fiscal, and external sectors that are critical to determining the longer-term economic outlook, in anticipation of, and following, climate change. In particular, the link between fiscal policy and the real economy is crucial: the government decides the level of alternative investment in SDG infrastructure, adaptation, and human capital, which translates into output growth and level of risk faced under climate change.

Standard and resilient infrastructure. Output is generated by an augmented Cobb-Douglas production function with both public and private physical capital, human capital, and labor. The model includes three sectors namely: primary, secondary, and tertiary.

Public capital comprises several types of infrastructure that are used by all sectors (non-rival). The model distinguishes three infrastructure assets that are crucial to advancing the SDGs namely, water, power, and road infrastructure. The model assumes that the amount of total available physical public capital is the same in all sectors, however their importance for production may differ. Human capital is likewise assumed non-rival, while labor is rival and sector specific. This reflects the idea that SDG investment advances education at the country level and improves labor productivity in all sectors. The model accommodates two types of public physical capital: standard and resilient.[19] The difference between the two types is their "resilience" to climate shocks and their cost. Resilient infrastructure is more expensive to build but is more resistant to climate shocks and may deteriorate at a slower pace.

The output produced in each sector *j* is represented by an augmented Cobb-Douglas production function:

$$Y_{jt} = A(D_{so,i})_{jt}(\theta\mathrm{R} + S)_{\mathrm{t}}^{\beta_j}\mathrm{K}_{\mathrm{jt}}^{\alpha}\left[L_{jt}\left(\frac{H_t}{L_{jt}}\right)^{\sigma}\right]^{(1-\alpha)} \qquad (1)$$

R = $\sum_i R_i$ and *S* = $\sum_i S_i$ are public resilient and standard public capital and *i* = water, roads, and electricity/power generation, respectively for SDG relevant assets. With $\theta > 1$, the productivity of resilient infrastructure is larger than the productivity of standard infrastructure, expressing a case in which there are development co-benefits (see for instance, Hallegatte et al., 2022). With $\theta = 1$

[19] For simplicity and because we focus on government's adaptation policies, private capital is only of one type (standard).

resilient and standard capital are perfect substitutes in the production function.[20] Public capital is non-rival, i.e., it is not sector specific. This reflects the nature of infrastructure such as water, roads, and electricity/power generation, which serve all sectors. The elasticity of output to public capital however is sector specific, i.e., the value of β_j reflects the intensity of use of public infrastructure in each sector. For instance, the elasticity of manufacturing output to electricity might be larger than the elasticity in the agricultural production.[21]

K represents private capital. It is sector specific, and we consider only one type given that the focus of the model is on the government's adaptation policies.

A represents total factor productivity (TFP), which can be affected by slow-onset climate change ($D_{so,i}$).

The level of human capital *H* is common across sectors, while labor (*L*) is sector specific. This reflects the idea that workers' ability is enhanced by education before the worker enters the job market. On-the-job training and working can also create sector specific skills; however the model focuses on the skills generated by general education as this is the main source of public spending.

Aggregate output is given by the sum of output in the three sectors: $Y_t = \sum_j Y_{jt}$

The accumulation of resilient and standard public capital follows the standard formulation with the stock of capital equal to the previous year stock minus depreciation and plus investment,

$$R_t = (1 - \delta_R - \rho D_{it})R_{t-1} + I_{Rt}(\boldsymbol{e}, \boldsymbol{i_R}) \tag{2}$$

$$S_t = (1 - \delta_S - D_{it})S_{t-1} + I_{St}(\boldsymbol{e}, \boldsymbol{i_S}, \boldsymbol{p}) \tag{3}$$

- Resilient infrastructure depreciates by $\delta_R \in (0,1)$ while standard infrastructure by the parameter $\delta_S \in (0,1)$. The two depreciation factors are independent; thus, it is possible to assume that standard infrastructure depreciates faster than resilient one ($\delta_R < \delta_S$), or that there is no difference in depreciation rate $\delta_R = \delta_S$.[22]

- Public investment expenditure, I_s and I_r, may not fully translate into public capital due to efficiency losses and therefore not all capital is assumed to be productive (such as due to low implementation capacity or corruption). The parameter $\boldsymbol{e} \in (0,1]$ reflects the efficiency of public investment spending, with $e = 1$ representing full efficiency. For instance, if $e = 0.5$, for every 1 dollar invested only 50 cents

[20] The model does not consider possible spillovers across different types of public capital. For instance, improving the resilience of roads may also benefit the shielding of infrastructures in water and sanitation, or vice versa. This could be achieved by introducing a multiplicative function of public capital, rather than the current additive form. We leave this for future research.
[21] The output elasticities for public, private, and human capital affect the returns to scale and can drive the dynamics of growth. Default parameters for the labor share is taken from estimates from the International Labor Organization, which are country specific and vary over time. The capital share is set to be 1-labor share.
[22] The World Bank's Lifelines report (Hallegatte, et al., 2019) provides cross-country estimates of the cost increase for building resilient infrastructure in percent of baseline investments. The effectiveness and cost of non-structural adaptation options such as climate smart agriculture may be calibrated using available project experiences. While the framework can accommodate non-structural adaptation policies, they are currently outside the scope of this paper.

contribute to the stock of infrastructure, reflecting the institutional (absorptive) capacity constraints among other factors effecting the efficiency of public investment.

- $D_{it} \in (0, 1 - \delta_S)$ represents infrastructure damage from the climate shock to capital and affects the accumulation of physical public capital in period t across all sectors.[23] Resilient capital, however, is less affected than standard capital by the shock. The difference can be referred to as the "damage reduction" effect of adaptation policy and is measured by the parameter $\boldsymbol{\rho} \in (0,1]$, with 0 being maximum damage reduction (or no residual risk) and 1 no damage reduction. The impact of a climate shock on the infrastructure of a country can be expressed as the sum of the impact on resilient and standard infrastructure:[24]

$$Damages_t = D_t * S_t + \rho \;\; D_t * R_t \qquad (4)$$

And given that the amount of public capital in the economy at any point is equal to the sum of resilient and standard capital, we can rewrite the equation as:

$$Damages_t = D_t * (tot - R_t) + \rho \;\; D_t * R_t \qquad (5)$$

From this, we get the per shock gross benefit of investing in resilient capital:

$$\frac{\partial Damages}{\partial R} = (\rho - 1)D \qquad (6)$$

Given that $\rho < 1$, this equation indicates that the impact of a shock declines with the investment in resilient infrastructure and that the benefit depends on the degree of damage reduction (ρ), and the intensity of the climate shock, D. The shock will affect output via the reduction of the infrastructure stock.

- Investing in resilient infrastructure requires the use of public resources ($\boldsymbol{i}$) that are transformed into capital according to the efficiency parameter $\boldsymbol{e} \in (0,1)$ and the relative cost of standard versus resilient infrastructure capital $\boldsymbol{p} \in (0,1]$. Investing in resilient infrastructure is more expensive than investing in standard capital, with the difference captured by the relative price $\boldsymbol{p}$ (i.e., resilient infrastructure costs \$1 while standard \$$p$).

Available public resources to invest in SDGs and to adapt and respond to climate change include domestic and external sources of financing. The total available public finances is a sum of tax and non-tax

[23] In the current implementation of the framework, damage parameters are generally calibrated (assumed exogenous) drawing from literature/empirical estimates from catastrophe risk assessments including the impact of climate change. Non-linearities and thresholds are considered to the extend these are incorporated in the biophysical models that underly damage rate assumptions (e.g. global hydrological models).

[24] Damage to capital stocks may be calibrated using a variety of sources including, but not limited to, total estimated damage as reported in EM-DAT and catastrophe modeling outputs as per databases such as WRI's Aqueduct Floods and Global Infrastructure Risk Model and Resilience Index (GIRI). Slow onset decline of productivity may be estimated either top down or bottom up, with the latter taking into account transmission channels such as land and labor productivity declines across primary, secondary and tertiary sectors. Slow onset impact of climate change on primary sectors (e.g., Climate Adaptation in Rural Development (CARD) Assessment Tool (ifad.org)), those on labor impact may refer to existing econometric studies (e.g., Dasgupta et al. 2021 Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet Planet Health 2021 5(7) e455-465).

revenues, grants, and net-borrowing. The total tax revenue is determined as a function of the real per capita growth rate and exogenous elasticity, while non-tax revenue follows an observed trend. The model allows for an evaluation of a medium-term revenue strategy aimed at increased domestic resource mobilization. Grants include identified grants, set based on an observed trend, together with the needs of unidentified grants to meet the SDG objectives (with and without climate change). Borrowing options consist of domestic and external borrowing.

Available public resources are allocated as capital and current expenditures. Capital expenditure consists of SDG-related infrastructure including an additional cost of resilient capital and reconstruction expenditure following a shock, where applicable. Current expenditure consists of SDG subsidies to public-private partnerships (PPPs), interest expense, other current expenditure, and additional cost of fiscal transfer as applicable in case of climate shocks.

Private capital accumulation follows a classical Solow growth model, in which the stock of capital accumulates based on private investment decisions, which in turn depend on the saving rate in the economy, disposable income endogenously generated from production, and external private financing. As with public capital, private capital also depreciates and can further be reduced (destroyed) by climate shocks. However, the impact of the shock can be sector specific in the case of private capital. This reflects the differences in the capital in the different economic sectors,

$$K_{jt} = \left(1 - \delta_k - D_{jt}\right)K^R{}_{j(t-1)} + I^R{}_{jP} \tag{7}$$

Human capital accumulation and scarring. Human capital accumulates according to the share ω of new human capital generated by the education system ξ_{t-1} in the previous year, net of depreciation of the existing stock H_{t-1}. The latter reflects the idea that competences and skills of the labor force tend to deteriorate with technological progress,

$$H_t = (1 - \delta_h)H_{t-1} + \omega * \xi_{t-1} \tag{8}$$

The second term in the equation is a function of public and private resources invested in education ($\boldsymbol{h}$, which represents both education and health spending in our framework), spending efficiency (ϵ), the share of school age population n, and the human capital generated in the previous year by those who have not entered in the labor market $(1 - \omega)\xi_{t-2}$.

$$\xi_{t-1} = (1 - \omega)\xi_{t-2} + \left\{\left[\epsilon * \left(1 - D_h * \frac{S}{S + R}\right) * \boldsymbol{h}\right]^{\phi} * n^{\gamma}\right\}_{t-1} \tag{9}$$

Climate shock D_h does not directly affect the stock of human capital but reduces the additional human capital generated through schooling ξ_{t-1}.[25] In practice, a shock reduces the transformation of spending into new human capital in a manner similar to that of a low efficiency factor ϵ. The formula also captures the idea that the impact of a climate shock on educational attainment depends on the proportion of standard versus resilient

[25] While the framework explicitly incorporates some impacts of climate shocks and climate change on human capital accumulation via education spending, we acknowledge the potential impact through health-related factors. Given data limitations, their long-term effects, and complexity of integrating health effects of climate change, these are excluded in the current version of the framework.

infrastructure ($\frac{S}{S+R}$). In this setting, the private sector can contribute to financing education. The spending parameter *h* is the sum of government and private financing of health and education programs.[26]

Household behavior is modeled through reduced form relationships. Household savings rates are exogenous, reflecting the low degree of financial inclusion and large share of hand to mouth consumers, especially for developing countries. This assumption also reflects the reality that, particularly for developing countries, the domestic interest rate reflects factors external to the model such as political risk, rather than the result of endogenous intertemporal utility maximization of agents with unconstrained ability to borrow and lend.

Lastly, it is worth noting that while the production function approach embedded in the C-SDG framework provides a structured framework for analysis while maintaining tractability, it abstracts from certain general equilibrium effects, such as price dynamics, labor market adjustments, and their spillover effects on the government's budget constraint. Recognizing these factors may help refine assessments of the fiscal space available to finance SDGs under climate shocks and macroeconomic dynamics in future enhancements.

[26] A climate shock can reduce education spending efficiency due to the absence of affected students in school. A user may calibrate this impact using data such as the total number of affected populations reported in the EM-DAT. This indicator can be used as a proxy to the number of students missing schools, assuming that the proportion of affected populations to the total population in a country is identical to that of affected students to all students in a country.

IV. Calibration

It is recommended that climate change impact parameters are calibrated using country specific information on fast and slow-onset climate change, where such data is available. The default parameterization of the model draws on comparable cross-country databases and academic literature, with country-specific estimates to the extent available. But the default parameterization can be adjusted according to future research and country-specific knowledge. A user may collect locally relevant climate impact information through appropriate government agencies such as the meteorological agency and sectoral ministries including environment, infrastructure, and agriculture. Technical studies by development partners including the World Bank's Country Climate Development Report (CCDR) may also serve as sources of information. In the case of data limitations, a user may refer to global and regional proxy information as surveyed in Annex II. The IMF also compiles relevant climate impact studies including FADCP Climate Dataset (Massetti and Tagklis, 2024), which includes temperature, precipitation, extreme event risks and sea level rise under alternative climate scenarios for all IMF member countries. The model is flexible and can accommodate the information availability for each country. Parameters of the framework can be adjusted for production technology, capital accumulation, climate impacts, and adaptation policy at sectoral levels.

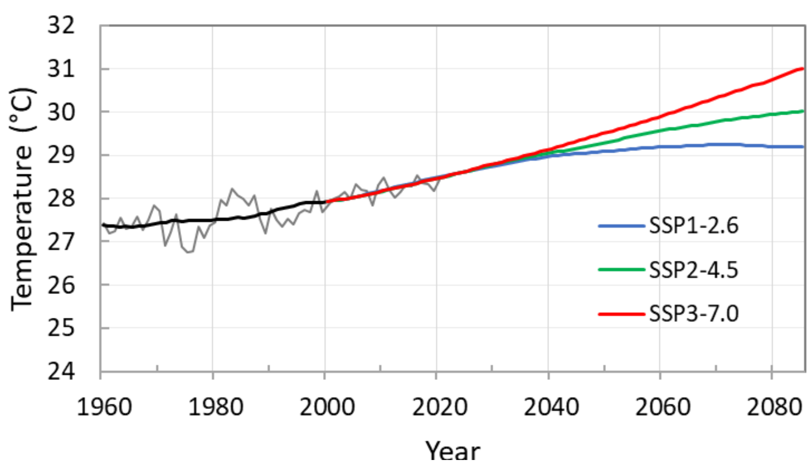
V. Country Applications

We illustrate the impact of climate shocks on different infrastructure through two country applications that face climate shock challenges: Benin and Jamaica. Although the framework is designed to incorporate the effects of slow-onset climate events, our current analysis focuses on the macroeconomic impact of specific climate disaster events, leaving the detailed analysis of macro-fiscal impacts of slow-onset effects for future study.[27]

A. Benin

Benin is one of the most vulnerable countries to climate change. This is due to its geographical location, economic structure, and limited adaptive capacity (IMF Country Report 24/003, Annex III. Building Resilience to Climate Change). The country faces high vulnerability owing to its coastal regions, which are prone to sea level rise and coastal erosion. Under a 2.7°C global warming scenario, based on current policies, Benin is projected to have one of the highest exposures to extreme temperatures by 2070 (IMF Country Report 24/003, The World Bank's Assessment Letter). It is estimated that 98 percent of Benin's landmass will be impacted by these severe temperature conditions, making it one of the most affected countries globally (IMF Country Report 24/003). According to the INFORM Climate Change Vulnerability Index, Benin ranks 163 out of 185 countries (where 185 is the most vulnerable). This vulnerability is exacerbated by the country's reliance on agriculture, a sector highly sensitive to climate variability and extreme events (Figure 2).

Figure 1. Historical and Simulated Annual Average Temperature (ºC)



Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020), and CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021).

Benin faces significant challenges from climate change impacts, including floods, droughts, and coastal erosion (Table 1). Historical episodes of these events have profoundly impacted the country's economy and infrastructure. Flooding, often resulting from heavy rainfall and inadequate drainage systems, has led to considerable agricultural losses, infrastructure damage, and community displacement. For instance, floods in 2010 affected over 830,000 people, or 9.1 percent of the population (EM-DAT), causing extensive

[27] In the context of fiscal risk, the Fiscal Affairs Department has recently developed the tool Q-CRAFT, an approach to assess and quantify long-term fiscal risks under different climate change scenarios. This tool can be used in the future to calibrate the fiscal impacts of slow-onset climate change, further strengthening the C-SDG model.

damage to homes and public infrastructure and resulting in significant agricultural losses. These floods also displaced thousands of people and caused substantial economic losses, highlighting the country's vulnerability to such events. Conversely, droughts severely impact agricultural output, compromising food security and economic stability. Furthermore, the risks posed by climate change, particularly sea level rise, will render Benin's population the most exposed in Sub-Saharan Africa. Coastal erosion poses a significant threat to coastal settlements and critical infrastructure (IMF Country Report No. 24/003, Annex III). These events collectively strain Benin's economy, particularly affecting the agriculture, fisheries, and infrastructure sectors, due to the country's limited capacity to effectively respond and adapt to such changes.

Table 1. List of Significant Disasters in Benin

Year	Natural disaster	Population affected (%)	Total damage (USD millions)	Damage/ GDP
1980	Drought	56.3	2.3	0.19
1982	Flood	14.7	n/a	n/a
1985	Flood	11.1	13.1	1.24
1995	Flood	2.1	6.0	0.37
1999	Flood	0.9	0.4	0.04
2010	Flood	9.1	n/a	n/a

Source: EM-DAT database and IMF calculations. n/a = not available.

In response to these challenges, Benin has initiated several climate policies and strategies aimed at mitigating the impacts of climate change. The government has developed a National Adaptation Plan (NAP) and integrated climate considerations into its national development plans. Key policies include promoting sustainable agricultural practices, improving water resource management, and enhancing disaster risk reduction measures. Additionally, Benin is focusing on achieving the SDGs by aligning its climate actions with broader development objectives, such as poverty reduction and sustainable economic growth.[28]

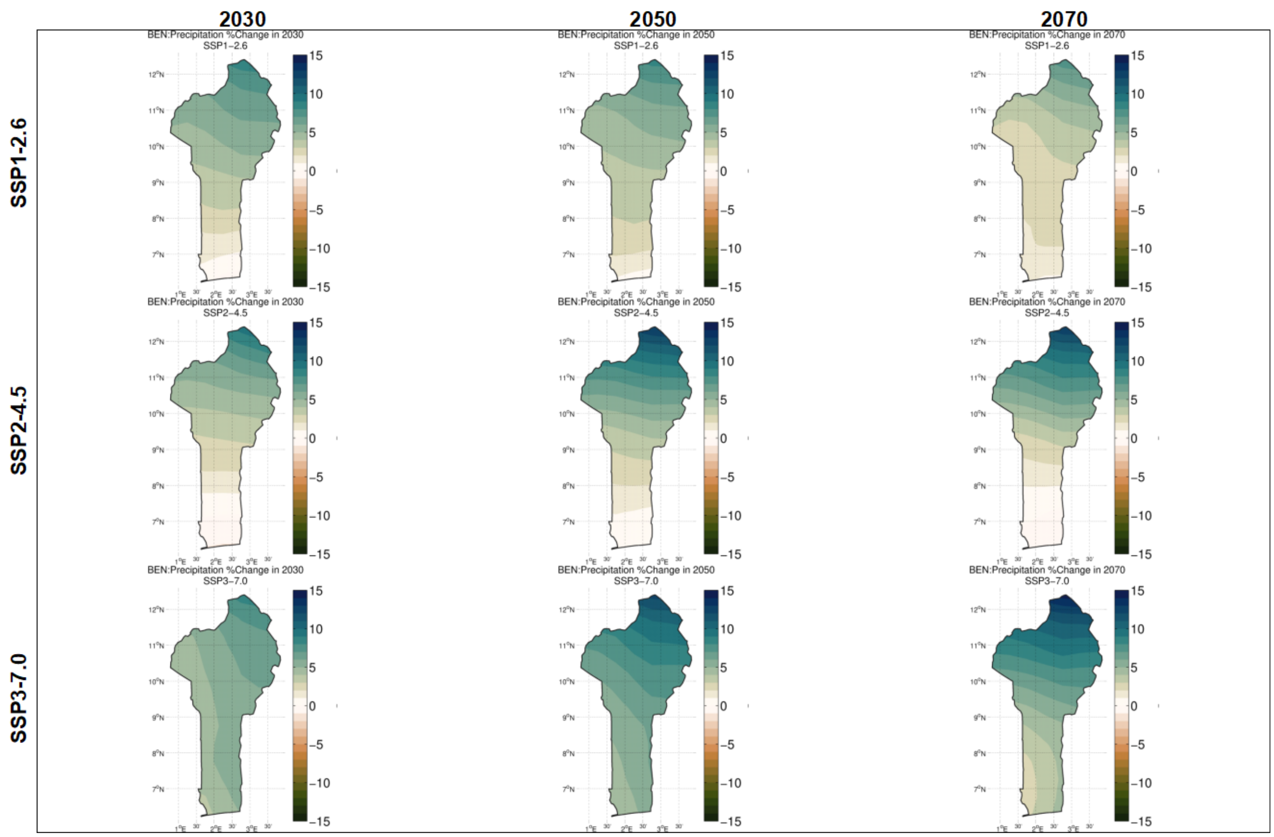
However, Benin faces significant financing needs related to climate change. The 2022 NAP estimates adaptation needs alone at approximately US$4.2 billion by 2032. The World Bank's CCDR estimates that Benin's additional financing needs due to climate change amounts to an annual investment of 0.1 percent of GDP until 2030, increasing to 0.3 percent of GDP by 2040 and 0.8 percent by 2050. This represents an annual average of 0.3 percent of GDP over 2022–2050. The IMF is supporting Benin's climate agenda through its Resilience and Sustainability Facility (RSF), providing US$200 million financing, with a focus on mainstreaming the climate agenda in policymaking and PFM/PIM processes, enhancing adaptation to climate change and strengthening populations' resilience, supporting mitigation efforts, and mobilizing climate finance from the private sector (building on the SDG bond framework and sustainable debt issuance). The RSF complements traditional credit lines under the Extended Fund Facility (EFF) and the Extended Credit Facility (ECF), which is focused on enhancing Benin's socio-economic resilience and achieving the SDGs. While the adaptation investments requirement is substantial given the country's fiscal space, these financing needs are in addition to the substantial investments already included in the baseline macroeconomic framework focusing on achieving the SDGs.[29]

[28] The IMF's EFF/ECF program aims to assist Benin in addressing its urgent financing needs to achieve the SDGs (IMF, 2024). Additionally, the World Bank's recently approved Catastrophe Deferred Drawdown (CAT-DDO) instrument provides contingency financing in the event of a natural disaster, further enhancing the resilience of the economy.

[29] Benin issued €500 million SDG bond in July 2021 after establishing an SDG Bond Framework.

In calibrating the C-SDG framework for Benin, the focus is on floods, the most frequent climate-related disaster facing the country. Since 1980, the country has been exposed to a flood every 2.2 years, affecting as much as 15 percent of the total population. Additionally, precipitation is expected to increase by 5.5 percent by 2070 under the SSP2-4.5 (i.e., current policies) and by 18.1 percent under the pessimistic scenario (SSP3-7.0 90th percentile), which will increase the probability of more frequent and intense floods (Figure 3).[30] The World Bank's CCDR estimates that extreme floods can decrease GDP by more than 2 percent by 2050 for the mean scenario under SSP3-7.0, and as high as 6 percent of GDP in an higher bound scenario under SSP3-7.0, and additional capital losses ranging between 4.9 and 6.5 percent of the capital stock.

Figure 2. Average Annual Precipitation Change Relative to 1985-2014 (percentage)



Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020), and CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021: CMIP6 climate projections).

[30] FADCP Climate Dataset (Massetti and Tagklis, 2024), using CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021). The pessimistic scenario, SSP3-7.0 90th percentile is not shown in Figure 3.

Table 2. Parameters of Production Function (Benin)

Production technology	Parameter
β: output elasticity to public capital	0.15
α: output elasticity to private capital	0.55
θ: efficiency gains from investing in resilient infrastructure	1
σ: elasticity of labor productivity to human capital	0.7
δ_R: resilient public capital depreciation	0.04
δ_S: standard public capital depreciation	0.04
δ_P: Private capital depreciation	0.06
ω: human capital diffusion parameter	0.09
δh: human capital depreciation	0.05
ϕ: elasticity of human capital w.r.t. edu/health spending	0.54
γ: elasticity of new human capital w.r.t. students	0.51

Source: Atolia et al. (2017).
Note: The framework makes it possible to differentiate the parameters by sector when applicable.

Public infrastructure damage is calibrated based on available catastrophe risk modeling outputs. Public infrastructure damage has considerable multiplier effects as it ensures network access to national electricity grid, water and sanitation system and road network. For Benin, we calibrated the capital stock damage due to riverine floods under climate change using data from the World Resources Institute's Aqueduct Floods database. To simulate the economic impact of large-scale floods in Benin, we estimated an urban capital stock damage rate of approximately 26 percent for a 25-year return period flood by 2030 under a high emissions scenario. [31] This figure is then translated into a national capital stock damage rate of 13 percent, based on the assumption that an urban flood would affect infrastructure critical to the secondary and tertiary sectors (comprising about 50 percent of the total capital stock) given these sectors are generally located in the urban areas. The simulation also indicates that the flood impacts 5.6 percent of the population, thereby hindering human capital accumulation. Additionally, to calibrate the share of public resilient infrastructure that the government should target, we consider the most severe scenario: a riverine flood with a 1,000-year return period under the high emission scenario, which estimates an urban capital stock damage rate of approximately 37 percent. Therefore, this estimated extreme damage level guide the upper limit of adaptation investment.

The framework can shed light on the trade-off between higher damage reduction from climate shocks of public resilient infrastructure and their higher cost of production with respect to standard infrastructure. Hallegatte et al. (2019) highlight that for low- and middle-income countries, if only exposed assets are made more resilient to hazards, the incremental construction cost in power, transport, and water and sanitation investment needs would increase from US$11 billion to US$65 billion a year. This represents 3 percent of baseline infrastructure investment needs and less than 0.1 percent of GDP of these countries. However, these investments would reduce the damage by a factor of two to three for new infrastructure assets. In the case of Benin, we follow Hallegatte et al. (2019) who based on an survey of engineering studies related to resilience infrastructure options estimates that, on average, the incremental cost of resilient infrastructure is 3 percent relative to standard infrastructure (i.e., $p = 0.97$), and this reduces the damage by about a factor of 2 (implying $\rho = 0.40$, i.e., reducing capital damages by more than half). Given these assumptions on the relative cost and damage reduction of resilient infrastructure, we can conduct a simulation

[31] Under the RCP 8.5 SSP2 scenario.

exercise to assess the impact of climate shocks under different adaptation policies. The adaptation policy involves altering the composition of the public capital stock by allocating a specified (exogeneous) percentage of the new public investment towards resilient infrastructure. In other words, the adaptation policy involves changing only the composition of the public capital stock by allocating a specified percentage of the new public investment towards resilient infrastructure (overall infrastructure spending is determined by total spending, conditional on matching the targeted deficit). As resilient capital is more expensive, this exogeneous share (and constant over time) "buys" less units of capital every period (including in the long run) relative to the baseline and no adaptation policies.

The framework is calibrated based on 5 different scenarios in addition to the baseline. The model parameters for Benin are based on a combination of available information in the literature and IMF projections. The baseline reflects current policies and growth projections from historical data, which implicitly incorporates the average weather-related shocks in the IMF's WEO and DSA projections (see Table 3). The first counterfactual scenario provides projections incorporating extreme flood shocks, which are larger than the historical average flood and are interpreted as deviations from the baseline. The counterfactual models two extreme floods, in 2027 and 2035, each affecting 13 percent of the public capital stock and 5.6 percent of the population. The choice of these two extreme shocks in such a reduced period of time is to (i) see the impacts on the SDGs financing needs, assumed to be achieved by 2040 (Aggarwal et al., 2024), and (ii) to show the increasing effects of investing in resilient infrastructure, and progressively changing the composition of the public capital stock.[32] In this scenario, we assume that the government's reconstruction costs are deficit financed, where the reconstruction cost is such that the government replaces the damaged public infrastructure within a three-year period. This implies that greater damages will result in higher reconstruction costs, which will subsequently increase the fiscal deficit and impact public debt dynamics. The second, adaptation policy, scenario consists of replacing standard infrastructure with climate resilient infrastructure (i.e., lower damages). We assume that 50 percent of new public investment (flow) is directed toward increasing the stock of resilient capital until it reaches the targeted share of resilient infrastructure (19 percent). We include two additional scenarios as robustness exercises with (i) a larger relative price of resilient infrastructure (called "Higher p") and (ii) higher share of resilient infrastructure targeted by the government (called "Higher R"), to account for climate uncertainty. Finally, fiscal policy is impacted by the floods: fiscal revenues decrease by 0.2 p.p. due to the lower GDP and potential tax relief measures, and the government responds by increasing transfers to the affected population by 0.1 p.p. This response is based upon Akyapi et al. (2022)'s estimates, which finds that fiscal policy helps to mitigate the impacts of climate shocks. In the fifth scenario, we assume that the government is unable to rebuild damaged public capital due to binding limited fiscal space and the inability to finance the reconstruction costs. While this is an extreme scenario, it serves as a useful benchmark for comparing different reconstruction and adaptation policies, and their macroeconomic impacts. Table 2 presents the remaining parameters calibration.

Adaptation policy reduces public capital damages caused by weather shocks by 13 percent in the short-run (2027) and by 19 percent in the medium-run (2035), reducing the GDP impacts of climate shocks. The difference in the reduction in public capital damages is based to the fact that, by 2027, about 10 percent of the capital stock is resilient to flood shocks, while by 2035 the share of resilient capital reaches the target. This shows that building resilience takes time and delaying its investment has a cost. The extreme flood shocks reduce GDP growth by 2.1 p.p. relative to the baseline in 2027 and 2035 in the scenario without adaptation policy (Figure 4). Whereas in the scenario with investment in resilient infrastructure, the flood

[32] Conducting this exercise under the goal of achieving the SDGs in 2030 would not leave sufficient time for a country to show the impact of beginning to invest in resilient infrastructure and experience two extreme weather shocks.

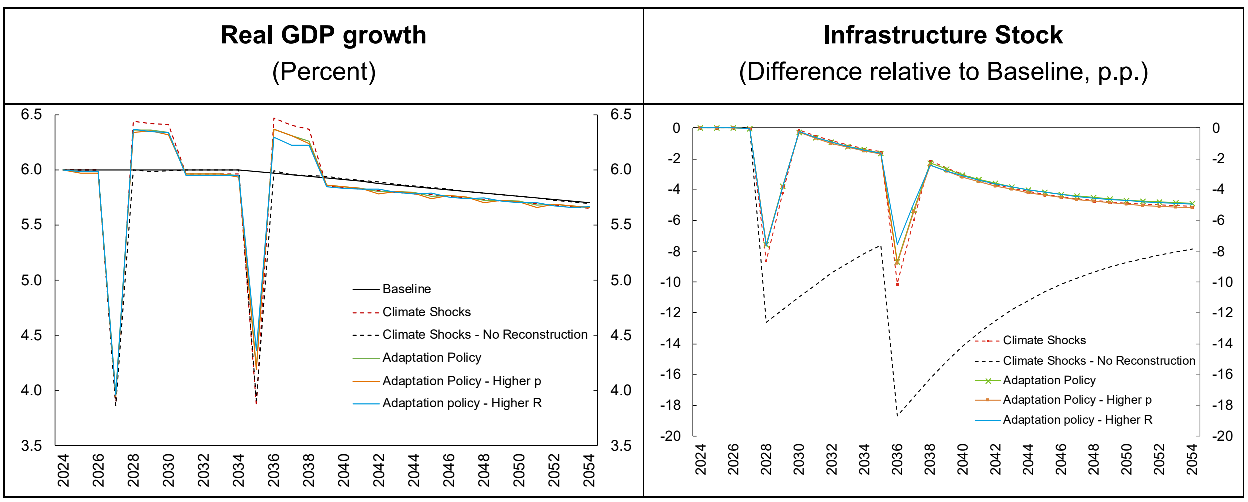
shocks reduce GDP growth by 2.0 p.p. in 2027 and 1.8 p.p. in 2035, when the stock of public resilient infrastructure is larger. In other words, the adaptation policy reduces the GDP growth losses by 0.10 p.p. and 0.34 p.p., respectively in 2027 and 2035, implying a growth yield of about 16 percent relative to the scenario with the extreme flood shocks.[33]

Table 3. Exogenous Macro-Fiscal Data and Sources (Benin)

Category	Actual	Projections			Source
Real	**2023**	**2024**	**2034**	**2054**	
Real GDP growth rates	5.8	6.0	6.0	5.7	WEO (Apr 2024) & SR No. 24/3
CPI inflation (percent)	2.8	3.0	2.0	2.0	WEO (Apr 2024) & SR No. 24/3
Fiscal					
Revenue and Grants (percent of GDP)	15.2	15.2	17.1	18.9	WEO (Apr 2024) & SR No. 23/175 (DSA)
Primary spending (percent of GDP)	17.7	17.4	18.6	20.4	WEO (Apr 2024) & SR No. 23/175 (DSA)
Nominal interest rate on public debt (percent)	2.5	2.3	2.6	3.3	SR No. 23/175 (DSA)
Overall fiscal balance (percent of GDP)	-4.5	-3.7	-2.9	-2.9	WEO (Apr 2024) & SR No. 24/3
Efficiency of government spending (percent)	0.58	0.58	0.58	0.58	PIMA & C-PIMA (2023)

Note: *2034 and 2054 data are the latest available; **The latest available data are for 2019; SR No. 24/3 = IMF Staff Country Reports (IMF, 2024).

Figure 3. Real GDP growth and Infrastructure: Adaptation Policy Scenario (Benin)



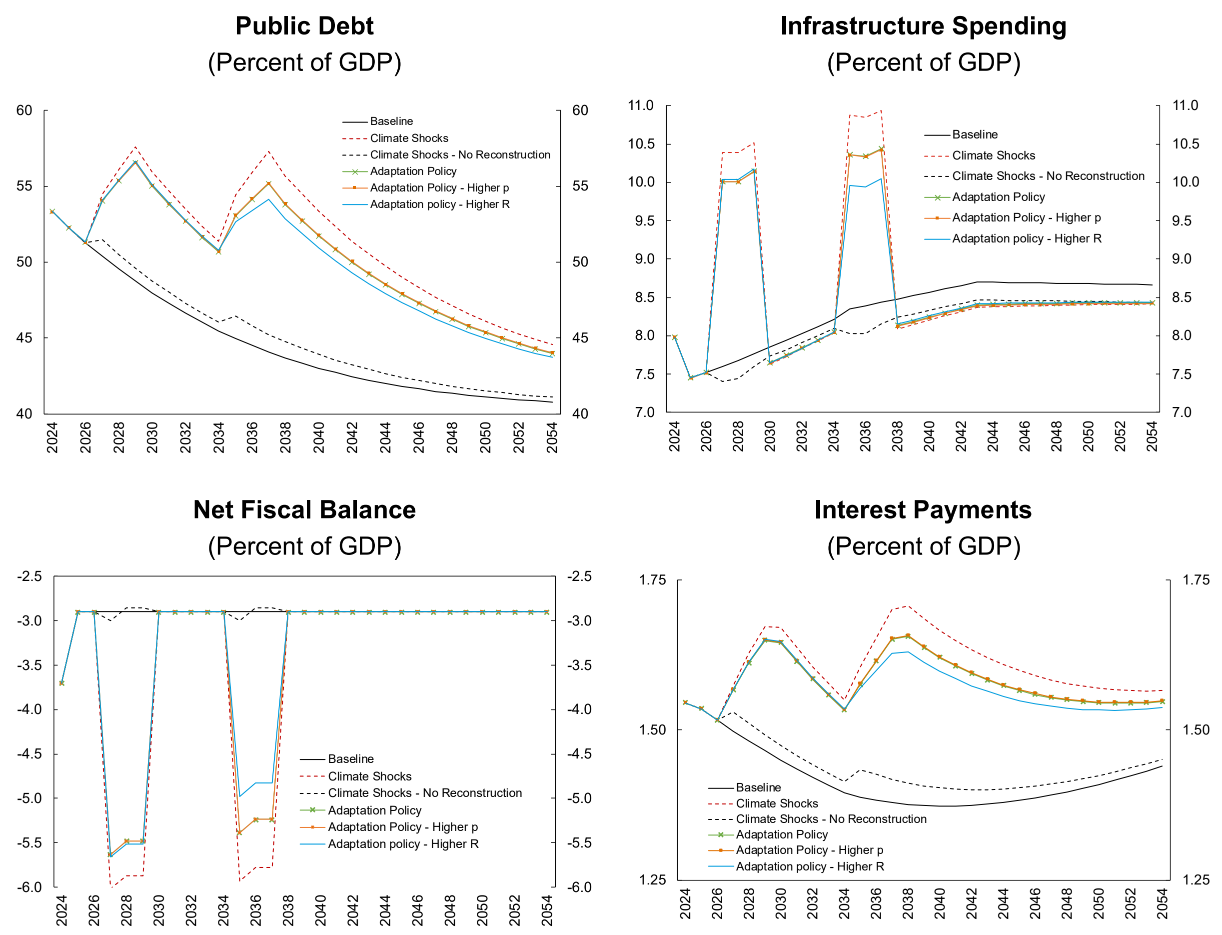
Source: IMF staff estimates.

Adaptation policies decrease the debt stock in the long run (Figure 5). As public capital damages are lower with resilient infrastructure, reconstruction costs are reduced leading to a reduction in public debt levels and interest payments, and an improved fiscal balance. The debt levels under the adaptation policies are 1.6

[33] While our GDP impacts are lower than those shown in the DIGNAD model, our results are consistent (IMF Country Report No. 24/003, page 78). The simulation in the DIGNAD model is different in nature, as it does not calibrate a specific public capital damage per event and parameter calibration differs. It shows that an extreme climate event decreases GDP growth by 4 p.p. relative to the baseline (i.e., almost double as our calibrated exercise), and investing in resilient infrastructure reduces GDP growth losses by 1 p.p., implying a growth yield of about 25 percent. Both model results highlight the potential benefits of investing in resilient public infrastructure for Benin, leading to substantial reductions in climate shock damages (lowering post-disaster reconstruction costs), reducing public debt accumulation in the medium term, and positive impacts on GDP growth. Thus, adaptation policies create a damage reduction effect against climate shocks by maintaining infrastructure for longer periods and reducing GDP less than the scenario with standard infrastructure.

p.p. lower compared to the current climate shock scenario by 2040 and by 0.6 p.p. lower by 2054. Importantly in a country with limited fiscal space, the overall fiscal deficit jumps by about 3.1 p.p. and 3.0 per year over the reconstruction period (i.e., 3 years) without the adaptation policy to rebuild the destroyed public capital after the 2027 and 2035 shocks, and by 2.7 and 2.5 p.p. per year with the adaptation policy (0.4 and 0.5 p.p. lower fiscal deficit), respectively (implying a fiscal deficit yield of about 18 percent). Consequently, interest payments are lower, improving the fiscal space and reducing the crowding-out of public investment and other (SDG) spending over the medium term. This demonstrates that the higher costs associated with building resilient infrastructure is offset through savings in the medium term as resilient infrastructure generates a damage reduction effect against output and revenue losses. It is important to note that the framework assumes the reconstruction of damaged capital can be deficit financed through non-concessional borrowing, thereby avoiding any crowding out of spending on other SDGs during this period. However, a more realistic scenario is likely to involve a combination of partial crowding out and partial borrowing for reconstruction, potentially supported by grants and concessional financing from the Multilateral Development Banks (MDBs). We leave this scenario for future research.

Figure 4. Public Debt, Reconstruction Costs, and Fiscal Balance: Adaptation Policy Scenario (Benin)



Source: IMF staff calculation.

A higher relative price for resilient public infrastructure (10 percent more expensive) reduces the effectiveness of the adaptation policy scenario, as it leads to lower public capital accumulation. Consequently, by 2054, GDP per capita and the public infrastructure stock are 0.04 and 0.1 percent lower, respectively, compared to the scenario without an adaptation policy. However, due to the benefits of having climate-resilient infrastructure that mitigates damage and deficit-financed reconstruction costs, the public debt-to-GDP ratio is 0.5 p.p. lower than in the scenario without an adaptation policy. This result underscores the importance of considering multiple metrics in the welfare function, such as economic stability, fiscal sustainability, and resilience to climate shocks when evaluating alternative adaptation policy intervention options. When evaluating adaptation policies solely based on the long-term level of GDP per capita, while ignoring public debt and growth volatility, the net benefit of investing in resilient infrastructure may appear negative. Yet, if the evaluation criteria were expanded to include the reduction of economic disruptions from climate events and the mitigation of public debt growth due to repeated reconstruction costs, the benefits of resilient infrastructure become more evident. By weighing these factors, governments can better assess the trade-offs and justify investments in resilient infrastructure that support sustainable growth, even if the immediate impact on GDP per capita alone seems limited.

A higher targeted share of public resilient infrastructure would increase the net benefits of the adaptation policy scenario. With the larger share of resilient infrastructure, the debt-to-GDP is 2.4 p.p. and 0.8 p.p. lower and the growth yield increases to 23 percent by 2040 and 2054, respectively. However, as resilient infrastructure is more expensive than standard infrastructure, GDP per capita will be 0.2 percent lower by 2054 compared to the scenario without adaptation policy. Consequently, in designing optimal adaptation policies, governments must accurately identify exposed public capital and define the target share of resilient infrastructure to balance the trade-offs associated with the marginal return on public funds.

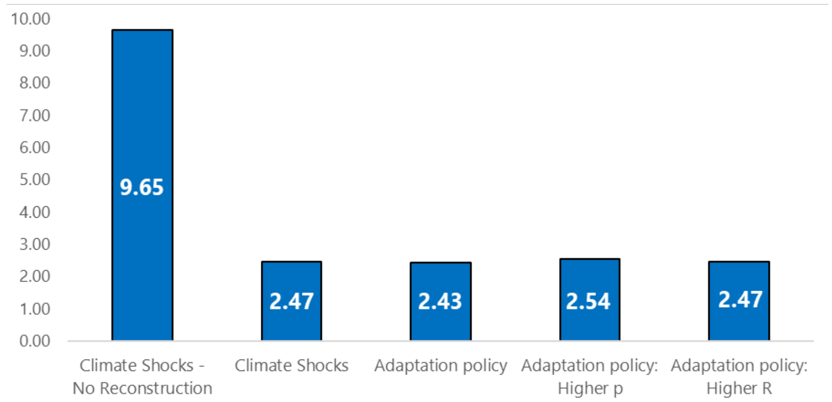
While the reconstruction of the damaged public capital deteriorates the fiscal balance and debt levels, the no rebuilding of infrastructure and human capital losses increases the already large SDG spending gaps. Therefore, the no reconstruction scenario leads to a GDP per capita 2.2 percent lower by 2040 relative to the scenario with reconstruction (and no adaptation policies).

Without external grants, Benin is unable to achieve the SDGs under the baseline scenario, with extreme climate shocks delaying progress and increasing SDG financing needs by 9.65 percent of baseline GDP by 2040 if the economy does not invest in reconstruction (Figure 6). Reconstruction efforts reduce additional SDGs financing needs to 2.47 percent of GDP by 2040, driven by higher endogenous accumulation in public infrastructure and human capital. Adaptation policies, particularly investing in climate-resilient public infrastructure, further narrow the financing gap by approximately US$120 million in 2027 (0.8 percent of GDP) and US$320 million in 2035 (1 percent of GDP) relative to the climate shock scenario with reconstruction (but no resilient public infrastructure). By 2040, the financing gap with adaptation policies decreases by 0.04 percent of baseline GDP. This reduction is attributed to lower damages to the capital stock, a reduced fiscal deficit, and decreased debt accumulation, which in turn lower interest payments and mitigate the crowding out of SDG-related spending. Cumulative discounted gains from adaptation policies by 2040 are estimated at approximately US$ 400 million, equivalent to nearly 3 percent of 2024 GDP or 24 percent of 2024 tax revenues – comparable to two RSF programs (120 percent of quota, equivalent to about US$200 million).[34] Given Benin's substantial development needs and limited fiscal space, adaptation policies can play a critical role in closing the SDG financing gap and accelerating progress toward achieving sustainable development goals.

[34] Aggarwal et al. (2024) estimated that climate-oriented adaptation and mitigation spending for selected SDGs in Sub-Saharan Africa will require an additional 0.6 percent of GDP annually by 2030. Although Aggarwal et al. (2024) do not distinguish between adaptation and mitigation costs, it is noted that mitigation investments in the electricity sector likely constitute a significant portion of the total. Similarly, Aligishiev et al. (2022) estimate average annual adaptation needs at 0.3 percent of GDP per year for Benin through 2030, factoring in the upgrading and retrofitting of infrastructure exposed to flood and storms.

Figure 5. Additional SDG Spending Needs from Adaptation Policies (Benin)

(Percent of 2040 Baseline GDP)



Source: IMF staff estimates.

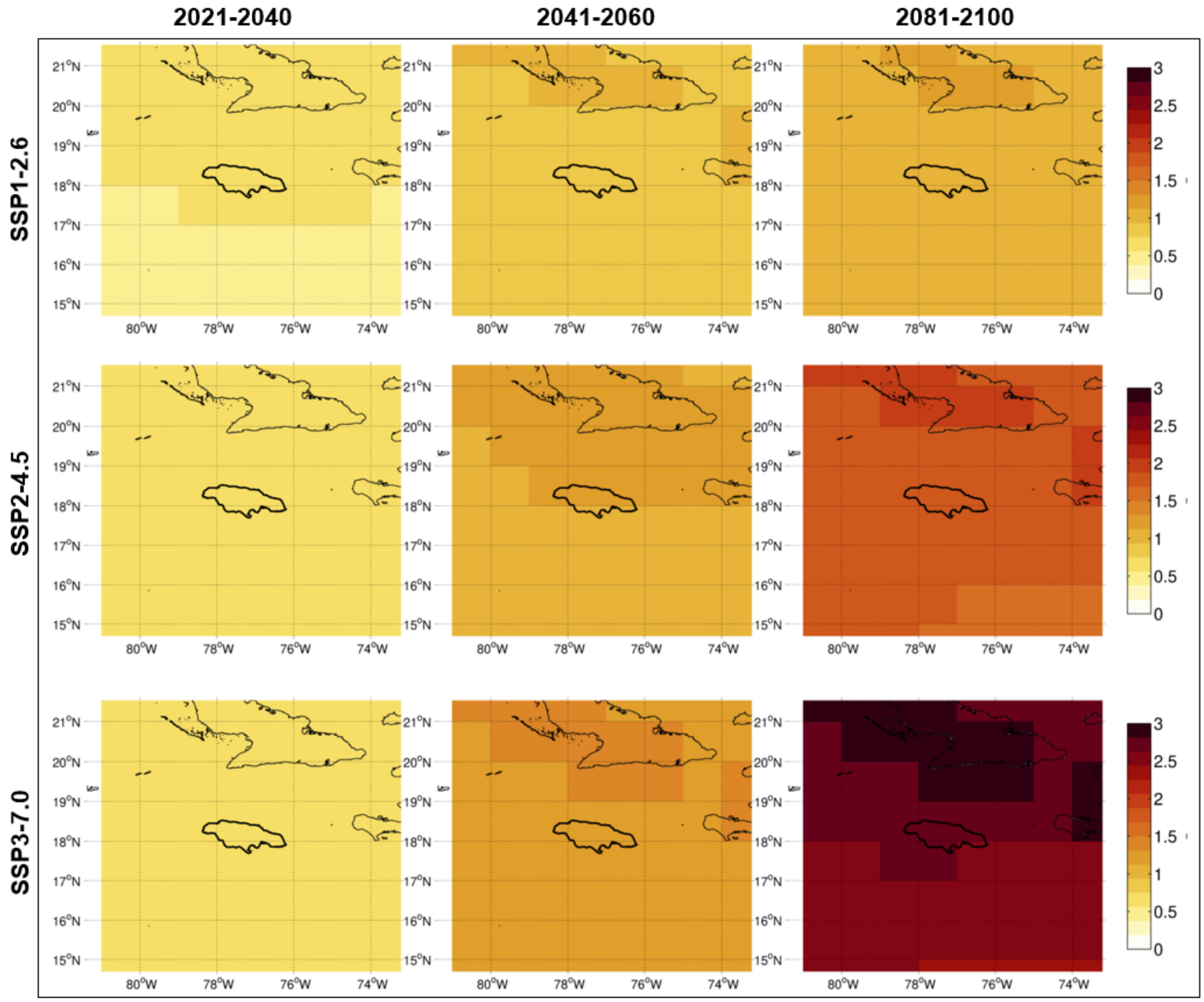
Note: This chart illustrates the change in SDG financing needs required to achieve targets by 2040 across five different scenarios relative to the baseline scenario. The 'Climate Shocks – No Reconstruction' scenario assumes two extreme flood shocks occur, and the government is unable to undertake reconstruction. In the 'Climate Shocks' scenario, the same shocks hit, but the government is able to reconstruct. The 'Adaptation Policy' scenario includes government investments in resilient public capital, allowing for reconstruction of the reduced-damage public capital. The next scenario, 'Higher p,' considers a higher relative price of resilient infrastructure, while the final scenario, 'Higher R,' reflects a targeted increase in the share of resilient public infrastructure investments.

Investing in public resilient infrastructure reduces damages, GDP growth volatility, and debt accumulation, therefore yielding positive returns for Benin. However, the frequency of climate disasters, intensity, efficiency assumptions of resilient infrastructure, damage reduction factors, and relative prices of resilient infrastructure are critical factors that can influence the outcomes. Policymakers should consider these factors carefully to maximize the economic benefits of resilient infrastructure investments.

B. Jamaica

Jamaica is highly exposed to multiple natural hazards, including tropical cyclones, floods, and droughts. Jamaica ranks 47th out of 191 countries in the 2023 Inform Risk index. Average temperature levels in the country have risen steadily over the last several decades and are projected to increase further in the future. In a business-as-usual (BAU) global emission scenario (RCP 4.5), Jamaica is projected to face a 1.8°C increase of mean temperature by 2100 relative to the 1984–2014 baseline (Figure 7). This would likely result in increased frequency of prolonged high heat and drought. The frequency of tropical storms or hurricanes is expected to remain steady while their intensity will increase with extreme rainfalls, high wind speed, flooding, and increased damages. Additionally, sea level is rising and threatening Jamaica’s infrastructure and population that are concentrated in the coastal areas. According to the 2020 ND-GAIN Vulnerability Index, climate change and natural disasters in Jamaica affect the costal, energy and transport infrastructure, as well as urban areas (buildings, water supply and sanitation, etc.).

Figure 7. Average Annual Temperature Change Relative to 1985-2014 (ºC)



Source: FADCP Climate Dataset (Massetti and Tagklis, 2024), using CRU data (Harris et al., 2020), and CMIP6 data (Copernicus Climate Change Service, Climate Data Store, 2021: CMIP6 climate projections).

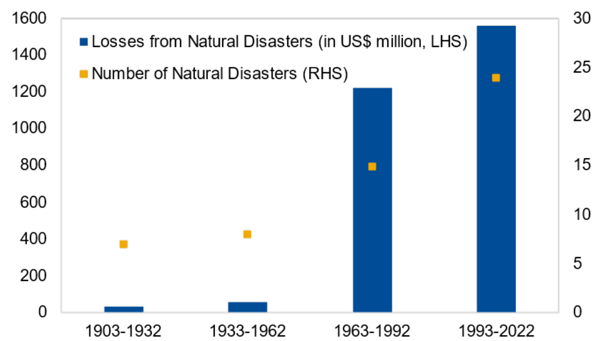
The country has suffered significant economic losses caused by repeat disasters over the past decades, and plausible future climate events will likely lower potential growth in critical economic sectors. Hydrometeorological events (floods, tropical storms, hurricanes etc.) have been the most prominent hazards in Jamaica. The number of storms passing by or directly affecting Jamaica in the 2000s has been at its highest since 1940-1996. Hurricanes Ivan (2004) and Dean (2007) caused damages of US$ 580 million and US$ 329 million each (8 and 3 percent of GDP, respectively). In 2010, tropical storm Nicole was an important reminder of a persisting vulnerability to natural disasters, causing damages of US$ 239 million (2 percent of GDP), while most recently in July 2024 Hurricane Beryl caused damages of about US$ 200 million (1.1 percent of GDP).[35] Looking ahead, the expected damages from the hydrometeorological events would also be significant. For a one in 100 years type of event, the fiscal losses are expected to exceed US$ 1,729 million (roughly about 10 percent of GDP[36]); in other words, there is a one percent probability in any given year that

[35] Hurricane Beryl wreaked $32b damage, sent Jamaican economy into decline | Business | Jamaica Gleaner.
[36] 2019 World Bank Jamaica probabilistic risk modelling.

losses will exceed US$ 1,729 million from such an event (Figure 8). The tourism sector is highly sensitive to the effects of climate change and equivalent to some 20 percent of GDP. Other sectors of the economy, especially agriculture, which already is coping with higher temperatures, rising sea levels, and volatile precipitation patterns, are highly sensitive to the effects of climate change as well.

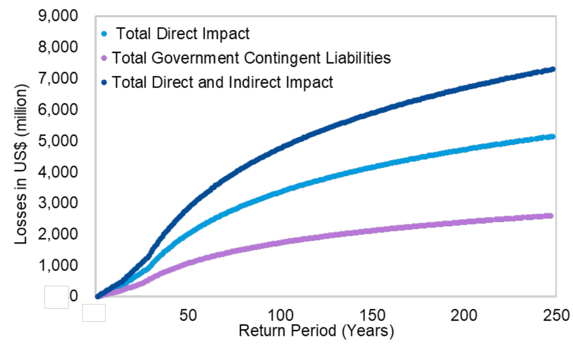
Figure 8. Natural Disaster Impacts in Jamaica

Frequency and Damages from Natural Disasters
(In US$ million)



Sources: Emergency Events Database and IMF Staff Calculations.

Estimated Flood and Hurricane Events Risk Profile
(Indicative probability curve, in US$ million)



Source: 2019 World Bank Jamaica probabilistic risk modelling.

Over the past few decades Jamaica has developed a comprehensive policy framework which sets out a set of measures and targets to mitigate and adapt to climate change. The Vision 2030 Jamaica-National Development Plan defines the country's long-term strategic development goals towards inclusive and sustainable growth. It rests on the foundation of three dimensions of sustainable development—social, economic, and environmental—as well as on equity and inclusiveness considerations. The Climate Change Policy Framework for Jamaica was promulgated in 2015 and recently updated in 2021, with the goal of creating a sustainable mechanism for integrating climate change considerations in governance systems (institution arrangement, polices, plans, etc.).

The IMF has supported Jamaica's climate agenda through its Resilience and Sustainability Facility (RSF), providing around US$700 million in financing. The RSF supported reforms that can reduce long-term vulnerabilities of the external position and build-up policy space and buffers to insure against risks from climate change. Measures undertaken addressed adaptation, mitigation, and transition risks. Reforms specifically focused on the enhancements to the fiscal framework to manage climate events, facilitate investment in climate-related projects, and take better account of climate risks in fiscal decisions. These reforms have been instrumental to foster investments to enhance efforts to adapt to climate change. Reform measures also aim at increasing renewables and curbing energy use to reduce the dependence on energy imports and achieve the NDC's emission reduction targets. They have the potential to increase energy generation through renewable sources, expand the electric vehicle share in both the private fleet and public transportation, and reduce energy consumption in public buildings, contributing to decarbonization of the Jamaican economy. The cost of climate related projects is estimated to be around 2.4 billion USD (14 percent of GDP).[37]

[37] See IMF Country Report No. 23/105.

In calibrating the C-SDG framework for Jamaica, the focus is on extreme hurricane events, one of the most significant risks facing the country. We have assumed that a one in a 100-year cyclone event will lead to national public capital stock damage of 8 percent of GDP.[38] The framework is calibrated based on a baseline, and five additional scenarios. The baseline is calibrated on current policies incorporating the latest projections from the IMF WEO and the recent published DSA[39] (Table 4). The second scenario provides projections incorporating the extreme cyclone event. Similar to the Benin case, two extreme cyclone events are modelled, in 2027 and 2035, each affecting 8 percent of the public capital stock. The choice of these two extreme cyclone events is to show the impact on SDG financing needs, as well as the effect of investing in resilient infrastructure early. It is assumed that the reconstruction cost in the scenario replaces the damaged public infrastructure over a three-year period is financed by a higher government deficit. The higher the reconstruction cost, the higher public debt and interest payments, which impacts availability of resources for SDG investment. The adaptation policy scenario consists of replacing standard infrastructure with climate resilient infrastructure. In the case of Jamaica, Hallegatte et al. (2019) estimates that the additional cost of resilient infrastructure is 4 percent relative to the standard infrastructure (p = 0.96), which reduces the damage by about a factor of 2 for new infrastructure capital (implying ρ = 0.44 reducing capital damages by around half). The more resilient infrastructure, the less damages and reconstruction costs. Consistent with the Benin case, two additional scenarios are modelled with a higher relative price of resilient infrastructure (“Higher p”) and a higher share of resilient infrastructure (“Higher R”) to account for climate uncertainty. In the last scenario, we assume that the government is unable to finance reconstruction costs either by debt or any other means. This scenario is useful to illustrate the trade-offs faced by countries that have limited access to financing due to factors such as debt sustainability issues, limited access to private capital or donor financing.

Table 4. Baseline Macroeconomic and Financing assumptions (Jamaica)

	2024	2030	2054
Real sector (year on year growth)			
Real GDP	1.8	1.6	1.6
CPI	7.0	5.0	5.0
Financing assumptions			
Overall fiscal balance (percent of GDP)	0.3	1.0	0.0
Revenue and grants (percent of GDP)	32.0	32.3	33.4
Non-SDG spending (percent of GDP)	12.8	12.9	15.0
Efficiency of government spending (percent)	0.85	0.85	0.85
Nominal interest rate on debt (percent)	9.0	8.0	7.0

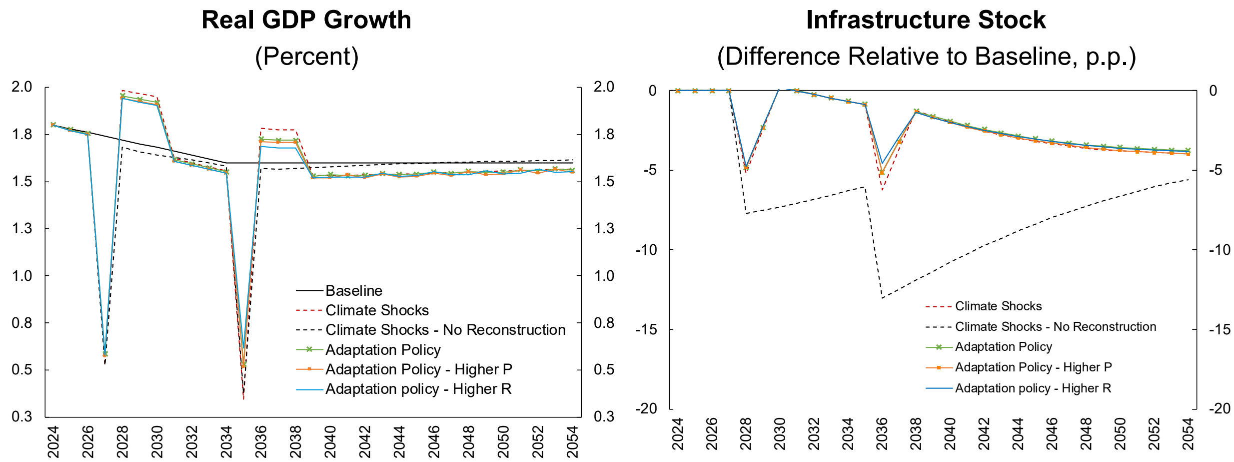
Source: IMF WEO, IMF Country Report 24/69, and staff calculations.

Adaptation policy reduces the shock to GDP growth by 0.2 percentage points of GDP by 2035 and reduces reconstruction costs by around 1.2 percent of GDP (Figure 9). In the short-run, adaptation policy has a limited impact on damages and to growth because the share of resilient capital stock is small. In 2027, the share of resilient capital stock is projected to be 14 percent, while this rises to 28 percent by 2035. Similarly, investment in resilient infrastructure reduces reconstruction costs by around 1.2 percent of GDP.

[38] While 10 percent was mentioned above, not all the cost is expected to be due to lost capital stock. Short-term recurrent expenditure will also be needed for the emergency response to the disaster and loss GDP production will also take place.

[39] See IMF CR No. 24/69.

Figure 9. Real GDP growth and Infrastructure: Adaptation Policy Scenario (Jamaica)

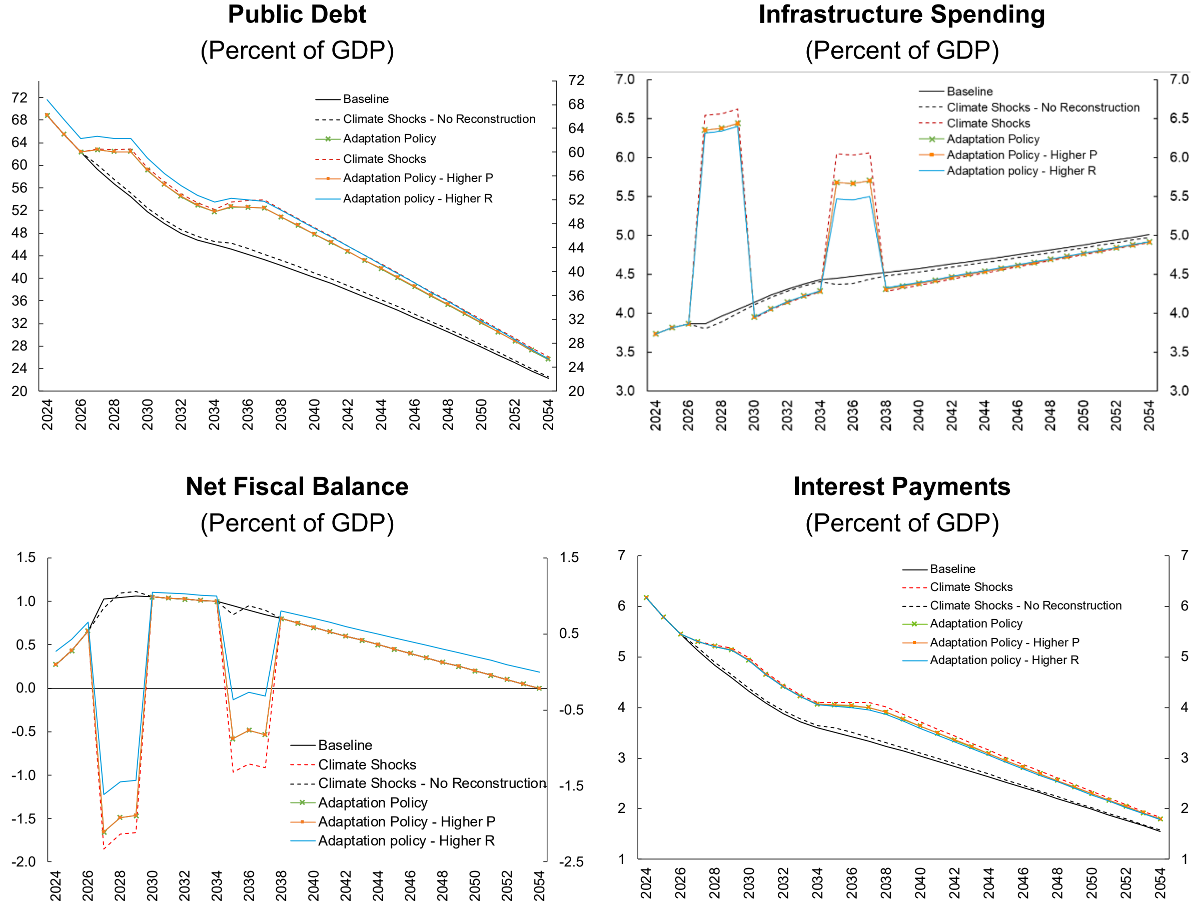


Source: IMF staff estimates.

Adaptation policies lead to lower debt in the long run when the government has access to financing (Figure 10). Given the cost of reconstruction is born by the public sector, and assuming the public sector has access to financing, debt levels increase by around 10 percent of GDP higher than the baseline by 2038 without adaptation policy, while adaptation policy reduces the level of debt by 1.3 p.p. by 2038. Similarly, adaptation policy reduces the need for the government to undertake reconstruction investment. While small, the lower government financing requirement, interest payments, and consequent lower fiscal deficit reduce debt levels over the long-run. Importantly, this creates fiscal space to spend on SDG priorities.

A higher cost of resilient capital slightly reduces the effectiveness of adaptation policy as it leads to less accumulation of resilient capital, while a higher share of targeted in resilient capital slightly increases effectiveness. The scenario with higher relative costs of resilient infrastructure would lead to 0.2 percentage points lower capital stock by 2054 relative to the scenario with standard adaptation costs. To illustrate the impact of a higher share of new investment toward resilient infrastructure, we have assumed that additional investment on SDGs is devoted toward resilient infrastructure while in the adaptation scenario we assumed only half of new investment was in resilient infrastructure. This higher share of resilient infrastructure shows only a marginal impact on GDP. The shock to GDP in 2035 is reduced by only 0.1 pp compared to the adaptation scenario, while in 2038 following reconstruction, the debt/GDP ratio is marginally lower (0.5 pp).

Figure 10. Public Debt, Reconstruction Costs, and Fiscal Balance: Adaptation Policy Scenario (Jamaica)



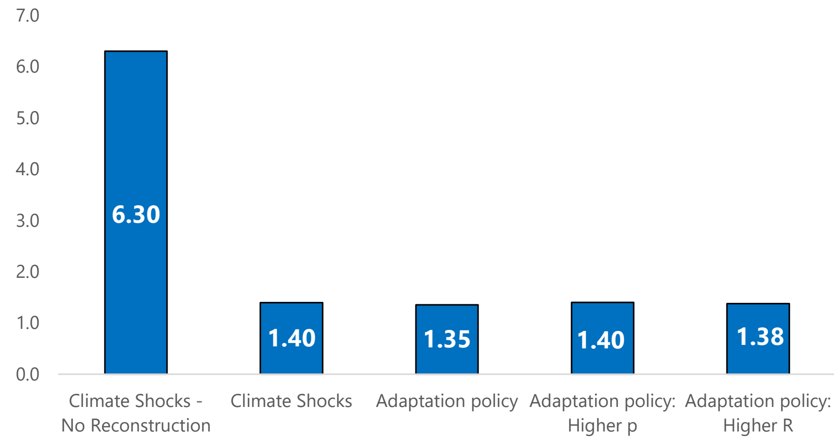
Source: IMF staff estimates.

Jamaica will not reach its SDG goals with extreme climate shocks in the baseline. Climate shocks increase financing needs by 6.3 percent of GDP (Figure 11) if the government does not invest in reconstruction. Reconstruction efforts, financed by a higher fiscal deficit, reduce additional SDG finance needs to 1.4 percent of GDP by 2040 due to a higher accumulation of physical and human capital. Adaptation policies will further narrow the financing gap. Investing in climate resilient infrastructure would narrow the financing gap to 1.35 percent of GDP. Investing in climate-resilient public infrastructure would narrow the financing gap by approximately US$15 million in 2027 (0.4 percent of GDP) and US$50 million in 2035 (0.8 percent of GDP) relative to the climate shock scenario with reconstruction (but no resilient public infrastructure). By 2040, the financing gap with adaptation policies decreases by 0.05 percent of baseline GDP. This reduction is attributed to lower damages to the capital stock, a reduced fiscal deficit, and decreased debt accumulation, which in turn lower interest payments and mitigate the crowding out of SDG-related spending. Cumulative discounted gains from adaptation policies by 2040 are estimated at approximately US$ 64 million, equivalent to nearly 2 percent of 2024 GDP.

While climate shocks delay reaching the SDG goals, reconstruction financed by the government deficit supports reaching SDG goals (Figure 11). Investment in adaptation compared with standard infrastructure will slightly reduce the required financing to reach SDG goals. We find that the two sensitivity scenarios involving higher resilient infrastructure costs and a higher targeted share of resilient infrastructure do not significantly affect the SDG-financing gap.

Figure 11. Additional SDG Spending Needs from Adaptation Policies (Jamaica)

(Percent of GDP at 2040)



Source: IMF staff estimates

VI. Conclusion

This paper describes a macroeconomic model (C-SDG) integrating climate change analysis into macroeconomic projections and policies for sustainable development. The C-SDG model allows for the quantification of climate change impacts on SDG achievement and macro-fiscal costs and benefits of adaptation options. It incorporates endogenous human and physical capital accumulation, fiscal policy interventions, and public debt dynamics embedded in a consistent fully integrated macro framework. The model is calibrated with default parameters from the literature, including country-specific estimates where available. Yet it is flexible enough to adjust to additional country specific information as well as refined estimates from future research. The model can be used for macroeconomic projections and scenario analysis for a range of public policy interventions to address current and future damages in fast and slow-onset climate change. Key channels of damage from climate change include lower productivity due to slow onset climate drivers and a rise in the frequency and/or severity of climate shocks. The model can be used to investigate the implications of these phenomena, including quantification of the impact on growth and debt, as well as the quantification of alternative adaptation strategies alongside other development initiatives.

For countries facing multiple development objectives, climate change adds an additional dimension to the challenge. Often these goals are complicated by constrained fiscal space, high public debt, low domestic revenue, and limited private investment. This calls for integrating climate action into the broader development agenda rather than treating climate as a separate, stand-alone objective. Compared to overall SDG spending needs, climate spending is small, yet in certain years when hit by a shock, spending needs will increase sharply. Countries need to recognize that building resilience takes time, so starting early will be necessary to reap the benefits over the longer-term. At times this could lead to a need for tradeoffs and prioritization given limited resources and highlights the need to find ways to imbed climate considerations into existing projects.

The country applications show that investment in adaptation policies and resilient infrastructure decrease the economic damages of climate shocks. The C-SDG model is especially suited to evaluate the macro-fiscal aspects of SDGs needs and financing among countries facing significant climate change risks (from disasters and slow-onset drivers). For the case studies of Benin and Jamaica, an adaptation policy that builds resilience to climate shocks results in lower damages to GDP compared with the scenario with standard infrastructure. Net benefits of adaptation strategies depend on many factors including a country's climate risk profile (i.e., types, frequency and intensity of disasters) and available adaptation options (i.e., relative prices and damage reduction potential). A macro-fiscal framework provides an important tool to assess all these aspects in a consistent way. The benefits of the adaptation policy rise with the frequency and magnitude of damage typically occurring due to extreme events. Whereas the case studies focused on the inclusion of a single hazard per country to illustrate the model dynamics clearly (hence the result represents the lower bound of climate change and adaptation investment impact), further inclusion of multiple climate shocks (e.g., floods, storms, droughts) plus slow-onset impacts in a form of fully stochastic simulation will give an improved sense of the macro-fiscal tail risk faced from climate change and effectiveness of adaptation in these countries. The case studies demonstrate the importance of embedding climate macro-fiscal analysis into an overall development framework. Doing so facilitates the examination of tradeoffs not only among adaptation policies but also among other development policies that affect growth and debt, and which may also interact with climate resilience.

The choice of adaptation policy should consider not only the direct economic impacts but also the frequency of climate shocks and the wider fiscal and welfare implications to accurately capture the value of resilience investments. The government's objectives in selecting these policies are often shaped by a welfare function that balances various priorities, including long-term economic stability and growth, reduced costs from frequent repairs, financing constraints, and the volatility of debt levels and GDP per capita. These factors, together determine the net benefits and trade-offs of investing in resilient infrastructure. Thus, an effective adaptation policy framework should integrate these broader considerations to maximize the long-term value of resilience investments.

In the future, the C-SDG framework could be strengthened to include additional important dimensions such as: improved representation of private sector risk reduction and recovery behaviors (including the role of fiscal policy to motivate private sector climate investment), elaboration of alternative ex-ante risk financing options to respond and recovery from shocks, persistence of damages and longer recovery, flexibility on the design of the (optimal) adaptation policy, a partially financing of reconstruction costs via donor-finance, and endogenous reaction of the interest rates to climate shocks. Effectiveness of policy options such as shock responsive social transfers and non-structural adaptation options such as climate smart agriculture, while already in the framework, should also be tested via further case study applications. Application of this framework to a broader set of countries and drawing more robust policy implications are also important areas for future studies.

Annex I. Data Sources for Calibration

Country applications of the SDG-C framework require an end-user to calibrate macroeconomic and climate change related parameters. The framework includes default parameterization of the model draws on comparable cross-country databases which may be adjusted accordingly to data availability. This section describes data sources which may be used for the calibration of country-specific aspects.

Parameters	Descriptions	Data Sources
Climate Change Aspects		
Disaster Damages to Capital Stock	Disaster shocks to capital stock can be calibrated based on available catastrophe modeling datasets. Catastrophe modeling outputs contain information related to annual average losses (i.e. probability weighted average damages) as well as a risk curve containing information regarding probable maximum losses related to disasters of alternative return periods. For scenario analysis, it is recommended that an end-user selects a particular disaster scenario from the existing risk curve, noting specific magnitudes and return periods of disaster events. Whereas typical global catastrophe modeling outputs report the total infrastructure damages valued per replacement costs of damaged infrastructure, the SDG-C takes damage data in the form of a percentage of capital stock. Hence data on the total value of damage must be converted to its equivalent in percentage of capital stock, drawing from the available information related to the country's total capital stock (e.g. FAD capital stock dataset).	***Multi-hazard risk curves:*** Global Risk Assessment (https://www.preventionweb.net/ english/hyogo/gar/2015/en/home/) Global Infrastructure Risk Model and Resilience Index (GIRI) (https://giri.unepgrid.ch/facts-figures/multi-hazards) ***Single hazard risk curves:*** Aqueduct Floods (https://www.wri.org/research/aqueduct-floods-methodology)
Slow-onset climate change related decline of total factor productivity	Slow-onset climate change related to impact to the total factor productivity may be estimated either through a top down or bottom-up methods. The top-down econometric estimates are available in Centorrino, Massetti, and Tagklis (forthcoming). For bottom-up assessments, an end-user may identify main channels through which productivity may be affected such as labor and land, collect available estimate of these channel specific impacts based on biophysical and econometric studies and estimate aggregate reduction in productivity, taking into the account the magnitude of climate impact on each impact channel and the ratio of each input used by an economy.	***Top down approach:*** Centorrino, Massetti, and Tagklis (forthcoming). ***Bottom up approach:*** Labor impact: Dasgupta S, van Maanen N, Gosling SN, Piontek F, Otto C, Schleussner C-F. Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet Planet Health 2021; 5: e455–65. Agricultural impact: https://www.ifad.org/en/w/publications/ climate-adaptation-in-rural-development-card-assessment-tool

Macroeconomic Aspects		
Macro-fiscal	For the macro-fiscal baseline calibration, we follow IMF sources publicly available.	IMF, World Economic Outlook; IMF's Fiscal Monitor Database; and IMF Country Staff Reports.

Annex II. Additional Studies on Specific Countries and Sectors

Climate Change Impact on Individual Sectors				
Roads Sector				
Parameter	**Best Guess**	**Methodology**	**Source**	**Climate Drivers**
Climate-inflicted damage costs to transports	€2.5 billion/year	Cost accounting framework	Doll, C., Klug, S., & Enei, R. (2014). Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years. Natural hazards, 72(1), 211-239.	Floods, storms, droughts
Global Expected Annual Damages (EAD) due to direct damage to road and railway assets	$3.1 to 22 billion (73% is caused by surface and river flooding). Global EAD are 0.02% relative to global GDP. In some countries reach 0.5 to 1% of GDP annually, which is the same order of magnitude as national transport infrastructure budgets.	Model calibration	Koks, E. E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S. A., ... & Hallegatte, S. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. Nature communications, 10(1), 1-11.	Floods, droughts, cyclones, earthquakes
Climate impacts to roads, bridges, coastal properties, and urban drainage infrastructure in US	Adaptation costs for roads rise under BAU scenario to $6 billion annually in 2075, but remain at about $2 billion per year through 2075 under both the Policy 3.7 and Policy 4.5 scenarios.	Using four models that analyze vulnerability, impacts, and adaptation with GHG emission scenarios, climate sensitivities, and global climate models	Neumann, J. E., Price, J., Chinowsky, P., Wright, L., Ludwig, L., Streeter, R., ... & Martinich, J. (2015). Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. Climatic Change, 131(1), 97-109.	Climate models
Physical impact of climate hazards on roads in Vietnam	Mean additional cost of maintaining the same road network through 2050 are US$10.5 billion	Stress response methodology with GCM climate projections	Chinowsky, P. S., Schweikert, A. E., Strzepek, N., & Strzepek, K. (2015). Road infrastructure and climate change in Vietnam. Sustainability, 7(5), 5452-5470.	SLR, precipitation, temperature and flooding
Repair and maintenance cost of road damages due to climate in Africa	US$183.6 billion price tag (US$2.3 billion per year) as a result of damages directly related to temperature and precipitation changes through 2100	Projected climate variations to determine the impact of climate change on infrastructure as in Chinowsky et al. 2011.	Chinowsky, P., Schweikert, A., Strzepek, N., Manahan, K., & Strzepek, K. (2011). Adaptation advantage to climate change impacts on road infrastructure in Africa through 2100 (No. 2011/25). WIDER Working Paper.	Temperature and precipitation

Impact of climate change on road infrastructure in Ghana	$473 million to maintain and repair damages caused to existing roads (no adapt, 2020-2100). Design and construction of new road infrastructure adaptation total cumulative cost: $678.47 million	Infrastructure Planning Support System (IPSS) by the Institute for Climate and Civil Systems	Twerefou, D. K., Chinowsky, P., Adjei-Mantey, K., & Strzepek, N. L. (2015). The economic impact of climate change on road infrastructure in Ghana. Sustainability, 7(9), 11949-11966.	Climate scenarios (GCM)
Impact of climate change on the road infrastructure in South Africa	Median and maximum climate scenario cost USD$116.8 million and USD$228.7 million annually in the 2050 decade if no adaptation. With proactive adaptation: these costs can be reduced to USD $55.7 million	Infrastructure Planning Support System (IPSS) by the Institute for Climate and Civil Systems	Schweikert, A., Chinowsky, P., Kwiatkowski, K., Johnson, A., Shilling, E., Strzepek, K., & Strzepek, N. (2015). Road infrastructure and climate change: Impacts and adaptations for South Africa. J. Infrastruct. Syst, 21(3), 04014046.	Climate scenarios (GCM)
Effect of climate change on the road infrastructure of Malawi, Mozambique, and Zambia	$596 million price tag based on median climate scenarios to maintain and repair roads through 2050	stressor-response approach with GCM climate scenarios	Chinowsky, P. S., Schweikert, A. E., Strzepek, N. L., & Strzepek, K. (2015). Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia. Climatic Change, 130(1), 49-62.	Climate scenarios (temperature, precipitation, flooding)
Energy Sector				
Parameter	**Best Guess**	**Methodology**	**Source**	**Climate Drivers**
Impact of climate change on the electricity market	1°C increase reduces power output by approximately 0.45%, nuclear power output by 0.8% and coal and gas power output by 0.6% due to the thermal efficiency loss.	Literature review	Mideksa, T. K., & Kallbekken, S. (2010). The impact of climate change on the electricity market: A review. Energy policy, 38(7), 3579-3585.	Temperature and precipitation
Climate change impact on electricity supply in US and Europe	Depending on cooling system type and climate scenario for 2031–2060, summer average decrease in capacity of power plants of 6.3–19% in Europe and 4.4–16% in the United States	Physically based hydrological and water temperature modelling framework in combination with an electricity production model	Van Vliet, M. T., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P., & Kabat, P. (2012). Vulnerability of US and European electricity supply to climate change. Nature Climate Change, 2(9), 676-681.	Water temperatures and river flows
Total global expected annual damage (EAD) from all hazards on power generator infrastructure	Around $15 billion, or around 0.2% of the global value of the power generation infrastructure.		Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). Lifelines: The resilient infrastructure opportunity. World Bank Publications.	All hazards

Impacts of climate change on electric power supply in the Western United States	For vulnerable power stations (46% of existing capacity), climate change may reduce average summertime generating capacity by 1.1–3.0%, with reductions of up to 7.2–8.8% under a ten-year drought.	Simulations of long-term changes in streamflow, air and water temperature, humidity and air density, joining downscaled climate forcings with a hydrologic modelling system	Bartos, M. D., & Chester, M. V. (2015). Impacts of climate change on electric power supply in the Western United States. Nature Climate Change, 5(8), 748-752.	Air and water temperature
Power-generation system vulnerability to climate change	Reductions in usable capacity for 61–74% of the hydropower plants and 81–86% of the thermoelectric power plants worldwide for 2040–2069	Global hydrological–electricity modelling framework to simulate streamflow, water temperature, hydropower and thermoelectric power usable capacity with data on 24,515 hydropower and 1,427 thermoelectric power plants	Van Vliet, M. T., Wiberg, D., Leduc, S., & Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. Nature Climate Change, 6(4), 375-380.	Water temperature
Climate impacts on global hydropower production	Change in net global hydropower production of between −8% and +5% under RCP8.5 and between −4% and +4% under RCP 4.5 by the end of the century	Simulation approach to assess climate change impacts on global hydropower production.	Turner, S. W., Hejazi, M., Kim, S. H., Clarke, L., & Edmonds, J. (2017). Climate impacts on hydropower and consequences for global electricity supply investment needs. Energy, 141, 2081-2090.	Climate realizations from sixteen CMIP-5 GCMs
Water/Sanitation/Hygiene				
Parameter	**Best Guess**	**Methodology**	**Source**	**Climate Shock**
Costs of CC adaptation for the supply of raw industrial and municipal water	Global costs of $12 bn p.a., with 83–90% in developing countries; the highest in Sub-Saharan Africa. Globally, adaptation costs are low compared to baseline costs ($73 bn p.a.)	Scenario simulations where adaptation costs are costs of providing enough raw water to meet future industrial and municipal water demand, based on country-level demand projections to 2050.	Ward, P. J., Strzepek, K. M., Pauw, W. P., Brander, L. M., Hughes, G. A., & Aerts, J. C. (2010). Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. Environmental Research Letters, 5(4), 044011.	Climate scenarios
Costs associated with changes in instream and abstractive water use in US	between $136 and $327 billion per year (adjusted to 2007$)	Simulations with scenario assumptions and general circulation model (GCM) projection	Frederick, K. D., & Schwarz, G. E. (1999). Socioeconomic impacts of climate change on US water supplies. Journal of the American Water Resources Association, 35(6), 1563-1583.	Climate scenarios

National damages of climate change on U.S. water resources	between a benefit of $12.3 billion per year (associated with a 15 % increase in precipitation and modest warming of 1.5 °C) and a cost of $54.5 billion per year (associated with warming of 5 °C and no change in precipitation nationally)	Information flow in a basin-level approach	Hurd B, Callaway M, Smith JB, Kirshen P (1999) Economic effects of climate change on U.S. water	Climate scenarios

Annex III. Tradeoff Between Costs and Benefits of Disaster Risk Reduction Investment

In the C-SDG framework, the relationship between ρ and p describes the trade-off between the benefits and costs of adaptation policies in public infrastructure investment. Investing only in standard infrastructure reduces financing need by a factor p; while investing in resilient infrastructure reduces the financing need by ρ when the economy is hit by a disaster. The financial benefit, i.e., lower cost, of standard infrastructure is always there, while the shock occurs only in some of the years. The opportunity cost of investing in resilient infrastructure in each year is $1/p$, is incurred every year and increases with the relative cost of resilient versus standard capital and the size of resources invested in public resilient capital.

Similarly, the benefit of investing in resilient infrastructures is the difference between the damage in case of resilient versus standard infrastructure. It depends on the degree of damage reduction ρ and the frequency of the climate shock. We can write the damage to the infrastructure capital associated with climate shocks as

$$\frac{\rho DR_{t-1} + DS_{t-1}}{f}$$

where $f \geq 1$ represents the interval between occurrences of the shock. If $f = 1$, the climate shock occurs every year, as f increases the frequency declines. The impact of the weather shock on the capital depends on the composition of infrastructure capital. The higher the share of resilient infrastructure (R), the lower is the impact. The gross benefit of investing in resilient infrastructure (in absolute value) is therefore,

$$\left|\frac{(\rho-1)D}{f}\right|$$

The net benefits of investing in resilient infrastructure are larger, the higher is the damage reduction factor, ρ, the more frequent are the climate shock (lower f) and the intensity of the climate shock (D) and the smaller is the cost advantage of standard capital (p closer to 1). In the current formulation of the production function resilient and standard public capital are perfect substitutes, so the trade-off does not depend on the existing stock of standard versus resilient capital.

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