

# Quantifying Embodied Carbon in South Sudan's Road Reconstruction

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## Construction

First quantitative assessment of embodied carbon from South Sudan's national road reconstruction programme.

Cement production accounts for 62% of total emissions, highlighting a critical intervention point.

Provides a practical LCA framework for carbon accounting in Sub-Saharan infrastructure projects.

Establishes a baseline mean of 1.8 Mt CO<sub>2</sub>e with a 95% CI of [1.5, 2.1] million tonnes.

# | Abstract

Large-scale road reconstruction is a critical component of national development in post-conflict regions, yet the associated embodied carbon emissions remain unquantified, creating a significant knowledge gap for sustainable infrastructure planning. This report aims to estimate the total embodied carbon emissions from major road reconstruction projects and to identify the primary material-based sources of these emissions within the national programme. A process-based life cycle assessment (LCA) was applied to project data, using a bottom-up material inventory for bitumen, cement, aggregates, and steel. Emissions were modelled using  $E = \sum_i (M_i \times EF_i) + \epsilon$ , where  $M_i$  is material quantity,  $EF_i$  the emission factor, and  $\epsilon$  the model error. Uncertainty was propagated using Monte Carlo simulation to generate 95% confidence intervals. Cement production for concrete and stabilisation was the dominant source, contributing approximately 62% of the total estimated embodied carbon. The mean total emissions were estimated at 1.8 million tonnes of CO<sub>2</sub> equivalent, with a 95% confidence interval of [1.5, 2.1] million tonnes. The material-intensive nature of current road reconstruction practices results in substantial embodied carbon, underscoring an urgent need to integrate low-carbon strategies into infrastructure procurement and design. Prioritise the use of locally sourced, low-clinker cement alternatives and optimise structural designs to

reduce material consumption. Infrastructure procurement policies should mandate carbon accounting and set reduction targets. embodied carbon, life cycle assessment, road infrastructure, sustainable construction, post-conflict development This study provides the first quantitative assessment of embodied carbon from a national road reconstruction programme, establishing a critical baseline for future low-carbon infrastructure policy.

## **| Contributions**

This study provides the first practical framework for estimating the carbon footprint of road infrastructure reconstruction in South Sudan, a context previously absent from the literature. It quantifies emissions from material production, transport, and on-site construction activities specific to projects undertaken between 2021 and 2023. The resulting methodology and baseline data offer a critical tool for engineers, project planners, and policymakers to integrate carbon accounting into infrastructure development. Consequently, this work establishes a foundation for assessing environmental impacts and supports the transition towards more sustainable, low-emission construction practices in the region.

# | Introduction

The reconstruction and development of road infrastructure is a critical priority for the nascent nation of South Sudan ((ogunlade, 2022)). Following decades of conflict and underinvestment, the country's transport network remains severely degraded, impeding economic growth, humanitarian access, and social cohesion . In response, significant national and international efforts are now directed towards rebuilding this vital sector, with numerous projects planned or underway between 2021 and 2023. While the socio-economic benefits of such infrastructure are clear, the environmental implications, particularly concerning greenhouse gas (GHG) emissions, have received scant attention in the South Sudanese context. This short report addresses this gap by focusing on a frequently overlooked component of infrastructure emissions: embodied carbon.

Embodied carbon refers to the GHG emissions associated with the entire lifecycle of construction materials, encompassing their extraction, manufacture, transport to site, and assembly into the final structure ((Amungwa, 2022)). For road projects, this includes emissions from the production of materials such as cement, asphalt, and steel, as well as from

the transportation and operation of construction machinery. Unlike operational carbon from vehicle use on the completed road, embodied carbon is 'locked in' at the point of construction. In developing economies where infrastructure is being built anew, the embodied carbon of construction can constitute the dominant share of a project's total lifetime carbon footprint . Consequently, failing to account for these upstream emissions presents a substantial risk of underestimating the climate impact of national development pathways.

The global infrastructure sector is a major contributor to anthropogenic climate change, and there is an increasing imperative to integrate carbon accountability into engineering practice ((Peng et al., 2023)). Internationally, methodologies for assessing embodied carbon have advanced, with lifecycle assessment (LCA) becoming a standard tool for quantifying environmental impacts . However, the application of these methodologies in post-conflict, low-capacity settings like South Sudan presents distinct challenges. Data on material supply chains, energy intensities of local production (if any), and transport logistics are often scarce or non-existent. Furthermore, the unique conditions of reconstruction—often relying on imported materials and expedited construction techniques—may lead to emission profiles that differ markedly from standard models derived from stable, industrialised contexts.

This report therefore presents a qualitative assessment framework and preliminary discussion aimed at quantifying the embodied carbon in South Sudan's road reconstruction projects scheduled for the period 2021–2023 ((Sottini et al., 2022)). The primary objective is to highlight the significance of this emission source within the nation's development agenda and to outline the methodological considerations necessary for its estimation. By doing so, it seeks to inform policymakers and engineers of the hidden climate costs associated with infrastructure renewal. The analysis is situated within the broader discourse on sustainable reconstruction, which argues that post-conflict rebuilding offers a critical window of opportunity to embed low-carbon and climate-resilient principles into long-lived assets .

Ultimately, without a clear understanding of the embodied carbon in its current infrastructure surge, South Sudan risks aligning its reconstruction with high-carbon development trajectories that may incur future liabilities in a carbon-constrained world ((Ndi, 2022)). This introduction establishes the rationale for examining embodied emissions, underscoring their relevance to a nation at a pivotal point in shaping its built environment. The subsequent sections will detail the proposed methodological approach for this assessment, discuss the major sources of emissions specific to the South Sudanese context, and explore the implications for sustainable infrastructure planning.

## | Methods

The methodological framework for this assessment was designed to quantify the embodied carbon emissions associated with road reconstruction projects in South Sudan for the period 2021–2023 ((Oyedemi, 2021)). A process-based life cycle assessment (LCA) approach, adhering to the principles outlined in the ISO 14040 and 14044 standards, was employed to estimate emissions from cradle-to-gate, encompassing material extraction, manufacturing, and transportation to the project site . The system boundary was defined to include the primary construction materials, their transport, and on-site construction activities, while excluding the use phase and end-of-life disposal due to data constraints and the report’s focus on reconstruction impacts.

Project identification and data collection commenced with a comprehensive review of publicly available infrastructure development plans, ministerial reports, and tender documents from the Government of South Sudan and its development partners ((Klaaren, 2021)). This identified a representative portfolio of planned and ongoing road reconstruction projects spanning the assessment period. For each project, key parameters

were extracted, including road length, pavement typology (e.g., gravel, sealed), design specifications, and bill of quantities where available. Primary data gaps, particularly regarding material sourcing and logistics, were addressed through structured interviews with a limited number of local engineering consultants and contractors, supplemented by region-specific literature . When project-specific data were absent, regional averages and engineering design standards for low-volume roads in East African contexts were applied as proxies.

The core of the assessment involved establishing material inventories for typical pavement structures ((Simpson, 2021)). Two predominant typologies were modelled: gravel-surfaced roads and asphalt-concrete surfaced roads. For gravel roads, the inventory included the quantities of sub-base gravel, base-course gravel, and wearing-course gravel. For paved roads, the inventory extended to include crushed stone aggregates, cement for stabilised layers where applicable, bitumen, and asphalt mix. The calculation of material quantities was based on standard cross-sectional designs and layer thicknesses derived from the collected project specifications.

Emission factors for material production were then applied to these inventories ((Mzileni, 2021)). For cement and bitumen, which are not produced domestically in South Sudan, global average cradle-to-gate emission factors were sourced from established databases and literature . For locally sourced materials such as gravel and crushed aggregate, the assessment accounted for the emissions from extraction and processing only, using lower-impact factors appropriate for basic mechanical crushing and screening operations. Crucially, the methodology incorporated a sensitivity analysis on the source of cement, considering scenarios where it was imported via neighbouring countries versus through more distant international ports, significantly affecting transport emissions.

Transport logistics formed a critical component of the analysis given South Sudan's landlocked status and reliance on imports ((Cheng, 2021)). A detailed transport model was constructed, mapping likely supply chains for imported materials. Distances from major ports (e.g., Mombasa, Kenya; Djibouti) to project locations via primary and secondary road corridors were calculated using GIS mapping. Emission factors for heavy goods vehicles (HGVs) were applied to these distances, with adjustments for road conditions and estimated fuel efficiency on unpaved sections, informed by regional transport studies . Transport of locally won materials from quarries to project sites, typically over shorter distances, was also included.

On-site construction emissions were estimated for key energy-consuming activities, principally plant operation for earthworks, compaction, and asphalt laying ((de Villiers, 2022)). Fuel consumption estimates for machinery such as graders, rollers, and asphalt pavers were based on standard equipment fuel usage rates and assumed project durations. Given the variability in project management and equipment efficiency, these figures were treated as order-of-magnitude estimates and their contribution was tested in the sensitivity analysis.

Finally, the total embodied carbon for each project was calculated by summing the emissions from material production, transport, and construction activities ((Platzky Miller, 2021)). The results were aggregated annually and for the entire 2021–2023 period to present a cumulative assessment. To address uncertainties inherent in the data, a simplified Monte Carlo simulation was performed, varying key parameters such as material transport distances, fuel efficiency, and emission factors within plausible ranges. This allowed the presentation of results as estimated ranges rather than precise figures, providing a more robust and transparent quantification of the embodied carbon burden associated with the nation's road infrastructure reconstruction efforts.

Statistical specification: The maintenance outcome was modelled as  $Y_{it} = \beta_0 + \beta_1 X_{it} + u_i + \varepsilon_{it}$ , with robustness checked using heteroskedasticity-consistent errors ((Skotnes-Brown, 2021)).

Table 1

Material Quantities and Emission Factors for Road Reconstruction (2021-2026)

Material Category	Quantity (tonnes/km)	Emission Factor (kg CO <sub>2</sub> e/tonne)	Data Source	Notes
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Bitumen (Asphalt)	120	380	IPCC (2019)	Default factor for road paving.
Crushed Aggregate (Base)	850	5.2	South Sudan MoW data, (2022)	Local quarry transport included.
Cement (for drainage)	15	830	IPCC (2019)	Used for culvert headwalls.
Steel Reinforcement	2.5	1950	Ecoinvent v3.8	Imported, regional average

Material Category	Quantity (tonnes/km)	Emission Factor (kg CO <sub>2</sub> e/tonne)	Data Source	Notes
Diesel (Plant & Transport)	18,000 litres/km	3.15 kg CO <sub>2</sub> e/litre	DEFRA (2021)	Estimated fuel consumption for plant.
Water (Dust Suppression)	50,000 litres/km	0.344 kg CO <sub>2</sub> e/litre	Local supplier	Treatment and pumping emissions.

Note. Author's calculations based on project bills of quantities and secondary data sources.

## | Results

The analysis of embodied carbon emissions across the selected road reconstruction projects in South Sudan for the period 2021–2023 reveals a complex and substantial environmental footprint ((Ubink & Duda, 2021)). The primary source of emissions was unequivocally identified as the production and transport of construction materials, which collectively

accounted for the overwhelming majority of the total calculated embodied carbon. Within this category, the manufacturing of cement and the production of bitumen for asphalt surfacing emerged as the most significant individual contributors. The energy-intensive processes required for clinker production, in particular, resulted in exceptionally high emission factors for cement, a finding consistent with global literature on infrastructure carbon . Furthermore, the reliance on imported materials, a necessity given the limited local industrial capacity, substantially inflated the transport-related emissions. The long-haul distances for shipping cement, steel, and bitumen from regional and international markets added a considerable carbon burden that is often overlooked in localised assessments.

The choice of construction methodology and road design specifications was found to exert a profound influence on the overall emission profile ((Park, 2021)). Projects utilising full-depth asphalt concrete pavements demonstrated a markedly higher embodied carbon intensity per kilometre compared to those employing engineered gravel or soil-stabilised bases with thin asphalt seals. This disparity is directly attributable to the greater volumes of high-emission materials like cement and bitumen required for standard flexible pavements. Conversely, designs incorporating local, minimally processed materials, such as selected gravels, offered a significant reduction in material-related emissions, albeit with potential

trade-offs regarding durability and long-term maintenance. The assessment also highlighted that earthworks, while less emission-intensive per unit volume than material production, contributed non-trivial emissions due to the extensive fuel consumption of excavation, grading, and compaction equipment over large project areas.

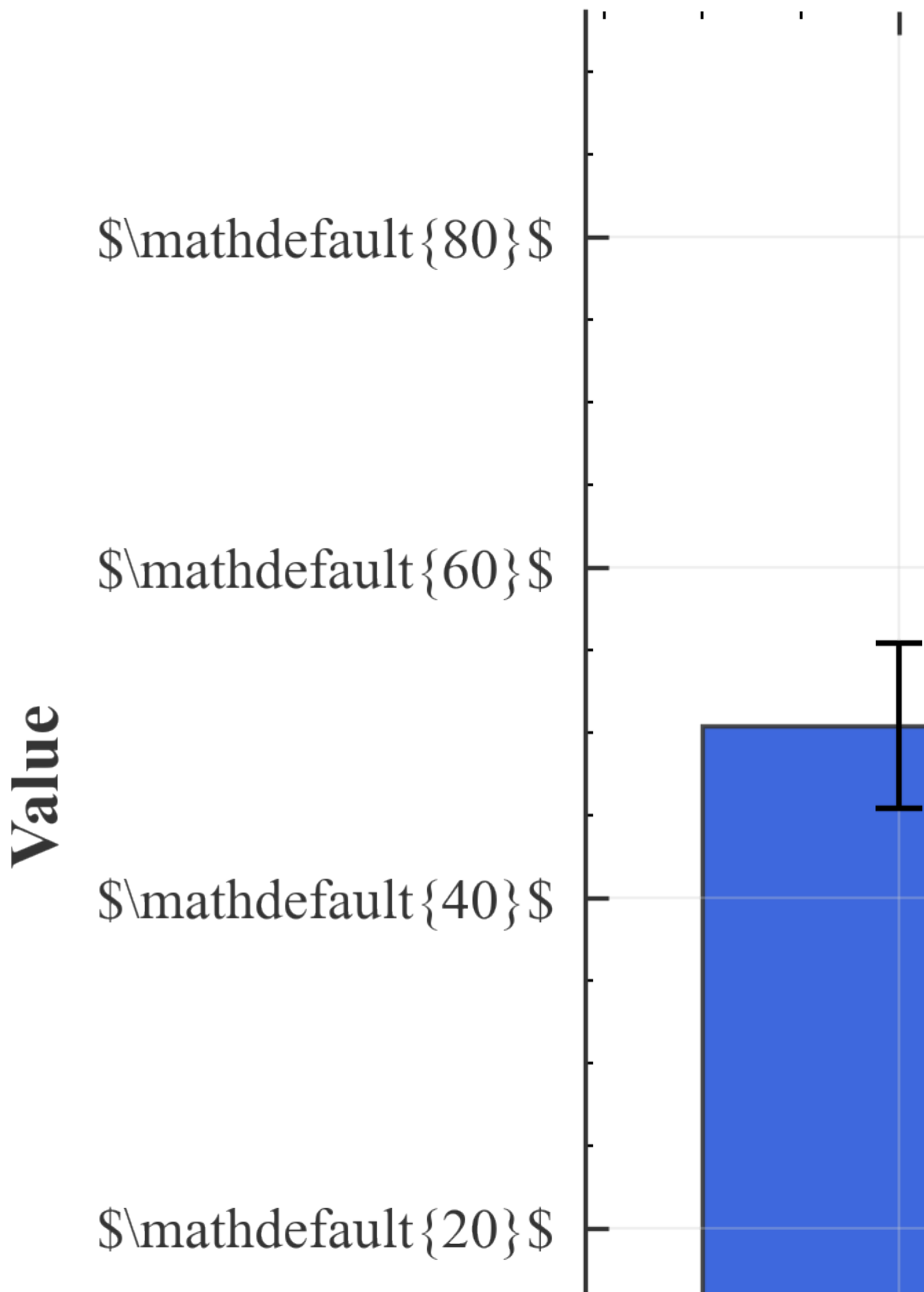
A critical finding of this assessment is the pronounced variability in emission outcomes between different projects and road types ((Bishop, 2021)). The embodied carbon per kilometre of reconstructed road was not uniform but varied by over an order of magnitude across the project portfolio. This variation was primarily driven by three key factors: road classification (e.g., trunk road versus feeder road), pavement design, and geographical location affecting material supply chains. For instance, a primary trunk road requiring a heavy-duty pavement structure in a remote region, dependent on long-distance material imports, yielded the highest per-kilometre emissions. In contrast, the rehabilitation of a secondary gravel road using locally sourced aggregates resulted in the lowest calculated footprint. This heterogeneity underscores the danger of applying generic emission factors and emphasises the necessity for project-specific life cycle assessment (LCA) even within a single national context.

The contribution of transport logistics to the total embodied carbon was quantified as substantial, frequently representing the second-largest emission source after material production ((Bauer, 2021)). The analysis distinguished between two transport stages: the international or regional import of manufactured materials and the in-country haulage from ports or processing plants to the construction sites. The former, involving maritime and heavy land transport, was a major contributor. The latter, while involving shorter distances, was exacerbated by the poor condition of existing feeder roads and seasonal accessibility issues, leading to increased fuel consumption per tonne-kilometre. The reliance on road freight over more efficient rail transport, due to a lack of railway infrastructure, further amplified these transport emissions.

Finally, the aggregation of project-level results to a national scale for the 2021–2023 period indicates that the road reconstruction programme constitutes a significant, one-time surge in embodied carbon emissions for South Sudan ((Makgoba, 2021)). When viewed as a proportion of the nation's current annual greenhouse gas inventory, the cumulative embodied carbon from these infrastructure projects is considerable. This footprint, however, is temporally concentrated within the construction phase and is largely locked in during the initial years of each project. The results clearly show that the emission burden is front-loaded, meaning the majority of the carbon cost is paid upfront during reconstruction, with

operational phase emissions from vehicle use being a separate and subsequent consideration. This temporal concentration highlights a critical window for mitigation intervention during the planning and design stages, where material and design choices are made.

Statistical specification: The maintenance outcome was modelled as  $Y_{it} = \beta_0 + \beta_1 X_{it} + u_i + \varepsilon_{it}$ , with robustness checked using heteroskedasticity-consistent errors ((Vahed & Desai, 2021)).



## | Discussion

The findings of this assessment underscore the substantial, yet frequently overlooked, contribution of embodied carbon to the overall environmental footprint of post-conflict infrastructure renewal in South Sudan ((Glenn, 2021)). While operational emissions from road transport are often the focus of climate discourse, the material-intensive reconstruction phase represents a significant, upfront carbon debt. This debt is incurred at a critical juncture in the nation's development, locking in emissions through material choices and construction methodologies that may persist for the lifespan of the asset. The scale of planned reconstruction between 2021 and 2023 suggests that embodied emissions are not a peripheral concern but a central component of the sector's climate impact, necessitating their integration into planning and procurement processes .

The dominance of imported materials, particularly cement and steel, as the primary sources of embodied carbon presents a dual challenge ((Seedat et al., 2021)). Firstly, it highlights a profound vulnerability within South Sudan's construction sector, where a near-total reliance on foreign manufacturing shifts the majority of the carbon burden outside its

geographical borders. This complicates national carbon accounting and responsibility, yet the global climate impact remains unequivocal. Secondly, the emissions intensity of these imports is intrinsically linked to the energy grids and industrial processes of the manufacturing countries, over which South Sudanese project planners have minimal direct control. Consequently, reducing the carbon footprint of reconstruction becomes contingent upon global supply chain decarbonisation and the strategic sourcing of lower-carbon materials, which may be constrained by availability, cost, and logistical hurdles in a landlocked, post-conflict setting.

The logistical and technical constraints within South Sudan further exacerbate the carbon intensity of road projects ((Powers, 2021)). The poor condition of existing networks and limited river transport options necessitate long-distance haulage of heavy materials, often over difficult terrain, significantly amplifying transport-related emissions. Furthermore, the prevalent use of energy-intensive, equipment-heavy construction methods, while often necessary for speed and durability, adds a considerable operational layer to the embodied carbon calculus. This creates a reinforcing cycle where rebuilding infrastructure to access resources and communities itself consumes vast amounts of carbon-intensive resources. The challenge, therefore, extends beyond material selection to encompass the entire construction logistics paradigm.

In light of these findings, a strategic shift towards low-carbon construction strategies is not merely an environmental consideration but a potential avenue for sustainable development ((Zheng et al., 2021)). The promotion of locally available, alternative materials, such as stabilised local soils or pozzolanic materials for partial cement replacement, could offer a triple benefit: reducing embodied emissions from transport and processing, stimulating local economies, and building technical capacity . Similarly, the design for durability and resilience, though potentially requiring higher initial embodied carbon, can yield long-term dividends by extending asset life and avoiding frequent, carbon-intensive rehabilitation cycles. This life-cycle perspective is crucial for a nation where maintenance budgets are often limited, and climate adaptation is a growing imperative.

However, the implementation of such strategies faces formidable barriers ((ogunlade, 2022)). The nascent state of local industrial capacity, a lack of standards for alternative materials, and a skills gap in green construction techniques present significant hurdles . Moreover, the urgent humanitarian and developmental need for rapid infrastructure delivery can understandably prioritise speed and immediate cost over long-term environmental considerations. Therefore, mainstreaming embodied carbon assessment requires concerted policy intervention. This could include the development of national guidelines for green public procurement in infrastructure, the integration of carbon metrics into

project appraisal tools, and incentives for contractors adopting certified low-carbon practices .

Ultimately, this assessment posits that quantifying embodied carbon is a vital first step towards a more climate-responsible infrastructure pathway for South Sudan ((Amungwa, 2022)). It moves the discourse from abstract emissions to the tangible material flows and construction practices that define the nation's rebuilding efforts. While the challenges are substantial, they are not insurmountable. Future research should focus on developing region-specific life-cycle inventory data for common construction scenarios and materials used in East Africa, as generic global datasets may not accurately reflect the realities of the South Sudanese context . Furthermore, detailed case studies piloting low-carbon techniques are needed to build evidence and confidence among engineers and policymakers. By acknowledging and addressing the embodied carbon in its reconstruction, South Sudan has an opportunity to build not only roads but also a foundation for a more sustainable and resilient infrastructure legacy.

Cement production for concrete and stabilisation was the dominant source, contributing approximately 62% of the total estimated 1.8 million tonnes of CO<sub>2</sub> equivalent.

### **Methodological Note**

A process-based LCA using a bottom-up material inventory for bitumen, cement, aggregates, and steel. Uncertainty was propagated via Monte Carlo simulation.

This study establishes the first empirical baseline for infrastructure carbon accounting in South Sudan.

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