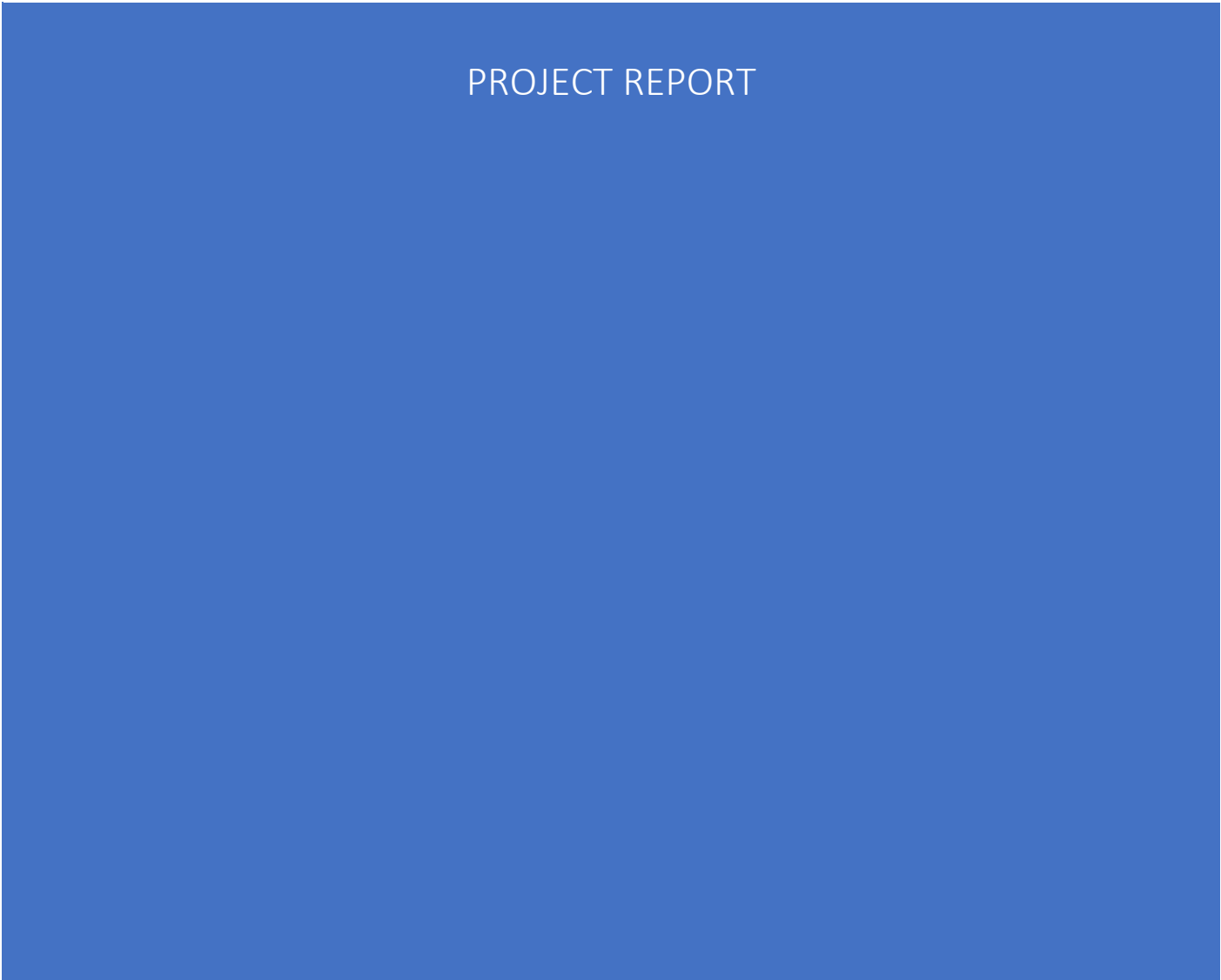




BUILDING RESILIENCE: ADDRESSING CLIMATE CHANGE THREAT MULTIPLIERS IN ZAMBIA USING THE iSD MODEL

PROJECT REPORT



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Executive Summary

Zambia is grappling with the intensifying impacts of climate change and variability, which are acting as threat multipliers across multiple national development goals. These climate-induced challenges are exacerbating existing vulnerabilities and creating new risks to human development, security, and sustainable development in the country. Zambia's Eighth National Human Development Report (NHDR) aims to stimulate national dialogue on policies and actions needed to overcome the threat of climate change, and engage stakeholders in building new visions, partnerships, and actions to accelerate human development.

In support of the 8th NHDR, the Millennium Institute applied the Integrated Sustainable Development (iSD) model to the Zambian context to assess the climate threat pathways and quantify the impacts on national development. The analysis was conducted by adapting the iSD model to the Zambian context using data from national and international sources, and developing two scenarios: a *Baseline*, and a *Climate Resilience Scenario* (CRS). The CRS was implemented based on the expenditure budget of the Zambia's most recent National Determined Contributions (NDC) (2021) framework and the national Green Growth Strategy, both consisting of climate adaptation and mitigation interventions with a total implementation cost equivalent to 12% of GDP over the respective period (2024-2030). Given Zambia's current fiscal constraints, the financing of the CRS is assumed to be external, mainly through grants and through foreign direct investment.

Assessment of the model scenarios were focused on national development indicators, but specifically the Human Development Index (HDI), the United Nations Sustainable Development Goals (SDGs), and key socio-economic indicators that capture the impacts of climate threat multipliers. The model findings provide policymakers with insights into 'how' climate change is affecting development goals and the extent to which climate mitigation and adaptation interventions can build resilience across economic, social, and environmental sectors, thus positioning Zambia on a sustainable development trajectory.

Key Messages

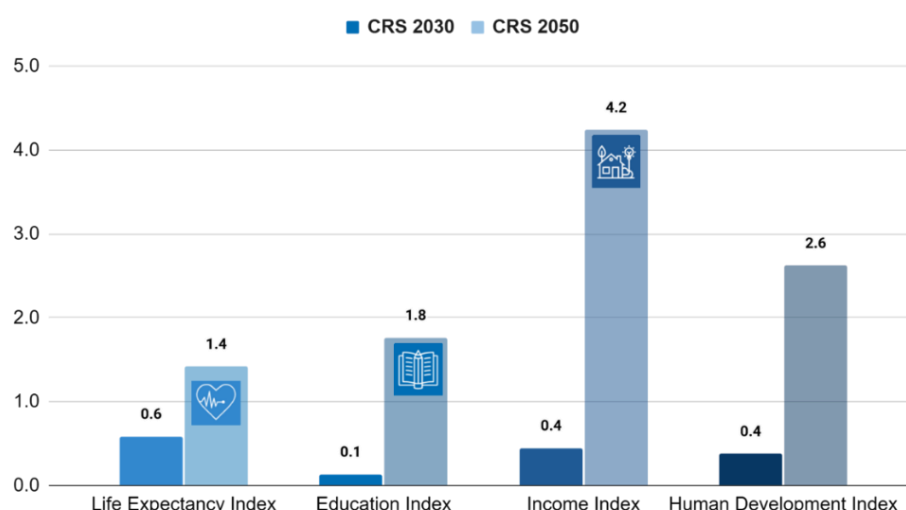


Figure 1. Net attainment (%) in the Human Development Indices for the CRS measured against the baseline for 2030 and 2050.

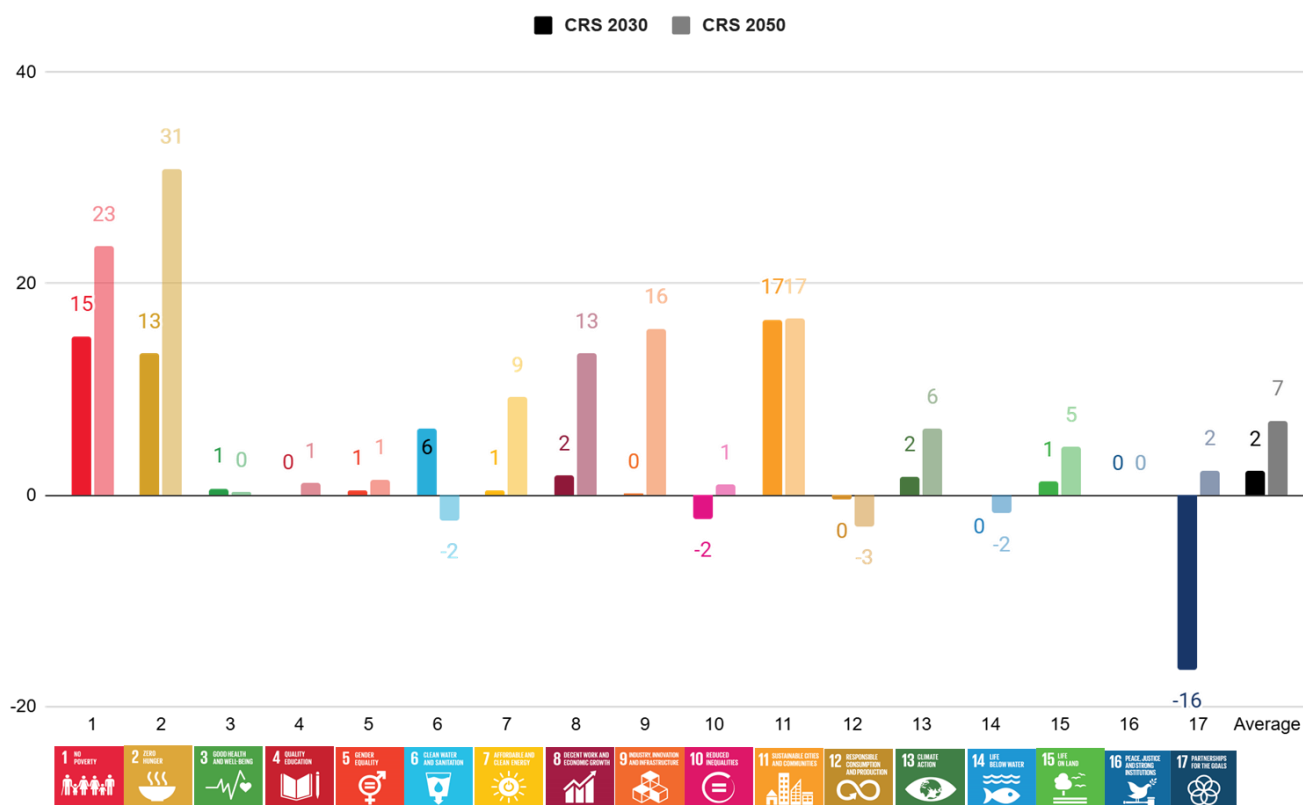


Figure 2. Net attainment (%) in sustainable development goals for the CRS measured against the baseline in 2030 and 2050.

Human Development

Implementing the CRS improves Zambia's Human Development Index (HDI) by 3% in 2050, with gains in life expectancy, education, and income. Additional investment in education and healthcare can further accelerate progress, given that these interventions have the largest return on investment, particularly in the short term (2030). In the long-term (2050), additional investment in climate adaptation shows the largest return on investment, by enabling resilience to human development against future climate impacts.

Sustainable Development

CRS positions Zambia on a sustainable development path, accelerating SDG attainment by 2% in 2030 and 7% in 2050, with notable improvements in poverty reduction, hunger alleviation, economic growth, infrastructure, climate action, and land conservation. Short-term trade-offs may occur in water access, inequality, consumption, and in government accounts.

Economic Growth & Stability

By 2050, CRS drives higher GDP growth, increases GDP per capita, reduces the debt-to-GDP ratio, generates jobs in industry and services, and lowers poverty levels while modestly improving income distribution.

Agriculture Transformation

Production in the agricultural sector increases by an additional 4 billion ZMW by 2050, as

adaptation and mitigation strategies enhance crop yields and boost cereal and non-cereal production.

Energy Security

CRS enables surplus electricity generation, primarily from solar and hydro, ensuring energy security, increased access and creating opportunities for increased electricity exports.

Mining

The mining sector increases value by 4 billion ZMW by 2050, with total metal ore extraction increasing by 108 million tonnes per year under the CRS scenario.

Environmental Sustainability

CRS contributes to climate change mitigation by reducing total greenhouse gas emissions and conserving forest land.

Governance & Finance

Successfully implementing the CRS requires strong governance, with opportunities to develop a finance compact and forge strategic partnerships to mobilize resources and ensure long-term sustainability.

1. Introduction

The world is on a warming trajectory. For the first time on record, global average temperatures breached the 1.5°C threshold in 2024, marking it as the warmest year since the pre-industrial period (1950s) (World Meteorological Organization, 2025). While climate change has gradually altered long-term environmental conditions, the intensification and frequency of extreme climate events has amplified socio-economic vulnerabilities worldwide (Ridder *et al.*, 2022).

The compounding effects of climate change are evident in Zambia. Despite the country being classified as a net-carbon sink, the 2020 University of Notre Dame Global Adaptation Initiative Index ranked Zambia as the 41st most vulnerable country to climate change out of 182 nations (Republic of Zambia, 2024). This classification reflects the country's heightened exposure to climate shocks, including floods, prolonged droughts and intense temperatures. Notably, severe droughts in 2015, 2018, and 2024 have led to national emergencies, with the 2024 drought being marked one of the worst in Zambia's history (African Centre for Biodiversity, 2024).

Recognizing climate change as a key driver of national peace and security (United Nations, 2019), the UN has emphasized the urgency of addressing climate threat multipliers in national development planning. Climate threat multipliers are the mechanisms through which climate change amplifies pre-existing socio-economic vulnerabilities and emerging development challenges. In Zambia, this translates to a complex interplay of factors, including diminished economic growth, increased poverty and inequality, forced displacement, food insecurity, and compromised public health. These interconnected challenges pose a significant barrier to achieving the SDGs and Zambia's Vision 2030.

In this context, Zambia's Eighth National Human Development Report (NHDR) aims to stimulate national dialogue on policies and actions needed to overcome the threat of climate change, and engage stakeholders in building new visions, partnerships, and actions to accelerate human development. As part of the NHDR, UNDP in partnership with the Millennium Institute (MI) have applied the Integrated Sustainable Development (iSD) model to the Zambian context to analyze climate threat pathways. This enabled a comprehensive analysis of the effects of climate change on national development goals in Zambia, with the objective to provide policymakers with actionable recommendations to mitigate climate impacts, build resilience across economic, social, and environmental dimensions, and position Zambia on a sustainable development trajectory.

2. Country Background

Zambia spans a total land area of 752,614 km², endowed with rich natural resources, extensive forest cover, and significant freshwater reserves covering roughly 9,220 km² of land area (Republic of Zambia, 2024). The country's terrain consists of a high plateau, interspersed with hills and mountains, and characterized by a tropical climate. Zambia experiences two primary seasons, the rainy season (November–April) and the dry season, with moderate conditions in between (Republic of Zambia, 2023).

The country's population stands at 19.6 million, with 60% residing in rural areas and 40% in urban centers (Republic of Zambia, 2024). Zambia's Human Development Index (HDI) has steadily improved, rising from 0.471 in 2005 to 0.584 in 2019 (Republic of Zambia, 2022). This

progress is largely attributed to increased life expectancy at birth, which grew from 48.5 to 63.9 years, alongside gains in education. The average number of completed years of schooling rose from 6.3 to 7.2, while the expected years of schooling for a child entering school increased from 10.9 to 11.5. Additionally, Gross National Income (GNI) per capita improved from USD 720 in 2006 to USD 1,190 in 2020 (Republic of Zambia, 2022).

Classified as a lower-middle-income country (World Bank, 2023), Zambia's economy is heavily reliant on mining, with copper serving as the primary foreign exchange earner (Republic of Zambia, 2022). Agriculture also plays a crucial role in economic activity, though largely small-scale, with production focused on maize and livestock farming (Republic of Zambia, 2024).

Zambia's energy supply constitutes three main sources, namely, petroleum, electricity and biomass. Biomass accounts for the largest share (~60%) of Zambia's energy supply mainly for household consumption. The country's power sector is primarily dependent on hydroelectric power, which accounts for approximately 80% of installed generation capacity, supplemented by alternative sources (Energy Regulation Board, 2023). Lastly, with limited domestic reserves, Zambia imports most of its petroleum resources. Access to electricity has improved over time, with the latest statistics indicating an average national electrification rate of 54% in 2024, with increases to 34% and 80% in rural and urban areas, respectively (ZAMSTAT, 2023).

The year 2024 was particularly challenging for Zambia, due to the onset of one of the worst droughts in Zambia's history, exacerbating water and energy shortages, disrupting agricultural production and contributing to the spread of Cholera (African Centre of Biodiversity, 2024). These adverse conditions have had significant consequences for power supply, economic growth, industry, and food security (ZIPAR, 2024), with GDP growth recorded at 2.3% in 2024, revised from the 6.6% target, and a total 2.1 million tonnes maize deficit (ZIPAR, 2024).

In response to climate threats, Zambia has developed a suite of policies to support adaptation and mitigation efforts. Key frameworks include the Climate Policy Act, the national Climate Change Response Strategy (CCRS), the National Green Growth Strategy (GGS), the National Adaptation Plan (NAP), and the upcoming 2025 Nationally Determined Contribution (NDC), which aims to build on the commitments outlined in the 2021 NDC. Findings from the most recent NDC stock take assessment suggest that Zambia is on track to reducing emissions and implementing NDC programs (UNDP, in progress) but that additional investments are required to build long-term socio-economic resilience.

In this context, this modelling study assessed Zambia's future development trajectories and related national goals under two scenarios, a baseline (business-as-usual) and a climate resilient scenario (CRS), to provide insights into socio-economic and environmental implications of climate inaction.

3. Model Overview

3.1 iSD Zambia

The Integrated Sustainable Development (iSD) model is a modelling tool developed and hosted by the Millennium Institute (MI). The model is designed to support integrated planning and policy analysis for sustainable development at the national level. The model is based on

the system dynamics method, which enables it to capture the complex interactions and feedback loops among different sectors and variables within a socio-economic system.

The primary objective of the iSD model is to assist policymakers and stakeholders in decision making by testing strategies that can improve sustainable development outcomes. It allows for scenario analysis, enabling users to explore different policy options and evaluate their effects on various sustainability indicators. By integrating multiple sectors, the iSD model facilitates a holistic approach to national development planning. It can be used to assess progress towards national goals or internationally agreed frameworks, such as the United Nations' Sustainable Development Goals (SDGs) and guide policy formulation that aligns with corresponding development agendas. MI has applied the iSD model and earlier versions thereof in 40 countries and have supported governments to use the tools to develop plans for national development initiatives such as for the green economy, net-zero transitions, sustainable agriculture and social development.

In this context, the iSD model provides a valuable framework to analyze climate threat pathways impacting sustainable development in Zambia. The model further provides stakeholders and policymakers with a broad understanding of systemic interdependencies between environmental impacts and socio-economic outcomes enabling them to identify climate resilient development pathways.

3.2 Model Structure

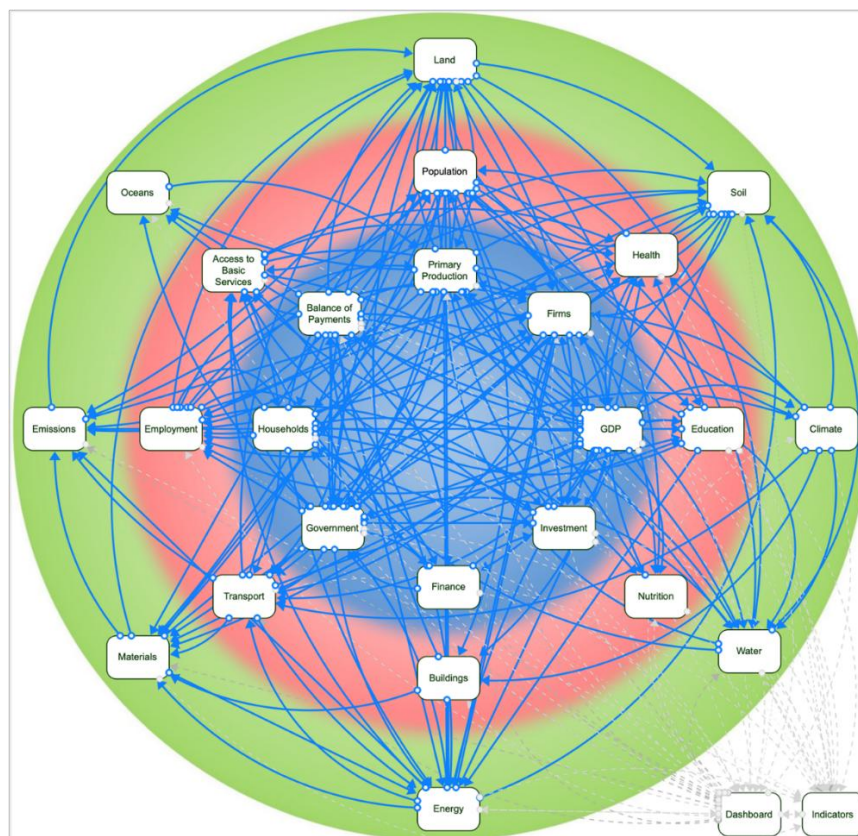


Figure 3. iSD model structure and sub-sector classification.

The iSD model is composed of 24 sectors including 8 social sectors, 8 economic sectors, and 8 environmental sectors (Figure 3). The sectors interact dynamically through a complex network of feedback loops that determine the system's behavior over time, formulated through a series of differential and algebraic equations. The model includes fundamental dynamics important for national-level decision-making and disaggregates related indicators according to international and national reporting standards, including the International Standard Industrial Classification (ISIC Rev. 4) for economic activities. Based on the model structure, economic activities take place within society (from which social resources are drawn to generate economic value) and within the broader natural environment (sources and sinks of natural resources, emissions, and waste). The accumulation of socioeconomic resources, and the use of environmental resources, drives development, which in turn generates socio-economic resources that further the development process. In instances where needs for long-term planning extend beyond the basic structure of the iSD, the model can be customized to address additional issues, or to capture countries' specificities.

3.3 Stakeholder Engagement

Model development was supported by two online workshops and one in-person multistakeholder event.

The aim of the first workshop (held in October 2024) was to identify and map the climate threat multipliers relevant to Zambia. This involved developing initial Causal Loop Diagrams (CLD) to elucidate perspectives and assumptions on climate impacts and to highlight the interdependencies across sectors (Appendix A). The workshop further facilitated a discussion on the model data and areas where national data sources could strengthen model calibration. Table 2 (Appendix B) provides an overview of the key data sources agreed upon and used in the model.

The second workshop, which was held in November 2024, provided an opportunity to validate model calibration, and to discuss and define the model scenarios. This included identifying key policy documents that highlight climate policy interventions and associated implementation costs to inform the model scenarios.

The final workshop, hosted in Lusaka in February 2025, served as a review and validation workshop in preparation of the eighth National Human Development Report. Here, the results of the four main workstreams, including the current analysis, were presented to provide stakeholders with the opportunity to provide feedback on the model findings to support final refinement of the modeling results.

3.4 Data and Calibration

The iSD model is structured to analyze medium to long-term development trends at the national level to provide policy insights. As such, the model does not provide forecasts but rather provides projections of future trends based on grounded and verified assumptions. Future projections thereby embed a degree of uncertainty over the time horizon of the simulation. To address the uncertainty, the iSD validation process focuses on strengthening the underlying assumptions based on available data and research.

During the initial stages of the modelling process, data was collected from both international

and national data sources. A comprehensive list of data sources for the inputs into the model and the data used to calibrate the model is reported in Appendix B. When available, national data sources were prioritized. If data was not available from national or international sources and if that data was necessary for calibration, interpolations and assumptions were made. Data was verified for internal consistency amongst project stakeholders during the engagement workshops.

Upon completion of data collection, the model underwent a robust calibration process. In practice, optimization algorithms search the parameter space across pre-defined thresholds to estimate each model parameter such as to minimize the residual error between the simulated variables and the historical data. To measure the model's ability to replicate the behavior of historical data, a range of summary statistics including the coefficient of determination (R^2), the Root Mean Square Percent Error (RMSPE) and the Theil Statistics for error decomposition were calculated and assessed. A summary of the calibration performance for key model variables is provided in Appendix C, with additional information on model validation and calibration documented in the accompanying calibration report.

4. Climate Threat Pathways

Figure 4 illustrates the key climate threat pathways captured in the iSD model, emphasizing the interconnected effects of climate change on Zambia's socio-economic and environmental systems. The conceptual model captures the key climate threat pathways that were discussed and mapped with project stakeholders during the engagement workshops (Appendix A).

As defined by the United Nations, 2019, "climate threat multipliers refer to mechanisms and pathways through which climate change and variability impact and exacerbate pre-existing as well as new threats to human development, human security and sustainable development". The systems diagram (Figure 4) offers a high-level representation of key connections between social, economic and environmental sectors, and potential intervention points. This further illustrates the threat pathways in which climate change can exacerbate impacts across sectors, highlighting the need for a holistic approach to climate adaptation planning.

Key sectors discussed and focused on in the analysis include Energy (e.g., electricity generation, hydroelectric power, fossil fuel consumption and imports), Water (e.g., supply and withdrawal), Economy (e.g., unemployment, GDP, debt), Education (e.g., gender disparities, school enrollment rates), Health (e.g., waterborne diseases, nutrition, sanitation-related illnesses), Infrastructure (e.g., road conditions, mobility of people and goods), and Agriculture (e.g., crop and livestock production, yields).

Figure 4 illustrates the interconnections between the sectors, particularly between water availability, agriculture, and energy. Variations in climate variables, such as precipitation and temperature, directly affect water resources. Reduced water availability constrains both irrigation for agriculture and hydroelectric power generation. These constraints exacerbate economic stress by diminishing agricultural yields and curtailing energy supply, with knock-on effects across other sectors.

Water availability also plays a central role in health outcomes. Limited access to clean water adversely affects sanitation, increasing the prevalence of waterborne diseases and negatively impacting public health. Poor health outcomes reduce labour productivity, which in turn places

additional strain on healthcare and water systems. This cycle is further aggravated by climate-induced damage to infrastructure. Disruptions to agricultural supply chains and transport networks slow economic activity, leading to stagnation and compounding existing vulnerabilities within the socio-economic system.

The agriculture-energy feedback dynamics further indicate that declining agricultural productivity may drive the expansion of farmland into forested areas, leading to deforestation. This, in turn, further diminishes forest cover, amplifies climate variability, and places additional strain on agricultural, particularly forestry production. Similarly, restricted energy access inhibits economic activity, reinforces poverty and socio-economic vulnerability, creating a self-reinforcing loop that is challenging to overcome without a targeted intervention.

While the challenges posed by these interconnected pathways are significant, they also present strategic opportunities for intervention. Targeted measures, such as reforestation, investments in renewable energy, advanced irrigation technologies, and water-use efficiency improvements, can mitigate cascading impacts.

The iSD model's depiction of climate threat pathways highlight the value of adopting a systems-based approach to national development amid increasing challenges from climate change (Figure 4). Addressing the interconnected nature of climate challenges requires cross-sectoral coordination and targeted interventions that recognize the feedback effects between water, agriculture, energy, health, and infrastructure. By leveraging strategic intervention points, policymakers can create conditions for sustained resilience, reduce socio-economic vulnerability, and foster long-term growth and sustainability in Zambia.

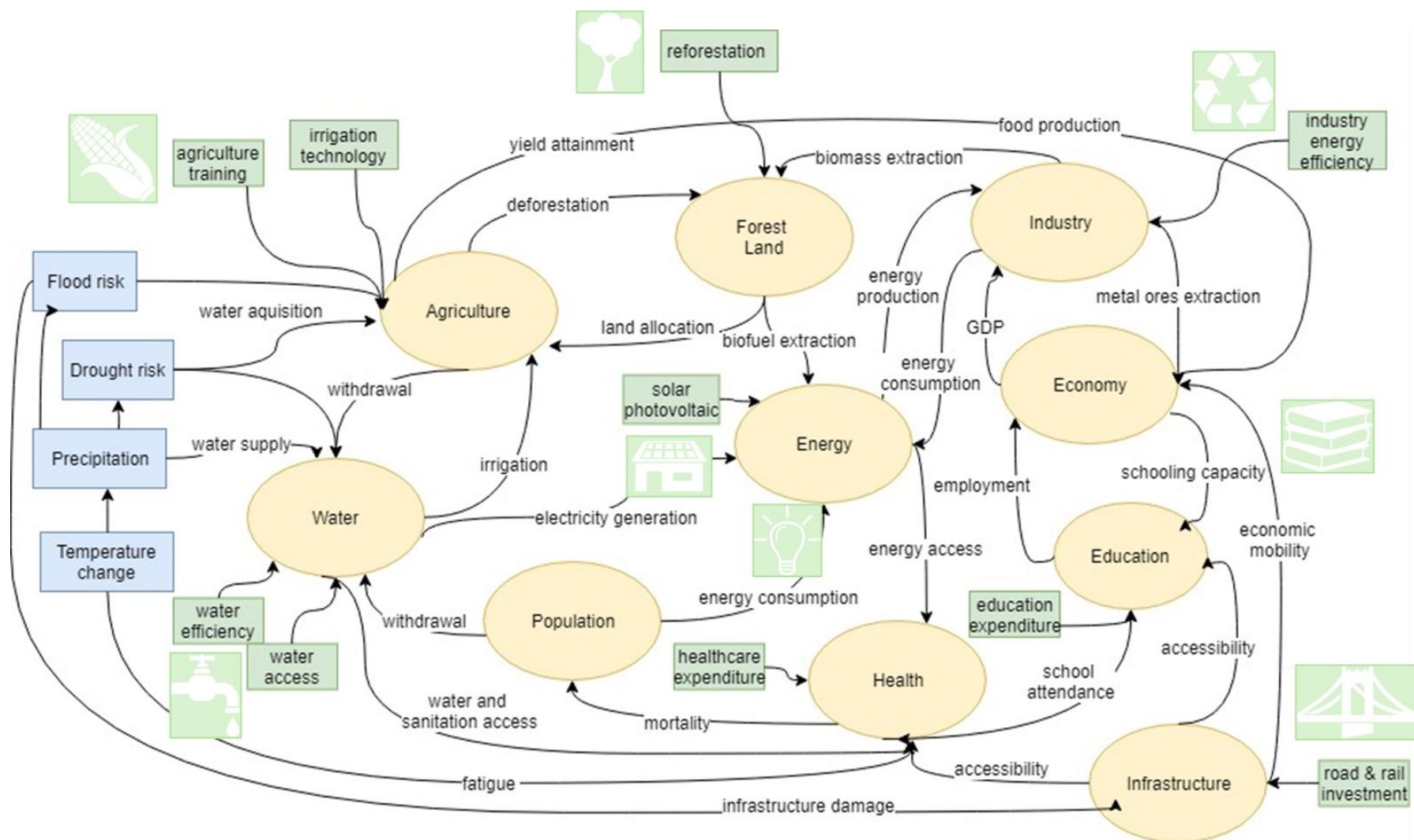


Figure 4. Primary climate threat pathways captured in the iSD model in relation to key development priorities in Zambia. Climate threat multipliers are shown in blue, key model sectors in yellow and policy interventions in green

5. Scenario Design, Narrative, and Assumptions

Two scenarios, a Baseline and a Policy scenario, were developed to facilitate the analysis of climate threat pathways and the respective impacts on national development outcomes in Zambia.

5.1 Baseline Scenario

The baseline scenario represents a business-as-usual (BaU) approach, assuming no changes to existing government expenditure, interventions or policies, and thereby serves as a benchmark for comparison. The projection period spans from 2022 to 2050, with 2022 chosen as the initial departure point as the model was calibrated to historical data up to this year. More recent data points for 2023 and 2024 were unavailable for most variables at the time of analysis, in instances when data was available, the data was included to validate the model data during the respective years.

Future climate scenarios and socio-economic conditions were modelled based on the Shared Socio-economic Pathways (SSP) framework that provides varying narratives for future global development. For the analysis, SS2, which represents the “Middle of the Road” scenario is assumed. This scenario represents moderate socio-economic growth, where population growth slows, economic development progresses steadily, and technological advancements continue, with limited reforms in governance and sustainability efforts. This is considered suitable for the baseline scenario as it further assumes that historical patterns of development are continued throughout the 21st century. In terms of climate projections, SSP2 corresponds to mid-range greenhouse gas emissions, leading to moderate warming scenarios, typically 2.5°C to 3.0°C above pre-industrial levels by the end of the century without major mitigation. For Zambia, SSP2 reflects a steady but limited adaptive capacity to climate impacts, serving as a balanced baseline for assessing climate change and policy effectiveness under realistic global conditions. Additional baseline assumptions are discussed in Appendix D.

5.1.1 Baseline Climate Conditions

Figures 5 and 6 illustrate the key climate variables that initiate climate change threat pathways in the model. The variables capture the historical and projected trends for key climate conditions in Zambia. These variables are exogenous to the iSD model, meaning that the underlying climate conditions are not simulated within the model but are derived from external data, specifically the Climate Change Knowledge Portal (CCKP) of the World Bank (World Bank, 2024). This approach is necessary since the iSD model is not designed to simulate climate dynamics and therefore relies on external data from global climate model compilations derived from observations and climate ensembles. This ensures that the climate variables incorporated into the analysis are grounded in robust projections.

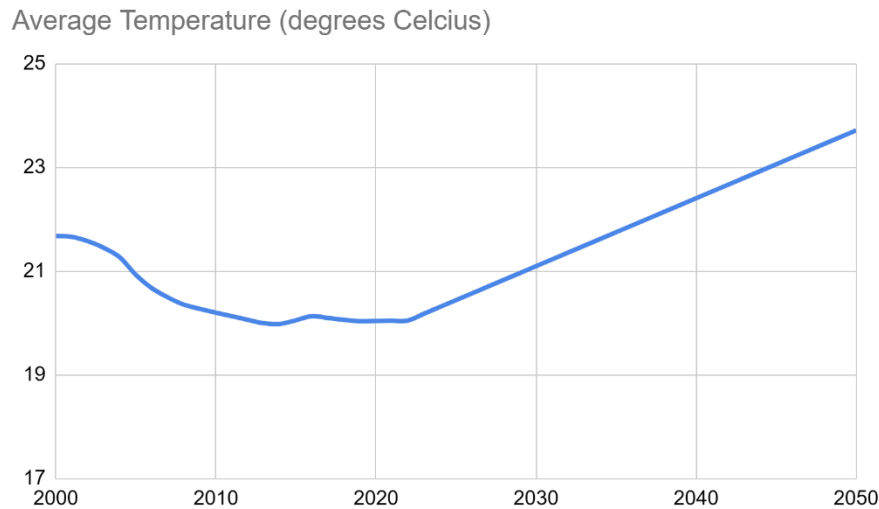


Figure 5. Trend in annual average surface air temperature in Zambia. Data: World Bank, 2024.

Figure 5 illustrates the trends in annual average air temperature for the historical period (2000–2020), based on the latest available data on historical temperature change, and projections until 2050 under the SSP2 scenario. The average temperature exhibits an initial period of relative stability, followed by a steady upward trend beginning around 2020. By 2050, a significant increase in the average temperature becomes apparent, reaching 23.5°C by 2050, aligning with national warming projections (Depsky, unpublished). This rise underscores potential stress on socio-economic systems, as elevated temperatures may exacerbate vulnerabilities across critical sectors such as agriculture, water resources, and public health.

Similarly, Figure 6 illustrates the trends for annual precipitation and related extreme events, measured specifically in terms of ‘days of heavy precipitation’ to capture flooding and the standardized precipitation evapotranspiration index (SPEI) to capture drought events. The historical data shows significant variability in annual precipitation levels, with peaks and troughs indicating alternating wet and dry years. From 2020 onward, projections show a mean trend in annual precipitation varying around 1200mm/year. According to the 2023 National Adaptation Plan, localized climate studies suggest that the mean annual precipitation has been decreasing at an average rate of 1.9mm per month since 1960 (Republic of Zambia, 2023). The short-term historical period and annual timescale of the CCKP data in this instance fails to illustrate this long-term declining trend. However, in terms of extreme events, trends in flooding measured as the number of ‘days of heavy precipitation’ remain relatively low until 2020 but are projected to increase steadily through 2050. This indicates a growing risk of flood-related disruptions, particularly in areas with inadequate drainage or infrastructure. Lastly, the SPEI index, an indicator of drought severity, is a measure of normalized, accumulated rainfall anomalies relative to an annual running-mean that includes the effects of evapotranspiration (Jabbi *et al.*, 2021 and Depsky, unpublished). In the absence of absolute SPEI values, the data shows the trend in the median SPEI index. The SPEI index for Zambia demonstrates oscillating wet and dry conditions over the historical period (Figure 6), nevertheless, the negative downward projection indicates a shift of the median value to drier, drought conditions by 2050. While numerous climate variables can represent changing climate

conditions, these key climate multipliers were identified as the primary indicators relevant to the Zambian context.

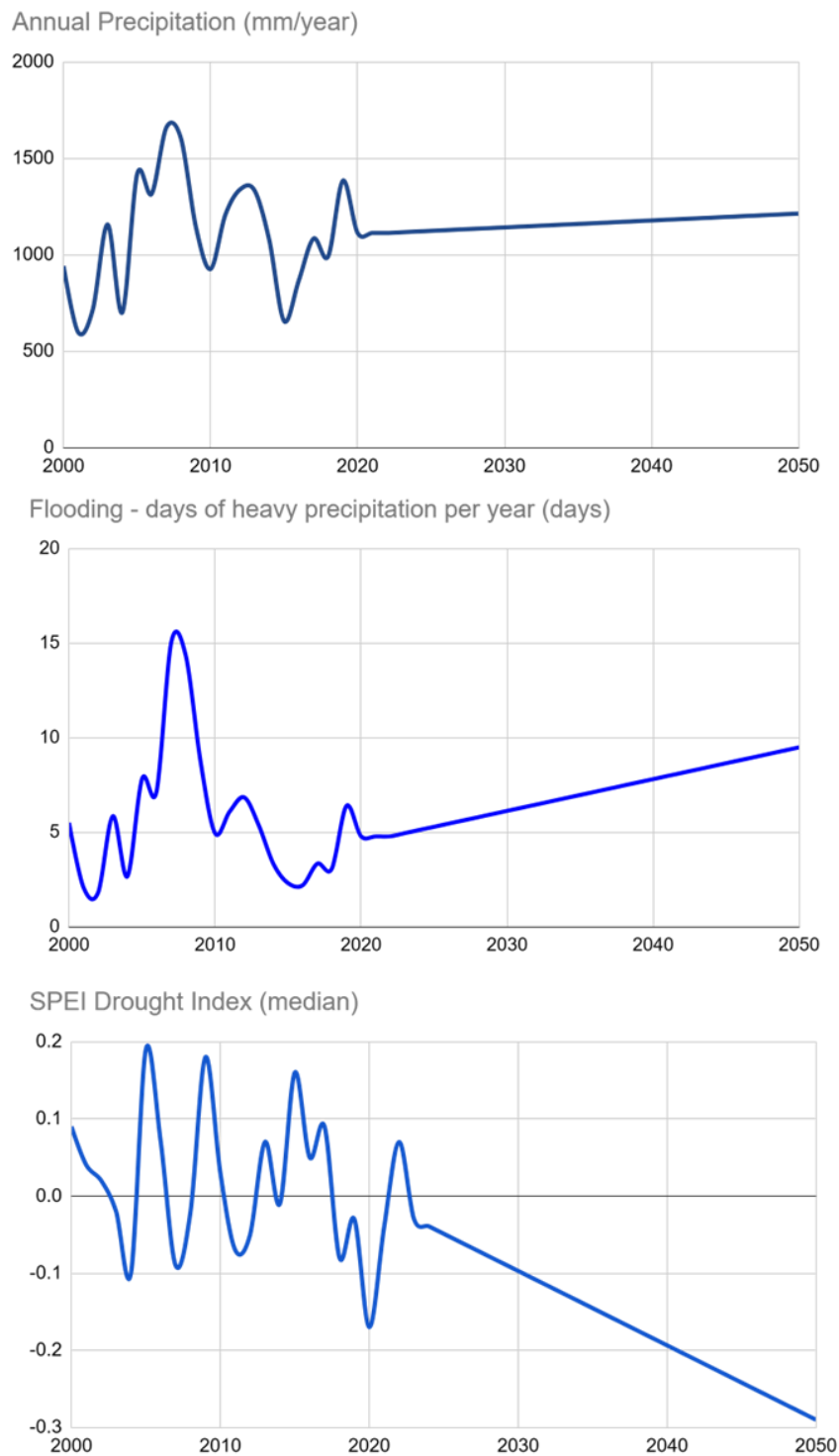


Figure 6. Annual precipitation (mm/year) (top), days of heavy precipitation per year (middle) and median trend in the SPEI drought index (bottom). Data: World Bank, 2024.

5.2 Climate Resilient Scenario

The Policy Scenario, referred to as the Climate Resilience Scenario (CRS), aims to capture the effects of additional interventions aimed at mitigating and adapting to climate change. The scenario was co-developed with project stakeholders by discussing and identifying potential government interventions that can strengthen Zambia's resilience to climate impacts while supporting key national development outcomes.

The formulation of the CRS was guided by a review of critical policy documents, with particular emphasis on Zambia's 2021 Nationally Determined Contribution (NDC) framework (Republic of Zambia, 2021) and the national Green Growth Strategy (GGs 2024-2030) (Republic of Zambia, 2024). Both frameworks provide a comprehensive outline of proposed climate adaptation and mitigation interventions, along with the associated implementation costs. These interventions were systematically mapped against the intervention points within the iSD model. These were then incorporated into the model as additional government expenditures relative to the baseline expenditure and implemented from present time (2024) until the end of the NDC implementation period (2030).

A key assumption in the CRS is the source of financing for climate interventions. Given Zambia's limited fiscal space and debt position, it is assumed that 80% of the financing required for the NDC and GGS interventions is provided by grant funding, such as international climate finance, development partners, and donor contributions and 20% by the private sector through foreign direct investment. This approach reflects Zambia's current fiscal constraints and acknowledges the role of international support in driving climate action.

The CRS is designed to assess the broader development impacts of climate action by analyzing its effects on key national development indicators. The evaluation focuses on critical metrics, including the Human Development Index (HDI), progress toward Sustainable Development Goals (SDGs), and other key socio-economic variables. This scenario offers a robust framework for understanding how targeted climate resilience interventions can shape Zambia's development trajectory, while providing insights into the potential socio-economic trade-offs and benefits of such interventions.

Table 1. Total expenditure allocated to model interventions based on the latest published NDC 2021 and GGS 2024. Expenditure as % of GDP is distributed across the implementation period 2024-2030. % GDP is calculated relative to total nominal GDP at basic prices over the corresponding period.

Model Intervention	NDC expenditure (USD)	GGS expenditure (USD)	Total expenditure 2024-2030 (USD)	% of GDP
general education	0	2 755 000	2 755 000	0.00
general health	128 744 093	67 800 000	196 544 093	0.08
general agriculture	36 043 345	91 250 000	127 293 345	0.05
fertilizer subsidies	167 085 818	0	167 085 818	0.07
water access	476 849 149	2 029 744 000	2 506 593 149	1.07
sanitation access	0	1 260 000 000	1 260 000 000	0.54
roads a	480 114 928	1 100 500 000	1 580 614 928	0.68
railways	4 418 184 633	0	4 418 184 633	1.89
waste management	377 816 257	1 755 000	379 571 257	0.16
land protection	129 133 586	69 337 000	198 470 586	0.08
reforestation	197 599 880	32 830 000	230 429 880	0.10
small photovoltaic	3 604 698	41 600 000	45 204 698	0.02
large photovoltaic	923 599 661	3 722 000 000	4 645 599 661	1.99
large hydropower	3 426 902 997	0	3 426 902 997	1.47
large wind	494 327 586	0	494 327 586	0.21
large biomass	307 071 125	56 100 000	363 171 125	0.16
vehicles efficiency	0	1 420 000	1 420 000	0.00
industry energy	42 451 532	17 600 000	60 051 532	0.03
households' energy	7 645 601	11 925 000	19 570 601	0.01
water efficiency	61 209 800	834 624 450	895 834 250	0.38
general transfers	1 956 433 709	750 000	1 957 183 709	0.84
climate adaptation	381 212 012	104 730 000	485 942 012	0.21
agriculture training	248 652 515	413 375 000	662 027 515	0.28
Other A - climate administration	12 447 042	22 323 000	34 770 042	0.01
Other B - other energy investment	2 919 459 343	500 000 000	3 419 459 343	1.46
Other C - tourism administration	0	12 080 000	12 080 000	0.01
Other D - mining investment	0	14 930 000	14 930 000	0.01
Total	17 196 589 310	10 409 428 450	27 606 017 760	12

6. Scenario Analysis: Base vs. CRS

The following section presents the results of the analysis for the two scenarios (Baseline and Climate Resilience Scenario) and reports on outcomes of key national development indicators, including the HDI and SDG outcomes.

6.1 Human Development

Figure 7 compares the attainment of the HDI in Zambia for 2024 and projected outcomes for 2030 and 2050 under the baseline and CRS scenarios. Attainment of the HDI is further disaggregated into its key indices: Life Expectancy, Education, and Gross National Income (GNI) in Figures 8-10.

In 2024, the indices show baseline values reflecting the country's current development status. By 2050, the baseline scenario projects improvements across all indices, indicating gradual progress but limited gains due to ongoing climate and socio-economic challenges. The CRS, represented by the lighter shading above the base projections, demonstrates improvements in all indices, with notable gains in the Life Expectancy (2%), Education Index (2%) and GNI Index (4%). These results highlight the positive impact of implementing targeted climate resilience interventions, although these are not directed specifically at improving the HDI. Overall, the HDI shows a 3% attainment in 2050, emphasizing the long-term developmental benefits of the CRS pathway. This shows significant impact, given that the education and health indicators underlying the HDI are inherently slow in achieving progress and underscores the importance of integrating climate resilience measures to enhance human development outcomes, particularly in areas such as education, health, and economic well-being. Figure 10 presents trends in the absolute values of the sub-indicators for the HDI, in terms of life expectancy, years of schooling and income per capita, comparing historical data (where available) with projections under the two scenario pathways.

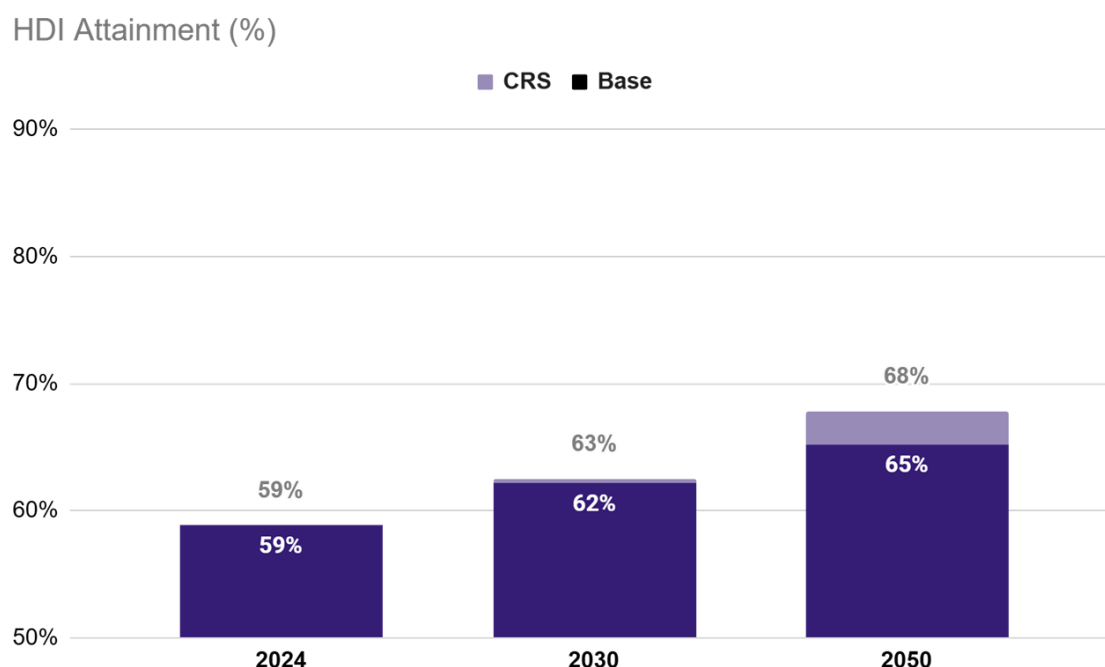


Figure 7. HDI attainment (%) in 2024, 2030 and 2050. Dark shading represents the baseline results, while light shading represents the additional attainment from the CRS scenario.

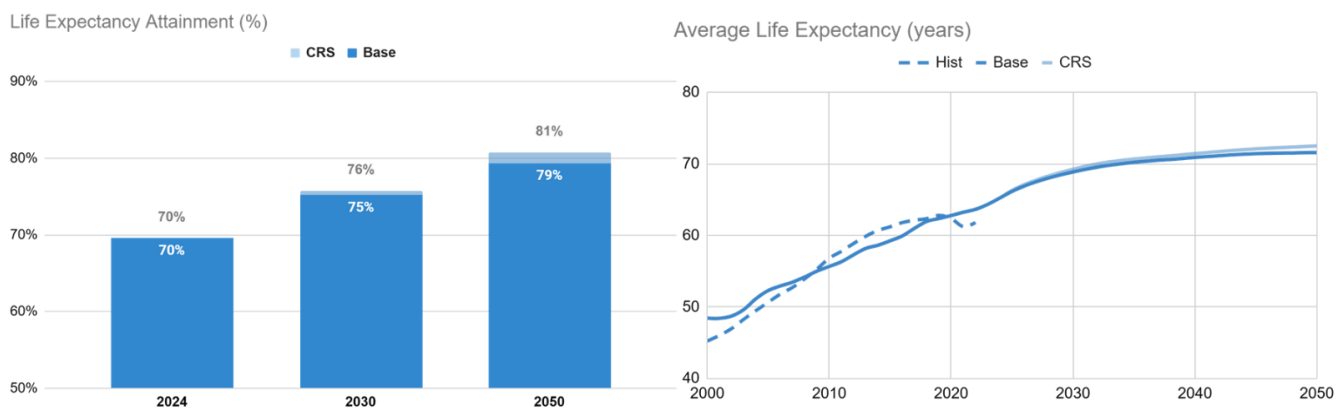


Figure 8. Life Expectancy index attainment (%), measured in terms of average life expectancy (years). Target life expectancy relative to the minimum of 20 years and maximum of 85 years.

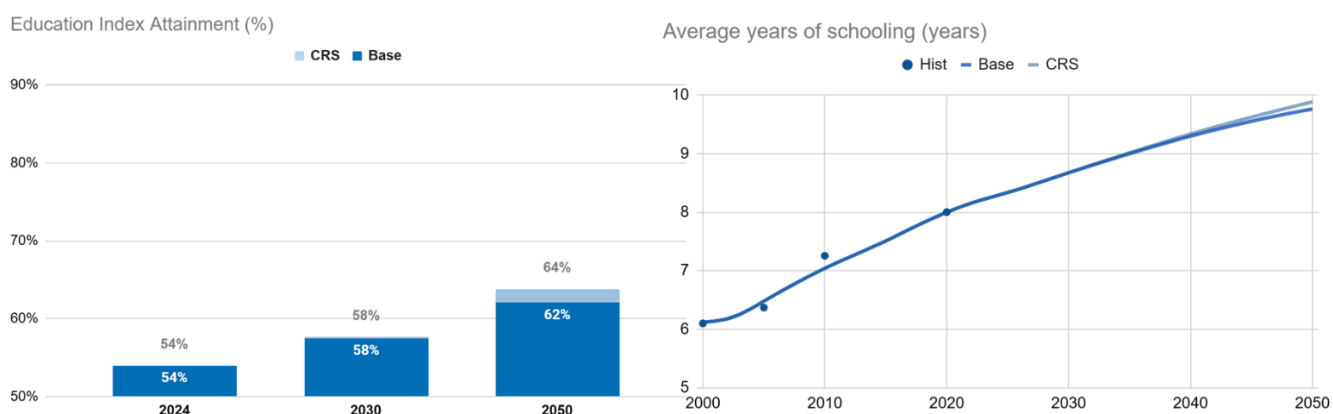


Figure 9. Education Index attainment (%) measured in terms of average years of schooling (years). Target year of schooling is equivalent to 15 years, equivalent to tertiary completion.

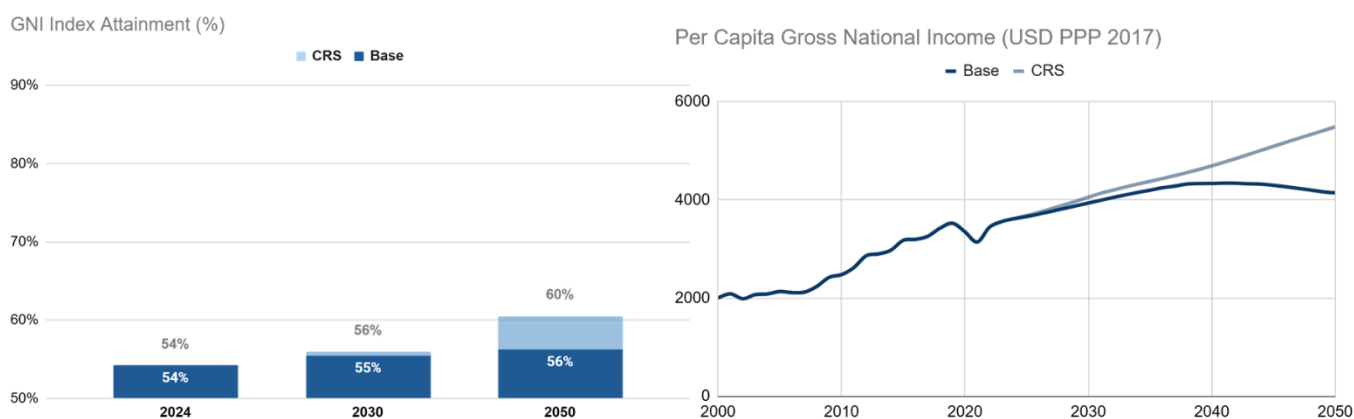


Figure 10. Attainment in the Gross National Income Index (%), measured in terms of per capita gross national income (USD PPP 2017). Target GNI measured in relation to the income range of 100-75000 USD PPP 2017.

From 2000 to 2024, life expectancy shows a steady increase, reaching 65 years in 2024. Under the baseline scenario, life expectancy is projected to plateau around 72 years by 2050, reflecting limited health improvements. In contrast, the CRS pathway shows a marginal gain by 1 year by 2050. In terms of schooling, historical trends indicate consistent progress, with average years of schooling increasing from 6 years in 2000 to 8 years by 2024. Under the base scenario, this upward trend continues, reaching 10 years by 2050. The CRS scenario accelerates these gains slightly, with schooling projected to surpass 10.2 years by 2050. The additional progress highlights the positive but marginal impact of targeted investments in education under climate-resilient pathways. Lastly, per capita GNI grows steadily since 2000, albeit with fluctuations around 2020, where values approached USD 3600 (PPP) in 2024. By 2050, the baseline scenario projects GNI to increase gradually to about USD 4100. The CRS pathway however demonstrates substantial improvements, with GNI reaching 5400 USD, driven by enhanced economic resilience and growth.

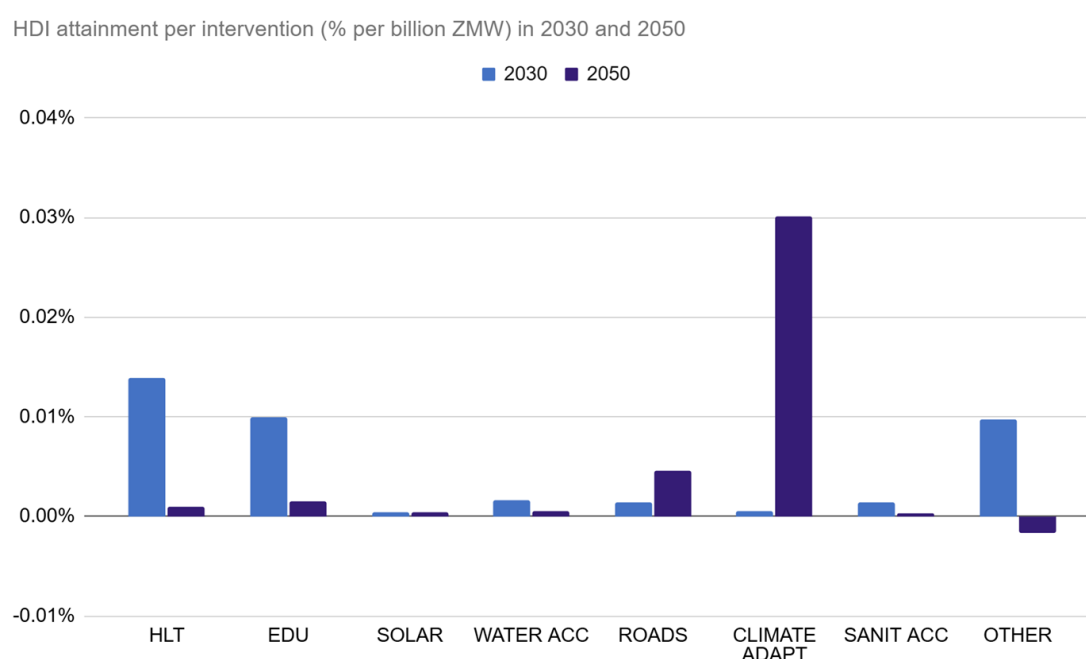


Figure 11. Policy interventions contributing to HDI attainment, measured per billion ZMW expenditure in 2030 and 2050.

To investigate the cause of HDI attainment, Figure 11 illustrates the return on investment for the interventions with the largest effects measured in terms of percentage HDI attainment per billion ZMW for 2030 and 2050. In other words, this represents the policy impact (i.e. CRS-base) divided by the expenditure dedicated to the specific intervention over the implementation period. Interventions in health (0.015%/billion ZMW) and education (0.01%/billion ZMW) have the largest impact on HDI attainment in the short-term 2030, whereas expenditure in climate adaptation results in even larger gains in the HDI in the long-term (2050) by 0.03%/billion ZMW (Figure 11). Other interventions with impacts on HDI include expenditure in solar electricity generation, access to water and sanitation and roads, with other expenditure (see Table 1) having larger combined impacts on HDI in the short-term. Though the results suggest that HDI attainment per billion is considered relatively small they highlight the key interventions with the potential for the highest impact.

To put this into perspective, 33 billion ZMW additional expenditure in climate adaptation by 2050 would result in a 1% gain in HDI, above the HDI attainment from the baseline expenditure. Similarly, an additional 66.67 billion ZMW expenditure in healthcare by 2050 would be required to achieve an additional 1% gain in HDI. Assuming, the government spends an additional 22 billion ZMW on healthcare per annum (ZIPAR, 2024), the government can achieve approximately 8% attainment in HDI by 2050 from healthcare spending alone, above the gains obtained from the baseline expenditure. This suggests that this can increase HDI attainment from 59% in 2024 to 67% in 2050. Additional expenditure in interventions including in education, social protection, WASH (water and sanitation) and roads further contributes to HDI attainment indirectly (Figure 11).

6.2 Sustainable Development Goals

SDG Attainment 2030 (%)

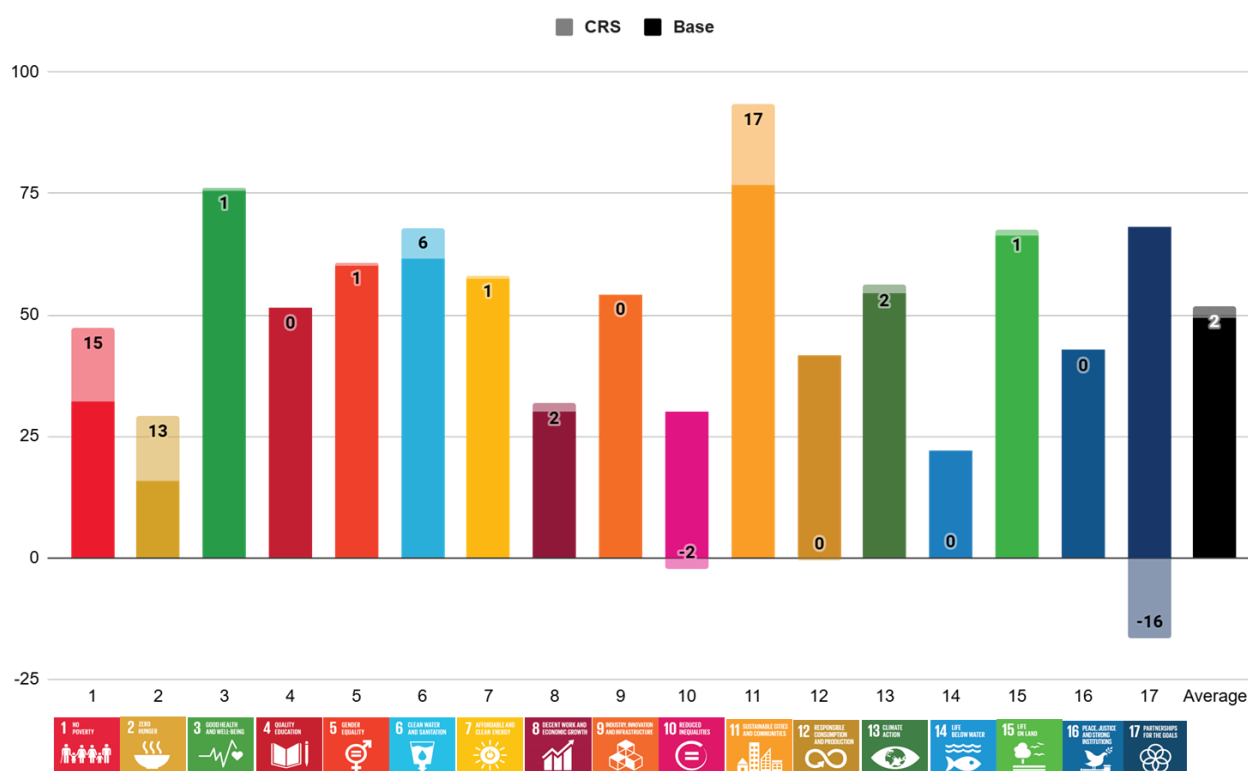


Figure 12. SDG attainment by 2030. Positive CRS gains shown in lighter shading are additive to the BAU result.

Figure 12 compares the projected attainment of the Sustainable Development Goals (SDGs) by 2030 under the two model scenarios. The results highlight significant variability across SDG attainment, with some goals demonstrating notable progress. Under the baseline scenario, goals including SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 11 (Sustainable Cities and Communities) show relatively high attainment, reaching close to or above 75% by 2030. In contrast, SDG 2 (Zero Hunger), SDG 8 (Economic growth), SDG 10 (Reduced Inequalities), and SDG 14 (Life below Water) show relatively poor attainment under the baseline scenario.

For some goals, the CRS further improves these outcomes, particularly in SDG 1 – No poverty (15%), SDG 2- Zero Hunger (13%), SDG 6 – Clean water and sanitation (6%) and SDG 11 – Sustainable Cities and Communities (17%). Environmental SDGs, including SDG 13 – Climate action and SDG 15 – Life on land, achieve a 2% and 1% gain respectively by 2030. Lastly, SDG 17 – Partnership of the goals achieves a 16% reduction in attainment by 2030, though this is because of the assumptions in financing interventions in the CRS scenario, which assumes 100% external financing, and hence a negative attainment for SDG sub-indicator 17.1.2 ('proportion of domestic budget funded by taxes'). If this indicator was removed from the calculation of SDG 17, the SDG attainment would show a positive attainment of 1%. The CRS scenario further delivers marginal improvements for the other SDGs, reflecting the systemic inertia and remaining challenges in these goals without targeted interventions. Overall, the baseline scenario suggests that Zambia is half-way (50%) to achieving the SDG on average, with some goals performing better than others, and that implementing the CRS increases the average attainment by 2% thus highlighting the benefits of integrating climate resilience strategies into development planning.

SDG Attainment (%) for CRS in 2030 & 2050

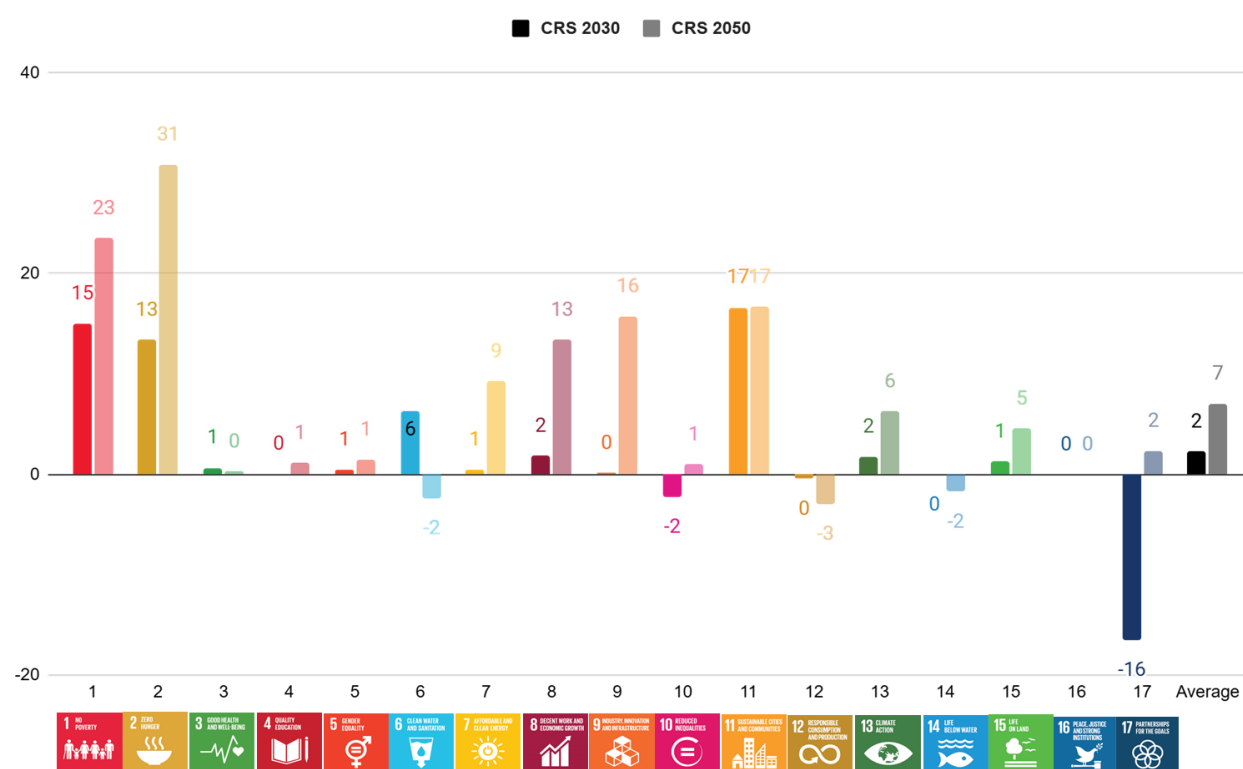


Figure 13. Net attainment in SDGs (i.e. CRS – base in 2030 and 2050).

Evaluating the SDG attainment over the short-term, with only 5-years remaining, suggests remaining challenges for governments. This also indicates that development inherently has delays and that more progress would be observed in the long term to enable favourable trajectories. Evaluating the SDG attainment over a longer-term (Figure 13), allows more time for CRS to achieve more desirable outcomes for certain goals. Additional progress in attainment is particularly relevant for SDG 1 (no poverty) by 23%, 2 (zero hunger) by 31%, 7

(Clean energy) by 9%, 8 (Decent work and economic growth) by 13%, 9 (industry, innovation and infrastructure) by 16%, 13 (climate action) by 6%, 15 (life on land) by 5%, and shows a positive result for SDG 17 (partnership of the goals) in the long-term by 2% by 2050.

SDG attainment per intervention in 2030 (%) (i.e. scenario-base)

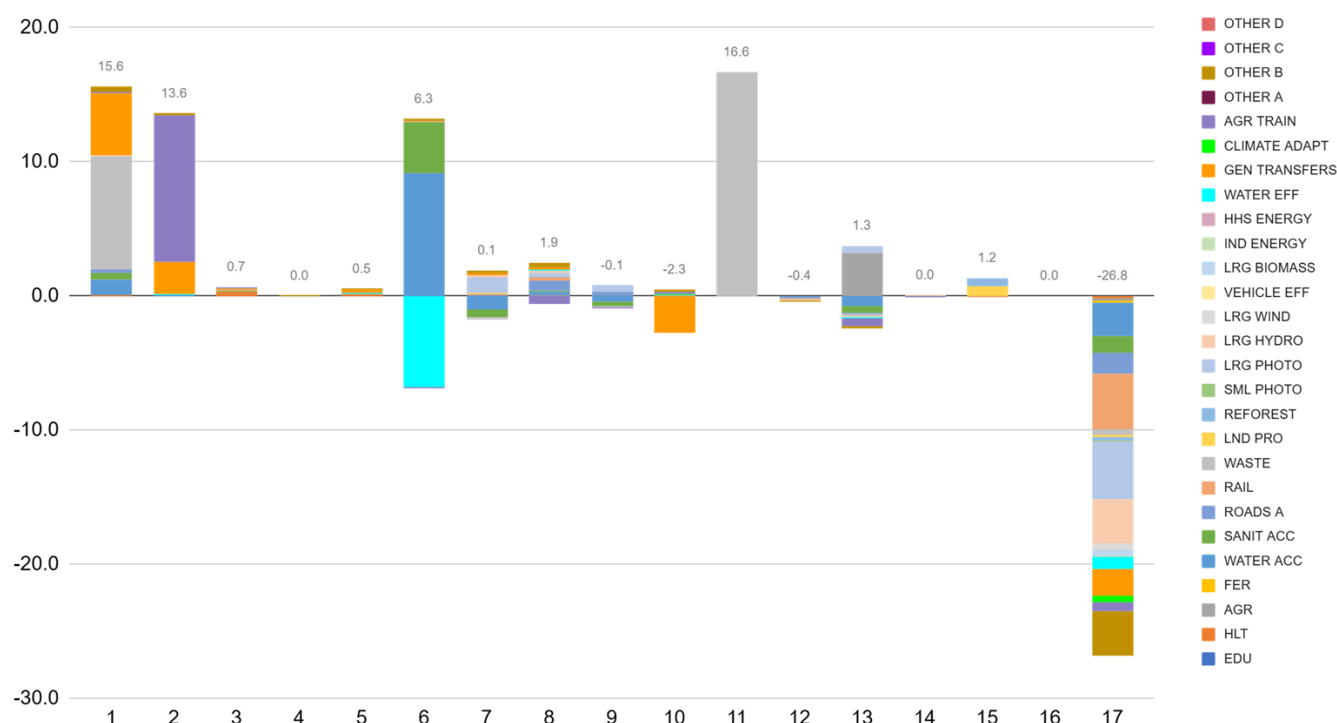


Figure 14. SDG attainment (i.e. CRS-base) in 2030 stacked by policy intervention.

Figure 14 illustrates the policy interventions impacting SDG attainment for 2030. For the analysis, each policy intervention was run separately, as opposed to being combined in the CRS policy, which can result in trade-offs across goals. This further demonstrates the direct pathways through which interventions affect the SDG results. Of the goals with the largest attainment, attainment of SDG 1 (Zero poverty) can be directly appropriated to expenditure in 'general transfers' and 'waste', the latter related to the outcomes of sub-indicator 'proportion of households with access to basic services'. Attainment in SDG 2 (no hunger) is largely attributed to expenditure in 'agricultural training', SDG 6 (clean water and sanitation) is positively impacted by water and sanitation access, but negatively impacted by expenditure in 'water efficiency' resulting in unintended increase in water use particularly related to increase in crop production, under an increasingly sparse water supply. Attainment in SDG 11 is attributed to expenditure on waste, which has a large impact on solid waste collection services. Finally, the negative attainment of SDG 17 is similarly attributed to the lower 'proportion of domestic budget funded by tax' since the expenditure for all policies is funded through external financing sources. Notably, certain SDGs benefit most from interventions, whereas other interventions result in policy trade-offs.

6.3 Social Outcomes

Figure 15 illustrates trends in population growth, and in poverty and income inequality for Zambia under the baseline and CRS development pathways. Population growth shows a steady increase from approximately 10 million people in 2000 to over 20 million by 2024. Both scenarios project continued growth, with Zambia's population expected to surpass 40 million by 2050. Under the CRS pathway, the population is lower by approximately 500 000 persons, due to improved access to education, healthcare, and family planning, which subsequently reduces fertility rates, and slows population growth. The proportion of the population below the international poverty line (USD 700/person/year/ 2500 RLCU/person/year) has remained high, peaking around 2010 at over 65%. Under the baseline scenario, poverty gradually declines to 49% by 2050, reflecting slow but insufficient progress. The CRS scenario accelerates poverty reduction, reducing it by a further 13%, emphasizing the role climate resilience strategies, but more specifically due to interventions directed to access to basic facilities and transfers through farmer household support programs. The Gini coefficient, a measure of income inequality, increases significantly up to 2010, stabilizing around 0.65 thereafter. Under the baseline scenario, inequality decreases only slightly by 2050, while the CRS scenario achieves a modest improvement, lowering the Gini coefficient by a further 2.3% owing to modest improvement in household income for the lower percentiles.

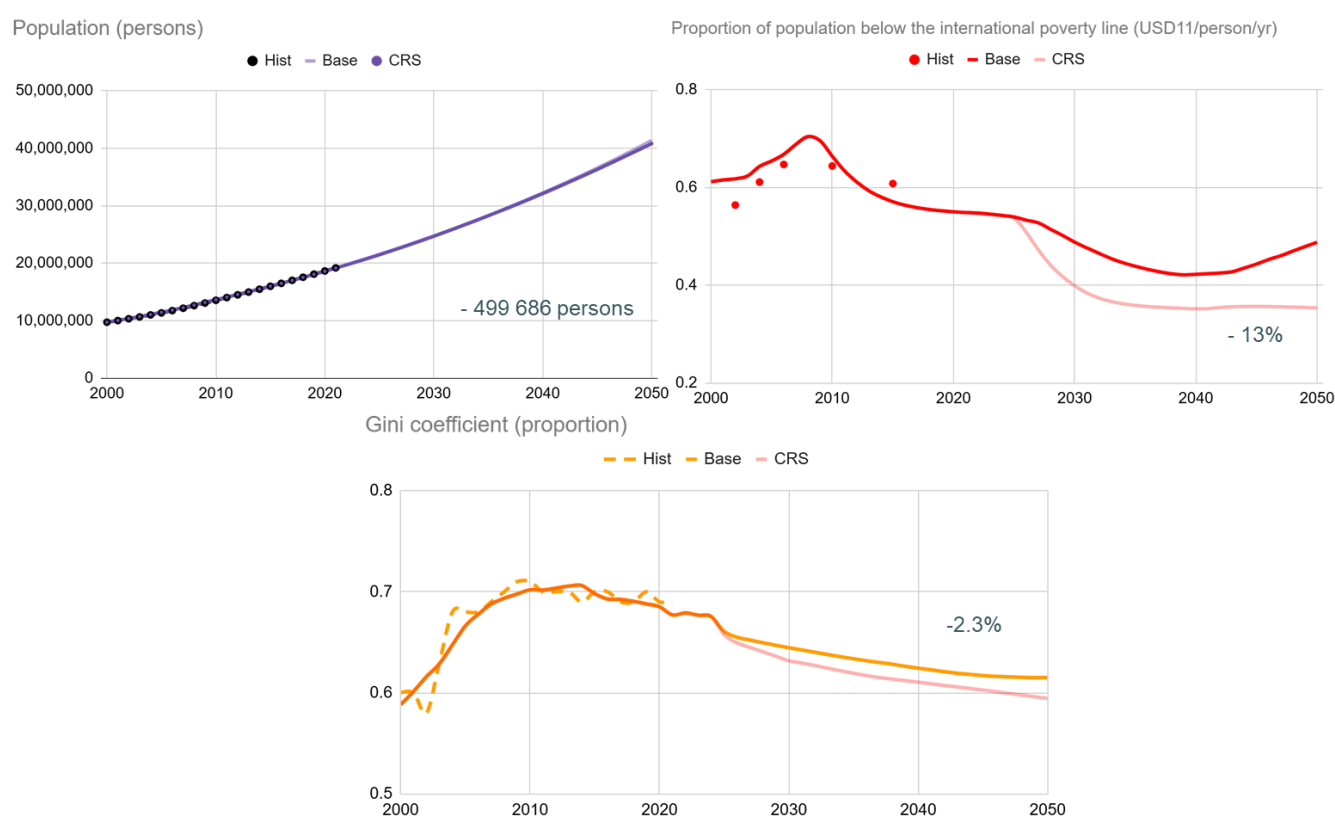


Figure 15. Zambia population and poverty indicators measured in terms of the proportion of population below the international poverty line and a measure of inequality (Gini coefficient).

6.4 Economic Outcomes

Figure 16 illustrates the projected economic trends in terms of real GDP growth rate and GDP per capita. The left panel shows real GDP growth at market prices against the historical data. Results show that the model follows that GDP growth trends though underestimates growth in the first decade of simulation and slightly overestimates growth in the second. Specifically, the model overestimates GDP growth in 2024 (4.8%) which was recorded to be 2.3% due to the impacts of the drought (ZIPAR, 2024). By 2050, the baseline projects a growth at an average rate of 2% per year, however, in the CRS scenario this increases growth by 1.8%, resulting in an average growth of 4% per year. This suggests that climate interventions can boost economic productivity, particularly from resilient productive outputs from the agriculture and mining sectors (Figure 19 and 20).

Real GDP per capita shows modest growth between 2000 and 2020. Post-2020, both scenarios project upward trends, though the CRS pathway accelerates progress, reaching nearly 17,500 ZMW/person/year by 2050. In contrast, the baseline scenario shows slower growth, plateauing closer to 13,600 ZMW/person/year.

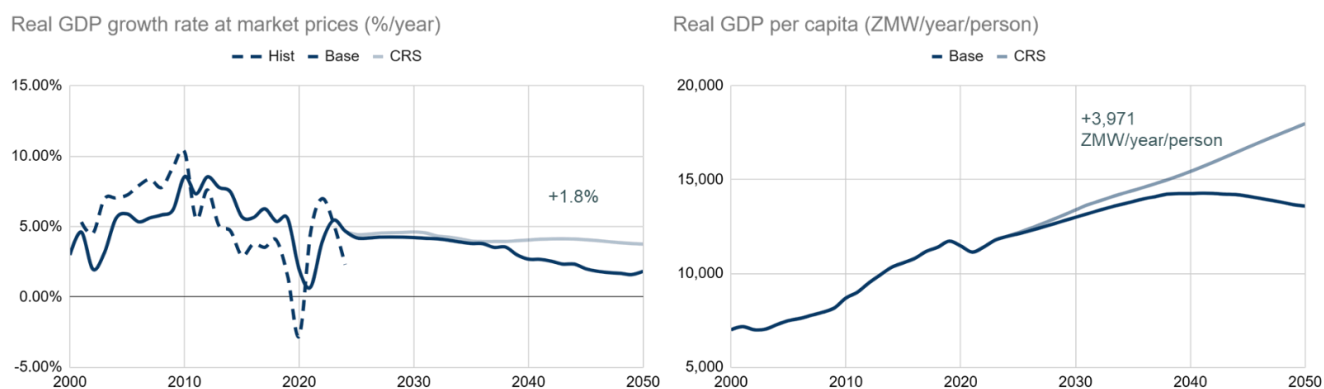


Figure 16. Economic outcomes: GDP growth rate (%/year) and GDP per capita (ZMW/year/person).

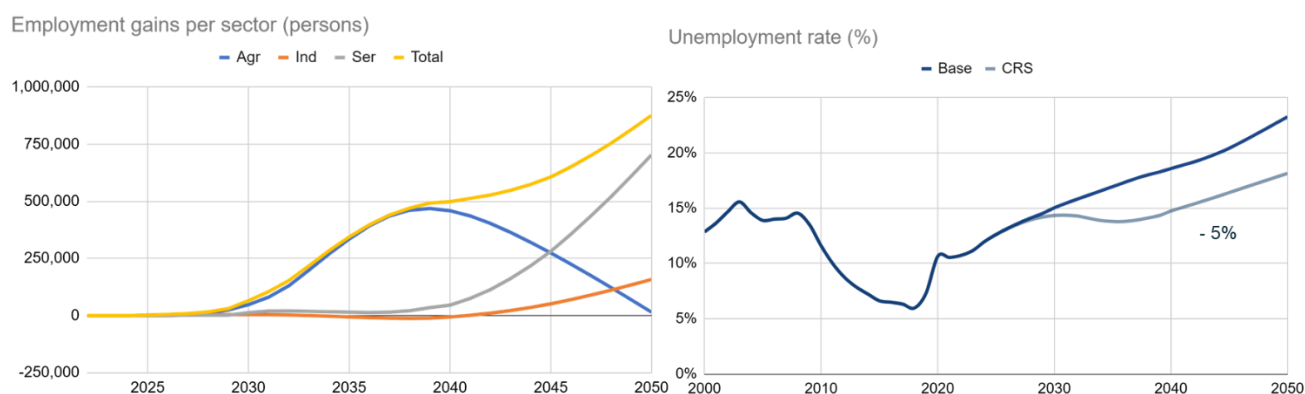


Figure 17. Employment and unemployment outcomes. Gains in employment by sector in the CRS scenario (left).

Total employment grows significantly over time, with 875 000 additional persons employed across sectors by 2050, under the CRS scenario (Figure 17), with the services sector emerging as the dominant employer. While agriculture initially holds a large share of employment, particularly in the short-term, its contribution declines over time, reflecting a structural shift toward higher-value sectors. As a result, the CRS scenario similarly reflects a 5% reduction in unemployment by 2050 (absolute value = 18%), whereas unemployment in the baseline scenario continues to increase, reaching 23% in 2050. This highlights the CRS pathway's role in supporting economic transformation and labor market resilience.

6.4.1 Debt

Figure 11 presents trends in Zambia's public domestic debt, in terms of government spending in relation to GDP and the Debt-to-GDP ratio under the model scenarios.

In the absence of targeted debt re-structuring interventions, the government deficit remains constant at a level of approximately 5% of GDP until 2050, though under the CRS scenario, the government deficit narrows by -0.5% over time, suggesting modest improvements in revenue generation or expenditure control. Domestic debt as a share of GDP rises in both scenarios, though it remains lower under the CRS pathway. By 2050, the CRS scenario achieves a reduction of 8 percentage points in the debt-to-GDP ratio compared to the baseline, indicating a more sustainable fiscal trajectory. This trend highlights Zambia's reliance on borrowing for development, though climate financing does play a minor role in supporting the development and addressing the broader debt challenge.

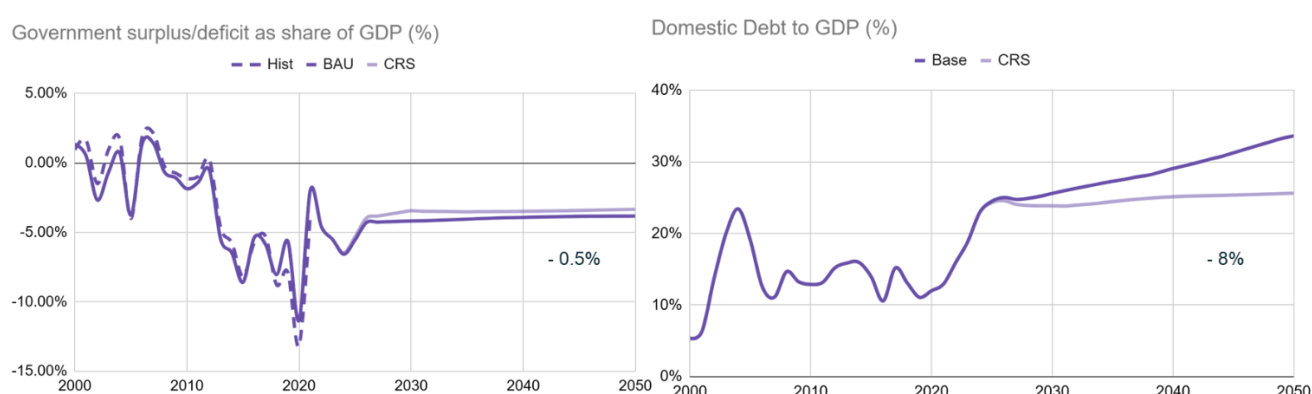


Figure 18. Government spending in proportion to GDP (%) and public domestic debt to GDP (%).

6.4.2 Mining

The Zambian economy is highly dependent on mining, particularly copper, which accounts for a significant portion of GDP (~10-15% depending on global market conditions), exports (70% of total export earnings), and government revenue (Republic of Zambia, 2022). Climate adaptation and mitigation are crucial to improve resilience of the mining sector, particularly from arising impacts from electricity shortages that disrupt mining operations (Republic of Zambia, 2022)

In this context, the CRS scenario results in a 4 billion ZMW increase in gross value added in the mining sector by 2050 (Figure 19). This is because of increased metal ores extraction, with

a projected increase of 102 million tonnes/year (Figure 19), as a result of combined positive effects from additional expenditure in electricity generation (predominantly solar), industry innovation and gross capital formation in the mining sector.

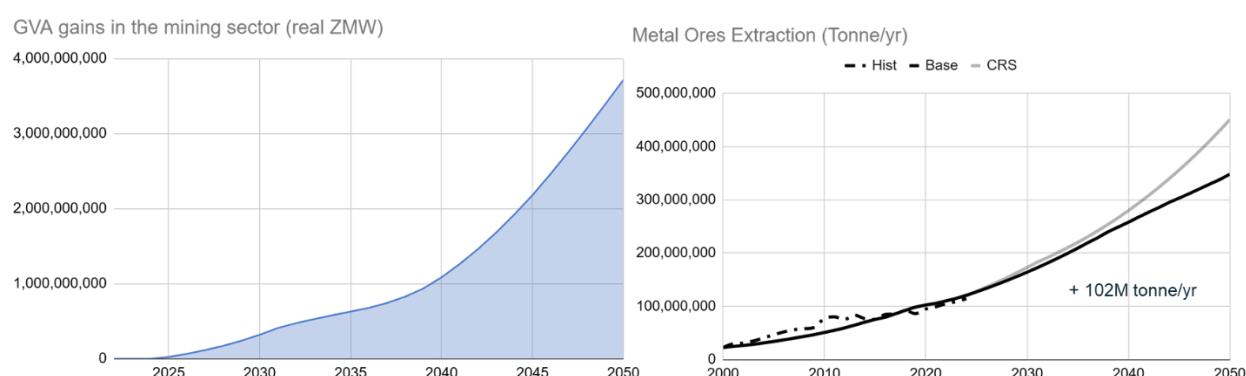


Figure 19. Gross value added in the mining sector in the CRS scenario (left) and change in metal ores extraction in tonne/yr (right).

6.4.3 Agriculture

Figure 20 highlights agricultural Gross Value Added (GVA) by sector. Agriculture provides livelihoods for much of the population and is central to food security and economic stability, yet it remains highly exposed to climate variability and shocks. The crops and livestock sector (A01) dominates GVA gains under the CRS scenario, suggesting it is the primary driver of agricultural growth, while A02 and A03 make smaller but increasing contributions. The overall upward trend indicates a steady expansion in agricultural output, reflecting improvements in productivity resulting from additional expenditure into key agricultural interventions in the CRS scenarios, including agricultural training, agricultural investment, fertilizer subsidies, and access to water efficiency solutions. The CRS thereby increases gross value added by a total of 3.5 billion ZMW by 2050 (Figure 20).

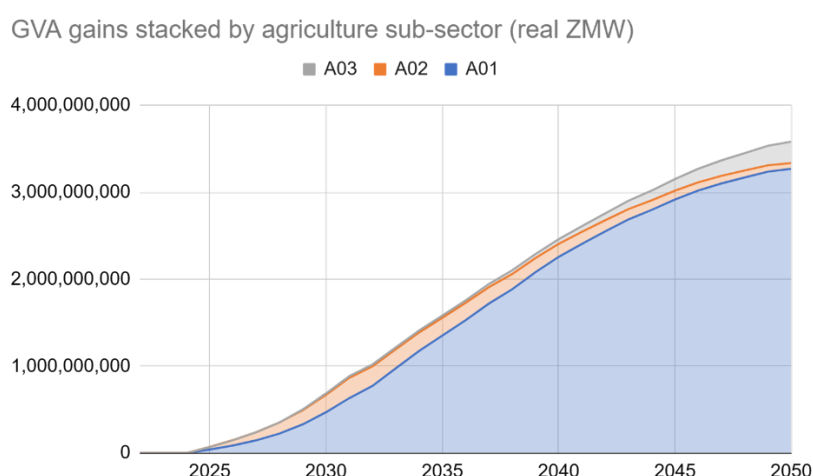


Figure 20. Gross value added by agriculture economic category under the CRS scenario. A01- crops and livestock, A02 – forestry and A03 – fish capture and harvest.

Increased value creation in the crops and livestock sub-sector under the CRS scenario are additionally attributed to increased production from cereal and non-cereal crops, showing an increase of 9.6million tonnes/year for non-cereal crops and 1.3 million tonnes/year for cereal crops (Figure 21). This is because interventions through the CRS scenario enhance the resilience of crop yields against unfavorable climate conditions. Though these long-term trends fail to project impacts from future climate shocks they highlight the role of climate adaptation in boosting long-term productivity in the agricultural sector.

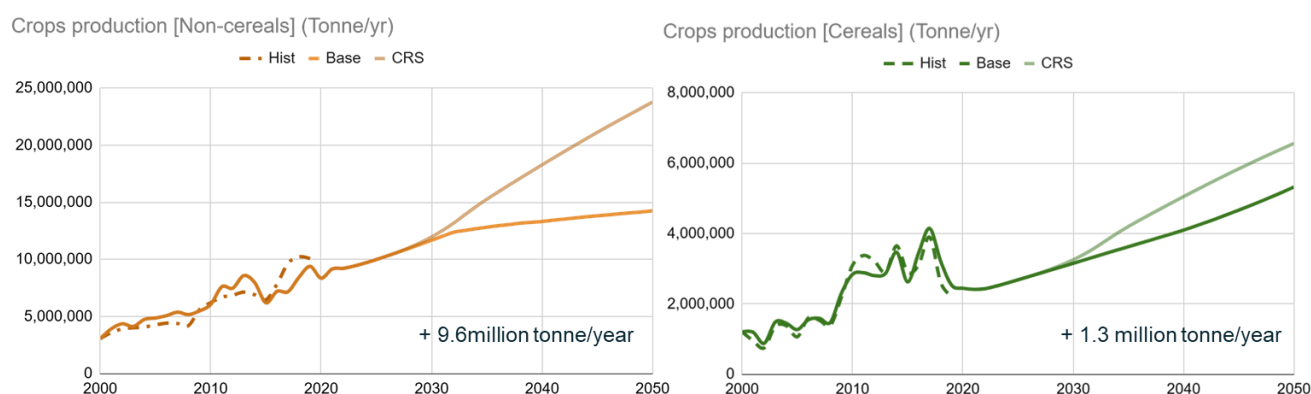


Figure 21. Crop production in tonne/year for non-cereal (left) and cereal crops (right).

6.4.4 Energy

Zambia's energy supply is largely dependent on hydropower, which generates over 80% of the country's electricity. However, the sector faces significant challenges from prolonged droughts that lower water levels and constrain generation capacity. Additionally, rising electricity demand from industries such as mining and agriculture, along with shifting access patterns between rural and urban areas, is driving increased electricity consumption. This is evident in trends in electricity generation and consumption as shown in the baseline projection (Figure 22). Investments in the energy sector are shown to result in an additional ~14 TWh/yr by 2050 under the CRS scenario (Figure 22), remaining above required consumption patterns.

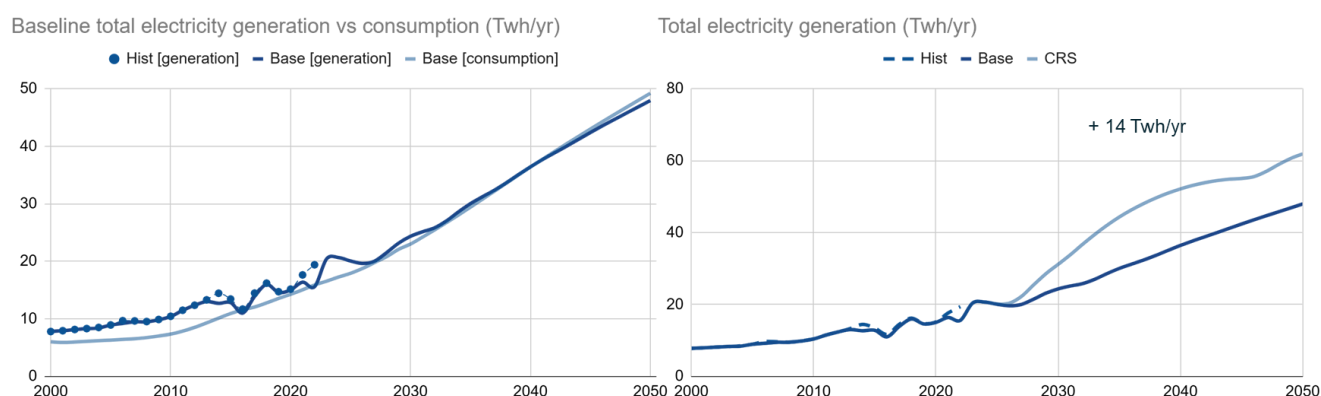


Figure 22. Zambia's baseline total electricity generation and consumption (left) and change in electricity generation in the CRS (right) in TWh/year.

This increase is due to increased electricity generation from both centralized and decentralized investments in solar photovoltaic, in addition to continual expenditure on hydro power sources, followed by smaller generation shares in coal, oil and gas resulting in a total generation of 60 Twh/year (Figure 23). This result highlights the importance of renewables in the CRS pathway, supporting higher electricity generation, energy diversification in providing long-term energy resilience. While the investment in solar power capacity simulated in the CRS reflect conventional systems, the characteristics of the energy sector in Zambia suggest that floating solar systems, deployed on large water reservoirs, could reduce evaporation and thus simultaneously increase hydropower output (Gonzalez Sanchez *et al.*, 2021).

Historically, Zambia experienced periods of net electricity exports up to 2020, reflecting its reliance on hydropower for domestic needs and surplus for trade (Figure 23) (Energy Regulation Board, 2023). The high reliance on hydropower further makes the electricity market highly vulnerable to droughts and future climate impacts. Post-2020, the baseline scenario shows a long-term shift towards electricity imports driven by exceeding electricity consumption relative to generation (Figure 22). Under the baseline, imports steadily increase to 9.5 Twh/year by 2050 (Figure 23). In contrast, the CRS scenario shows lower reliance on electricity imports, but rather potential for exports, peaking in 2038 at 4.8Twh/year, but slowly returning to reliance on imports, though much lower than in the baseline scenario (4.4 Twh/year) by 2050.

Lastly, historical trends in access to electricity are closely aligned with data observations from the (ZAMSTAT, 2023), which reports that 53.6% of total households at a national level has access to electricity, comprised of 34% of households in rural areas compared to 80.3% in urban areas. Future trends suggest a continual increase under the baseline scenario such that total national access to electricity in 2050 reaches 71% (Figure 24). The CRS scenario further increases overall access by 4%, such that access to electricity achieves 75% in 2050 (Figure 24).

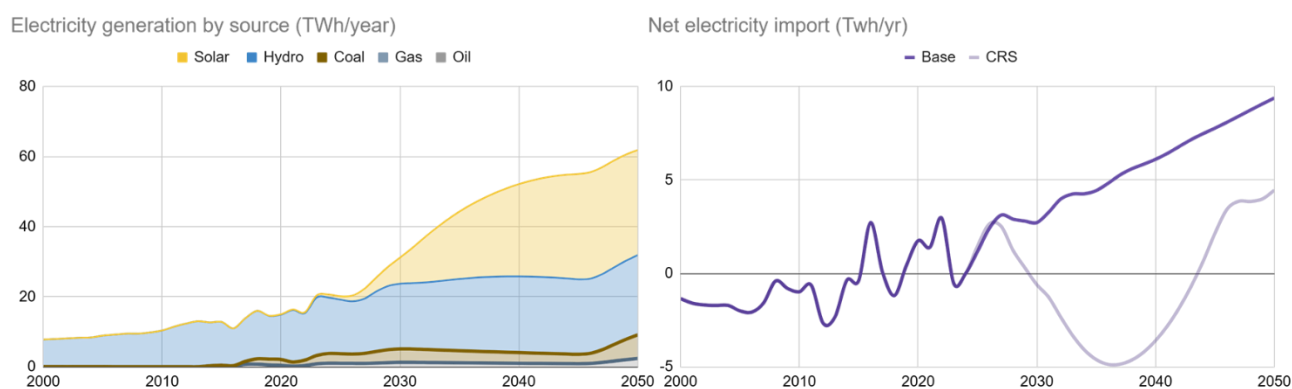


Figure 23. Electricity generation by source in the CRS scenario (left) and net electricity imports in Twh/yr, a positive representing import and negative corresponding to exports.

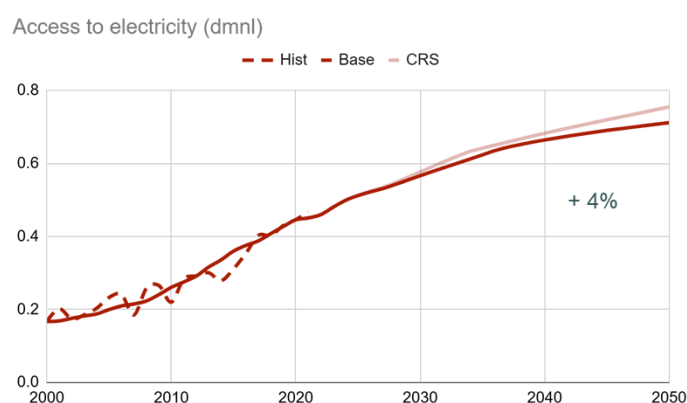


Figure 24. Average proportion of the population across urban and rural areas with access to electricity

6.5 Environmental Outcomes

From 2000 to 2020, total GHG emissions in CO_{2eqv} rose steadily, surpassing 34 million tonnes/year in 2024. Under the baseline scenario, emissions continue to rise, reaching 65 million tonnes/year by 2050 (Figure 25). The CRS scenario reduces total emissions in the long-term by 9.6 million tonnes/year by 2050 (Figure 25), but similarly shows an increasing trend, driven by development across economic activities. These results highlight the challenge of decoupling economic growth from carbon emissions, underscoring the need for stronger low-carbon policies and renewable energy investments to curb emissions in line with the NDCs.

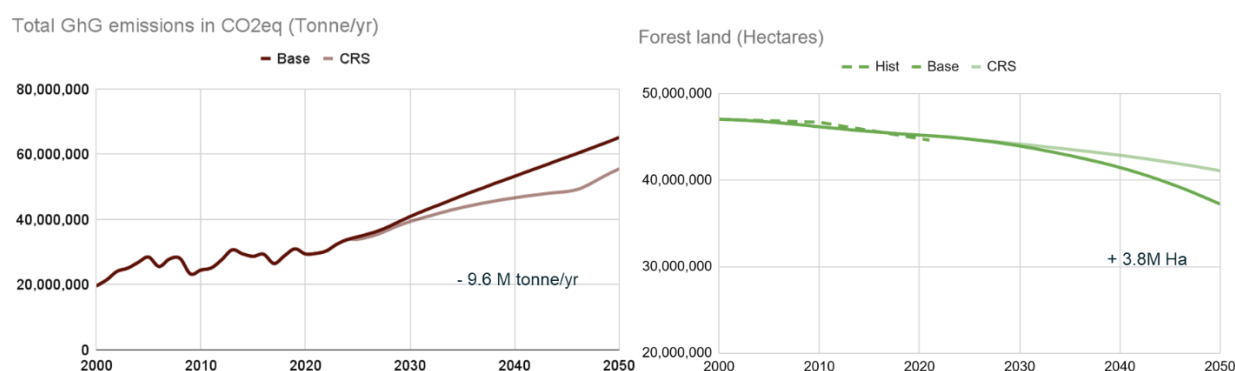


Figure 25. Total GhG emissions in CO_{2eq} (tonne/yr) and change in forest land under the modelled scenarios.

A decline in forest land in Zambia is evident as supported by the model results (Figure 25). From 2000 to 2024, forest cover steadily decreased from just under 50 million hectares to approximately 45 million hectares, primarily due to deforestation and land-use changes. Projections under the baseline scenario indicate a continued decline, with forest land falling to around 37 million hectares by 2050. The CRS scenario, while also showing a decline, moderates the loss, maintaining forest cover closer to 41 million hectares by mid-century. These results highlight the ongoing pressure on Zambia's forests, driven by agricultural expansion, energy needs, and unsustainable land practices (Republic of Zambia, 2014). The CRS pathway demonstrates the potential for better forest conservation through climate

resilience strategies, emphasizing the importance of implementing sustainable land management and reforestation initiatives to slow deforestation and protect ecosystems.

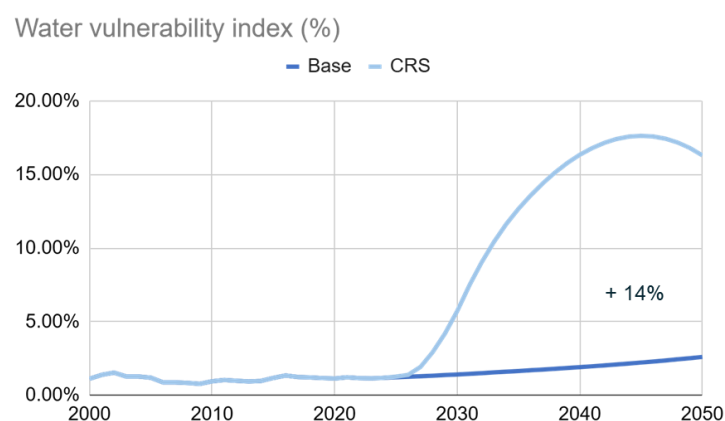


Figure 26. Change in the water vulnerability index measured as the ratio of total water withdrawal relative to total water supply

In terms of freshwater resources, Figure 26 shows the water vulnerability index (%), which measures the ratio of total water withdrawal relative to total water supply. Initially, both scenarios exhibit stable trends, but post-2024 water vulnerability experiences an increase above the baseline scenario. By 2050, water vulnerability is 14% higher under CRS, suggesting that despite resilience measures, pressures on water resources continue to grow due to increased water withdrawal from agriculture and industry sectors, despite interventions in water efficiency (Figure 26). This trend highlights the increasing risks of water scarcity, likely driven by climate change, rising demand, or reduced water availability, emphasizing the need for stronger water management strategies in an increasingly warmer and drier climate.

7. Summary of Results

The iSD climate threat analysis highlights the advantages of investing the Climate Resilience Scenario (CRS) over the baseline scenario across multiple sectors and national development goals, demonstrating the benefits of implementing climate adaptation and mitigation measures. In terms of human well-being, the CRS delivers notable gains in the HDI, and related sub-indicators (GNI, education, and life expectancy) underscoring the long-term benefits of investing in climate resilience. While progress toward SDGs is evident in areas such as poverty, hunger, education, infrastructure, economic growth, climate action and land conservation, other goals require more targeted interventions to address remaining and unintended challenges (water access, inequality, consumption, and government accounts). Demographically, the CRS moderates population growth through accelerated reductions in fertility rates. Both poverty and inequality improve, with CRS achieving greater reductions and promoting equitable economic growth. Economic performance under CRS surpasses the baseline, unlocking higher GDP growth and raising living standards, while also decreasing unemployment.

In agriculture, CRS supports sustained growth in crop production and highlights the need for targeted interventions such as agricultural training for sustainable land management and efficient irrigation methods. The energy sector shows a cleaner, more diversified mix under

CRS, with stronger solar uptake augmenting Zambia's reliance on hydropower, ensuring energy security and supporting economic growth. Lastly, the environmental results emphasize the importance of stronger low-carbon policies to decouple emissions from growth and mitigate deforestation through sustainable land management and reforestation initiatives. Central to the broadly positive impacts on economic indicators is the assumption that financing for the CRS will entirely come through external grants. This contributes to mitigating fiscal stress and boosting economic output, ensuring more manageable debt levels in the long term. These findings reinforce the transformative potential of climate resilience actions in driving inclusive development and promoting socio-economic prosperity in Zambia in the future.

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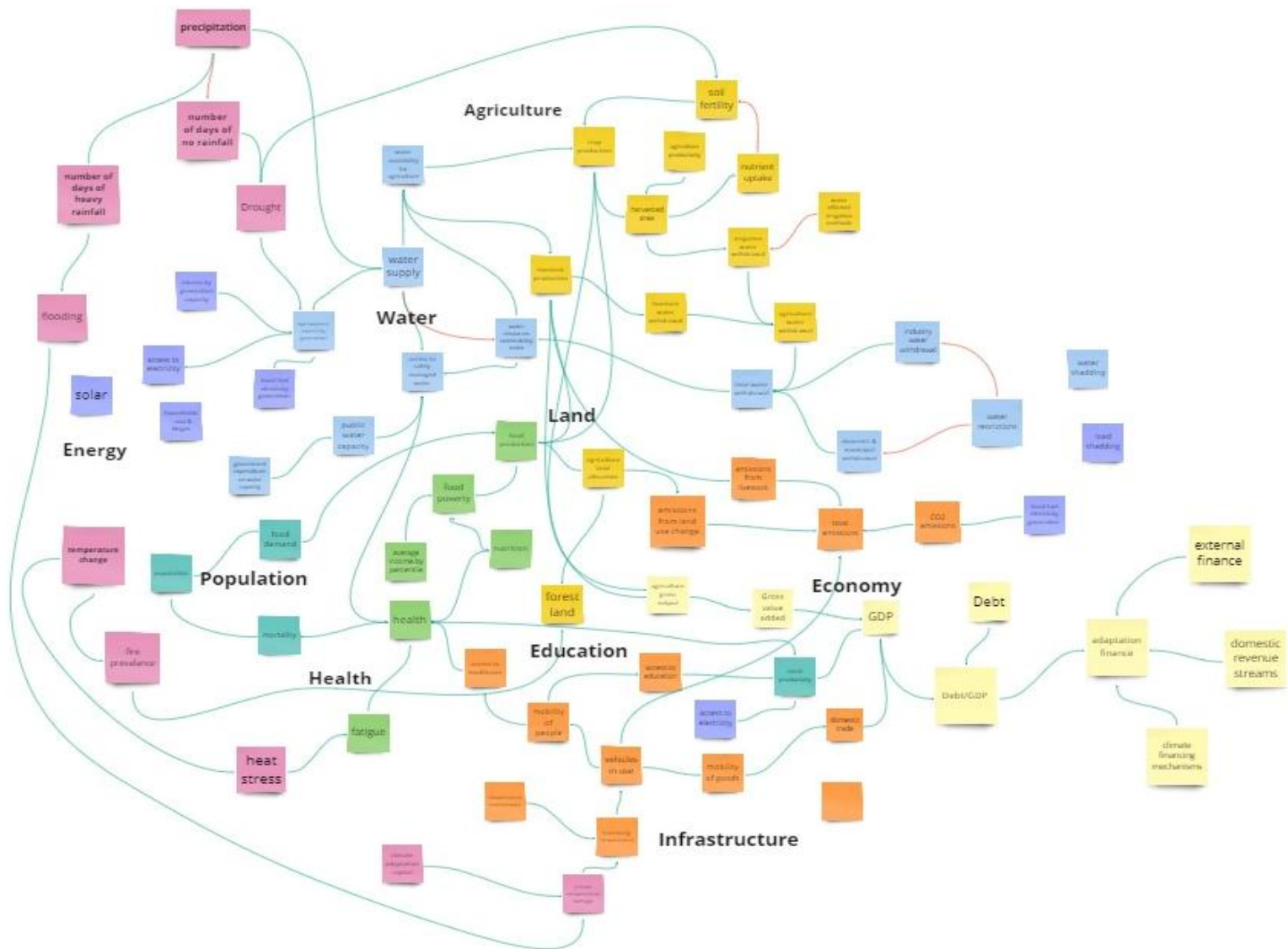
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Appendix A. Climate Threat Pathways Mapping (Workshop 1)



Appendix B: Data Sources

Table 2. Overview of international and national data sources used in the iSD model.

Variable	International Data Source
Government Finance Statistics	General government level data or Budgetary Central Government level data IMF: https://data.imf.org/?sk=a0867067-d23c-4ebc-ad23-d3b015045405&sld=1544448210372
Balance of Payments	IMF: https://data.imf.org/regular.aspx?key=62805740
GDP	UN Statistics: http://data.un.org/Explorer.aspx Where available, we prioritize ISIC Rev. 4 data, and we fall back on ISIC Rev. 3 as necessary. Where available, we aim to represent economic activities at the level of sections, e.g. B - Mining and Quarrying, C - Manufacturing, F - Construction and so on. Where not available, we aggregate economic sectors.
Employment	ILOSTAT: https://ilostat ilo.org/data/
Demographics	World population prospects: https://population.un.org/wpp/Download/Standard/Population/
Mortality by cause	WHO global health estimates: https://www.who.int/data/gho/data/themes/mortality-and-global-health-estimates/ghs-leading-causes-of-death
Health	World Development Indicators: https://databank.worldbank.org/source/world-development-indicators
Education	World Development Indicators: https://databank.worldbank.org/source/world-development-indicators
Population by education level	Barro-Lee dataset: https://github.com/barrolee/BarroLeeDataSet/blob/master/README.md
Energy Balances	International Energy Agency: https://www.iea.org/data-and-statistics/data-tables?country=WORLD
Electricity Generation Capacity by Source	Energy Information Agency: https://www.eia.gov/international/data/world/electricity/electricity-capacity

Temperature and Precipitation	Climate Knowledge Portal: https://climateknowledgeportal.worldbank.org/download-data
Water Supply and Withdrawal	AQUASTAT: https://www.fao.org/aquastat/statistics/query/index.html
Material consumption and trade	Global Material Flows database: https://www.resourcepanel.org/global-material-flows-database
Agriculture	FAOSTAT: https://www.fao.org/faostat/en/#data
Fishery and Aquaculture	FAO Fisheries Division: https://www.fao.org/fishery/en
Forestry	FAOSTAT: https://www.fao.org/faostat/en/#data
Poverty	World Development Indicators: https://databank.worldbank.org/source/world-development-indicators#
Income Inequality	World Inequality Database: https://wid.world
Transportation Infrastructure	World development Indicators: https://databank.worldbank.org/source/world-development-indicators# or International Road Federation: https://irfofficial.org/
Rural Access index	World Bank: https://datacatalog.worldbank.org/search/dataset/0038250
Vehicles	OICA: https://www.oica.net/category/vehicles-in-use/
Access to Electricity	World Development Indicators: https://databank.worldbank.org/source/world-development-indicators#
Water and Sanitation	World Development Indicators: https://databank.worldbank.org/source/world-development-indicators#
Waste collection and disposal	World Development Indicators: https://databank.worldbank.org/source/world-development-indicators#

Appendix C: Model Calibration Summary

Table 3. Summary statistics for the key performance indicators used to assess the goodness-of-fit of model data to historical data. *N* represents the number of data points. Data coverage indicates the availability of data (2000-2022). R^2 measures the coefficient of determination. RMSPE is a measure of the Root-Mean-Squared-Percentage-Error, decomposed into Theil statistics *Um* (Theil bias), *BPE* (the Bias percentage error) and *Us* (Variation) and *Uc* (Covariation).

Variable	N	Data Coverage	R^2	RMSPE	BPE	Um	Us	Uc	Sector
Ael.average proportion of population with access to electricity	22	0.96	0.93	0.10	0.00	0.00	0.03	0.97	Access to Electricity
Aws.access to safely managed sanitation facility[rural]	23	1.00	0.97	0.83	0.58	0.70	0.28	0.01	Access to Water and Sanitation
Aws.access to safely managed sanitation facility[urban]	23	1.00	0.41	0.07	0.01	0.21	0.01	0.78	
Aws.access to safely managed water source[rural]	23	1.00	0.78	0.19	0.15	0.81	0.03	0.16	
Aws.access to safely managed water source[urban]	23	1.00	0.55	0.09	0.01	0.06	0.81	0.14	
Bxp.total export share of GDP	23	1.00	0.68	0.13	0.02	0.14	0.03	0.83	Export
Eys.average years of schooling[FEMALE]	4	0.17	0.99	0.01	0.00	0.11	0.14	0.75	Years of Schooling
Eys.average years of schooling[MALE]	4	0.17	0.93	0.02	0.00	0.04	0.09	0.87	
Fgr.gross international reserves	23	1.00	0.80	0.37	0.02	0.05	0.09	0.86	Gross International Reserves
Hgn.gini coefficient	22	0.96	0.89	0.02	0.00	0.05	0.04	0.91	Global Gini Coefficient
Hgn.income share by quintile[qnt 1]	23	1.00	0.69	0.63	0.20	0.32	0.54	0.13	
Hgn.income share by quintile[qnt 2]	23	1.00	0.83	0.11	0.05	0.45	0.25	0.31	
Hgn.income share by quintile[qnt 3]	23	1.00	0.00	0.19	0.01	0.06	0.01	0.94	
Hgn.income share by quintile[qnt 4]	23	1.00	0.29	0.07	0.00	0.01	0.05	0.94	
Hgn.income share by quintile[qnt 5]	23	1.00	0.68	0.03	0.00	0.05	0.17	0.78	
Hip.proportion of population below international poverty line	5	0.22	0.36	0.06	0.02	0.27	0.03	0.70	International Poverty

Hnp.proportion of population below national poverty line	2	0.09	1.00	0.11	0.03	0.24	0.22	0.55	National Poverty
Hsv.private saving	22	0.96	0.98	3.66	0.89	0.24	0.56	0.19	Households Saving
Hsv.real private saving	22	0.96	0.96	3.66	0.76	0.21	0.54	0.26	
Jes.employment by sector[A01]	23	1.00	0.96	0.05	0.00	0.04	0.15	0.81	Employment by Sector
Jes.employment by sector[A02]	23	1.00	0.83	0.09	0.02	0.20	0.13	0.68	
Jes.employment by sector[A03]	23	1.00	0.95	0.07	0.00	0.01	0.00	0.99	
Jes.employment by sector[B]	23	1.00	0.74	0.12	0.00	0.01	0.00	0.99	
Jes.employment by sector[C]	23	1.00	0.92	0.12	0.04	0.30	0.33	0.38	
Jes.employment by sector[D]	23	1.00	0.84	0.20	0.00	0.00	0.13	0.87	
Jes.employment by sector[E]	23	1.00	0.05	0.73	0.05	0.07	0.32	0.61	
Jes.employment by sector[F]	23	1.00	0.90	0.30	0.00	0.01	0.23	0.76	
Jes.employment by sector[G]	23	1.00	0.98	0.05	0.01	0.18	0.18	0.64	
Jes.employment by sector[H]	23	1.00	0.82	0.12	0.02	0.19	0.00	0.81	
Jes.employment by sector[I]	23	1.00	0.99	0.05	0.01	0.17	0.27	0.55	
Jes.employment by sector[J]	23	1.00	0.93	0.27	0.00	0.00	0.41	0.59	
Jes.employment by sector[K]	23	1.00	0.88	0.11	0.01	0.12	0.16	0.72	
Jes.employment by sector[L]	23	1.00	0.85	0.16	0.00	0.00	0.30	0.69	
Jes.employment by sector[M]	23	1.00	0.81	0.27	0.00	0.00	0.45	0.55	
Jes.employment by sector[N]	23	1.00	0.66	0.23	0.00	0.00	0.33	0.67	
Jes.employment by sector[O]	23	1.00	0.66	0.19	0.08	0.45	0.00	0.55	
Jes.employment by sector[P]	23	1.00	0.96	0.22	0.04	0.17	0.73	0.11	
Jes.employment by sector[Q]	23	1.00	0.89	0.19	0.01	0.08	0.67	0.25	
Jes.employment by sector[R]	23	1.00	0.56	0.33	0.00	0.00	0.39	0.61	
Jes.employment by sector[S]	23	1.00	0.95	0.20	0.01	0.03	0.51	0.47	
Jes.employment by sector[T]	16	0.70	0.85	0.20	0.04	0.22	0.58	0.20	

Kva.real GVA by sector at basic prices[A01]	23	1.00	0.12	0.11	0.00	0.00	0.11	0.89	Gross Value Added
Kva.real GVA by sector at basic prices[A02]	23	1.00	0.71	0.11	0.06	0.58	0.26	0.17	
Kva.real GVA by sector at basic prices[A03]	23	1.00	0.51	0.12	0.02	0.20	0.10	0.70	
Kva.real GVA by sector at basic prices[B]	23	1.00	0.96	0.06	0.01	0.23	0.03	0.74	
Kva.real GVA by sector at basic prices[C]	23	1.00	0.95	0.19	0.16	0.83	0.01	0.16	
Kva.real GVA by sector at basic prices[D]	23	1.00	0.92	0.11	0.01	0.07	0.17	0.77	
Kva.real GVA by sector at basic prices[E]	23	1.00	0.15	0.53	0.18	0.35	0.49	0.17	
Kva.real GVA by sector at basic prices[F]	23	1.00	0.88	0.21	0.03	0.13	0.51	0.36	
Kva.real GVA by sector at basic prices[G]	23	1.00	0.82	0.18	0.07	0.39	0.00	0.61	
Kva.real GVA by sector at basic prices[H]	23	1.00	0.73	0.20	0.01	0.04	0.00	0.96	
Kva.real GVA by sector at basic prices[I]	23	1.00	0.85	0.26	0.09	0.34	0.37	0.28	
Kva.real GVA by sector at basic prices[J]	23	1.00	0.92	0.38	0.14	0.37	0.57	0.05	
Kva.real GVA by sector at basic prices[K]	23	1.00	0.92	0.23	0.10	0.44	0.35	0.21	
Kva.real GVA by sector at basic prices[L]	23	1.00	0.84	0.20	0.04	0.20	0.30	0.50	
Kva.real GVA by sector at basic prices[M]	23	1.00	0.96	0.09	0.02	0.17	0.00	0.83	
Kva.real GVA by sector at basic prices[N]	23	1.00	0.22	0.23	0.02	0.07	0.10	0.83	
Kva.real GVA by sector at basic prices[O]	23	1.00	0.94	0.15	0.07	0.50	0.31	0.19	
Kva.real GVA by sector at basic prices[P]	23	1.00	0.95	0.08	0.02	0.24	0.13	0.63	
Kva.real GVA by sector at basic prices[Q]	23	1.00	0.84	0.13	0.01	0.09	0.00	0.91	
Kva.real GVA by sector at basic prices[R]	23	1.00	0.34	0.54	0.02	0.03	0.01	0.96	
Kva.real GVA by sector at basic prices[S]	23	1.00	0.88	0.16	0.03	0.18	0.23	0.58	
Kva.real GVA by sector at basic prices[T]	16	0.70	0.97	0.06	0.02	0.30	0.31	0.39	Gross Value Added
Lus.agriculture land[cropland]	22	0.96	0.91	0.05	0.01	0.27	0.03	0.70	Land Use
Lus.agriculture land[pasture land]	22	0.96	0.23	0.02	0.01	0.39	0.45	0.16	
Lus.forest land	22	0.96	0.91	0.01	0.00	0.11	0.30	0.59	
Mte.domestic material consumption	20	0.87	0.95	0.10	0.05	0.47	0.02	0.51	Total Material Extraction

Ple.life expectancy[FEMALE]	23	1.00	0.95	0.03	0.00	0.00	0.44	0.56	Life Expectancy
Ple.life expectancy[MALE]	23	1.00	0.93	0.03	0.00	0.02	0.34	0.65	
Ppg.population by gender[FEMALE]	22	0.96	1.00	0.01	0.00	0.60	0.08	0.32	Population Groups
Ppg.population by gender[MALE]	22	0.96	1.00	0.01	0.00	0.24	0.43	0.33	
Ptf.total fertility rate	23	1.00	0.99	0.02	0.01	0.40	0.19	0.41	Total Fertility Rate
Qcp.yield[crop 1]	20	0.87	0.35	0.13	0.00	0.01	0.09	0.90	Crops Production in Tonnes
Qcp.yield[crop 2]	20	0.87	0.79	0.09	0.00	0.00	0.23	0.77	Crops Production in Tonnes
Qfc.relative fish capture in tonnes[fish 1]	22	0.96	0.49	0.13	0.00	0.03	0.27	0.70	Fish Capture in Tonnes
Qfh.relative fish harvest in tonnes[fish 1]	22	0.96	0.91	0.36	0.04	0.11	0.17	0.72	Fish Harvest in Tonnes
Qfm.relative forestry production in cubic meters[wood 1]	23	1.00	0.18	0.18	0.15	0.84	0.02	0.14	Forest Production in Cubic Meters
Qlp.livestock production in tonnes per hectare[animal 1]	20	0.87	0.89	0.06	0.00	0.00	0.09	0.91	Livestock Production in Tonnes
Rba.average access to basic health care	7	0.30	0.96	0.05	0.01	0.13	0.19	0.69	Access to Basic Healthcare
Snb.soil primary nitrogen balance	20	0.87	0.97	0.30	0.19	0.62	0.07	0.32	Nutrient balance
Tfi.infrastructure[rail]	16	0.70	0.85	0.03	0.00	0.10	0.84	0.05	Functioning Infrastructure
Tfi.infrastructure[roads a]	21	0.91	0.45	0.09	0.06	0.70	0.09	0.21	
Tfi.infrastructure[roads b]	21	0.91	0.36	0.10	0.07	0.68	0.30	0.03	
Tvp.total vehicles by body and engine[freight and bus, ic]	12	0.52	0.86	0.12	0.07	0.55	0.01	0.43	Road Vehicles Park
Tvp.total vehicles by body and engine[passenger cars, ic]	12	0.52	0.96	0.15	0.03	0.22	0.01	0.77	Road Vehicles Park
Vcs.total final energy consumption by sector[agr]	21	0.91	0.84	0.33	0.00	0.00	0.61	0.39	Final Energy Consumption by Sector
Vcs.total final energy consumption by sector[ind]	21	0.91	0.86	0.08	0.01	0.13	0.00	0.87	

Vcs.total final energy consumption by sector[oth]	21	0.91	0.93	0.09	0.03	0.29	0.37	0.34	
Vcs.total final energy consumption by sector[res]	21	0.91	0.96	0.04	0.00	0.10	0.42	0.48	
Vcs.total final energy consumption by sector[ser]	21	0.91	0.45	0.15	0.02	0.14	0.07	0.79	
Vcs.total final energy consumption by sector[tra]	21	0.91	0.97	0.12	0.06	0.51	0.34	0.15	
Vcv.final energy consumption[BIO]	21	0.91	0.99	0.02	0.00	0.11	0.43	0.47	
Vcv.final energy consumption[COAL]	15	0.65	0.62	0.13	0.01	0.04	0.37	0.59	
Vcv.final energy consumption[ELE]	21	0.91	0.87	0.13	0.03	0.21	0.25	0.54	
Vcv.final energy consumption[OIL]	21	0.91	0.95	0.10	0.03	0.26	0.38	0.37	
Wap.total water withdrawal	21	0.91	0.00	0.07	0.04	0.61	0.28	0.11	Water acquisition probability
Xco.CO2 emissions	23	1.00	0.97	0.15	0.01	0.04	0.32	0.64	Co2 Emissions

Appendix D: Baseline Data Assumptions

Table 4. Future baseline assumptions for exogenous variables. Latest data point was 2022, though where data was not available for 2022 additional assumptions were made.

Variable (units)	BAU assumption
Private factor income as share of gdp (%)	2022: -1 2050: 0
World GDP growth rate (%/yr)	Based on SSP scenarios, specifically SSP2. Data: IIASA Energy program
US average years of schooling (years)	2030: 14.2 2050: 15.2
Domestic debt changes from other sources (LCU)	2015: 0 Used to stabilize projection 2022: 0 as departure point for projection

Reference interest rate on domestic debt (%)	Interest rate for the BAU is estimated to decrease for the first 5-years of the simulation under the assumption of stabilizing debt 2022: 25 2023: 20 2024: 15 2025: 10 2026: 5
Foreign debt from other sources (USD)	2022: 0
Consumption shares of government expenditure	2022: Based on the 5-year average from 2017-2021
Government compensation of employees as share of consumption	
Government expenditure as share of GDP by main category (%)	2022: estimate to be equivalent to 2021 [adaptation exp] = 0 [administrative etc] = 14 [agriculture exp] = 0.6 [education exp] = 2.5 [energy exp] = 0 [grants] = 0 [health exp] = 2 [land protection exp] = 0 [marine protection exp] = 0 [sanitation exp] = 0 [social benefits and transfers] = 0.2 [transportation exp] = 0.1 [waste exp] = 0 [water exp] = 0
Target expenditure per beneficiary	2022: Based on the 5-year average from 2017-2021
Grants as share of GDP (%)	
Other government revenue as share of GDP (%)	
Taxes on goods and services as share of GDP (%)	
Taxes on income profits and capital gains as share of GDP (%)	
Taxes on international trade as share of GDP (%)	

Labor participation rate (%)	2050: 0.65 Future estimate to stimulate gradual increase in labour participation for the BAU to simulate labour productivity effects in the model
Effect of change in type of crop on yield (%)	2016-2022: estimates to stimulate increased crop [type 1] yields in line with historical data 2016: 0.9 2017: 0.9 2018: 1 2019: 1.2 2020: 1.2 2021: 1.2 2022: 1.2
Operations and maintenance costs by source of energy (USD10/MWh)	2050 assumptions: Oil; Gas; Coal; Hydro; Nuclear; Bio - IEA Projected Costs of Generating Electricity 2020; World Energy Outlook 2021 Solar & Wind: IRENA; IEA World Energy Outlook 2021
Reference electricity capacity cost by source (USD10/kw)	2030 & 2050 assumptions: IRENA; IEA World Energy Outlook 2021
Reference fuel price per mtbu (USD10/MBTU)	2030 & 2050 assumptions: EIA; IEA World Energy Outlook 2021
VALCOE adjustment factor (dmnl)	2030 & 2050: IEA World Energy Outlook 2021
Electricity generation efficiency by source	2035: IEA assumptions
Global average energy intensity (Kg Oil eq./\$1000 GDP 2011 PPP)	2025 & 2030 assumptions: IEA
Relative average global water efficiency (dmnl)	2050: WDI
Cement production non energy emission per ton (dmnl)	WDI and IPCC 2006
GDP bp deflator growth rate	2022-2029: assumption 5% inflation
Heating degree days	Assumptions based on SSP2 4.5 data from the World Bank Climate Change knowledge portal
Cooling degree days	
Expected SPEI drought index in 2050	
Expected temperature change by 2050	
Expected days of heavy precipitation in 2050	
Expected yearly precipitation in 2050	

