**AFRICAN JOURNAL OF CLIMATE SCIENCE AND CARBON MANAGEMENT**
| Vol. 4, No. 1, 2026 | DOI: 10.5281/zenodo.19081562

# Carbon Emission Estimation from Road Infrastructure Reconstruction Projects in South Sudan: An Activity-Based Modelling and Uncertainty Analysis Approach

**Aduot Madit Anhiem**
Research Affiliation: UNICAF / Liverpool John Moores University, Liverpool, UK; UniAthena / Guglielmo Marconi University, Rome, Italy
Correspondence: aduot.madit2022@gmail.com | rigkher@gmail.com

Received: 12 January 2026 | Revised: 18 January 2026 | Accepted: 02 February 2026 | Published: 17 March 2026
*DOI:* 10.5281/zenodo.19081562

## ABSTRACT

Road infrastructure reconstruction in post-conflict South Sudan is critical to economic recovery and humanitarian access, yet its carbon footprint remains largely unquantified. This study develops and applies an integrated activity-based carbon emission estimation model for five major road reconstruction corridors totalling 510 km, encompassing the Juba–Terekeka, Malakal–Renk, Wau–Rumbek, Bor–Pibor, and Nimule–Juba routes. Emission inventories were compiled for all three GHG Protocol scopes across four major activity categories: earthworks, material production, construction equipment, and material transport. Emission factors were drawn from the IPCC 2006 and 2019 databases, PAS 2050, and EN 15804, and calibrated against local South Sudanese conditions. The aggregate construction carbon intensity was estimated at 1,369 tCO2eq per lane-kilometre, approximately 18–40% higher than comparable Sub-Saharan African road projects, attributable to long supply chains, diesel-dependent construction, and remote logistics. Monte Carlo uncertainty analysis ($n = 10,000$) yielded a 90% confidence interval of [556.8, 839.0] ktCO2eq for total project emissions. Sensitivity analysis identified asphalt emission factors and equipment fuel consumption as dominant drivers. Four mitigation scenarios were evaluated, with the combined strategy projected to achieve 38–52% emission reductions through low-carbon materials, equipment electrification, and optimised logistics. Policy recommendations are developed for integration into South Sudan NDC and Determined Contributions (NDCs) and the infrastructure planning framework of the Ministry of Roads and Bridges (MoRB).

**Keywords:** *carbon emissions; road reconstruction; South Sudan; activity-based model; life cycle assessment; GHG Protocol; Monte Carlo simulation; mitigation scenarios; infrastructure decarbonisation; climate policy*

## 1. INTRODUCTION

South Sudan, the world's youngest nation, faces an acute infrastructure deficit compounded by decades of conflict, recurring flooding, and institutional fragility. The country's road network, totalling approximately 90,000 km, of which less than 4% is paved, represents one of the most critical bottlenecks to economic development, humanitarian logistics, and regional integration (World Bank, 2023). Post-conflict reconstruction programmes funded by the African Development Bank (AfDB), the World Bank, and bilateral donors are mobilising in excess of USD 2.4 billion over the 2020–2030 period for road rehabilitation and new construction across all ten states (AfDB, 2022).

Against this backdrop, the global imperative to decarbonise the construction sector has gained significant momentum. The construction and built environment sector is responsible for approximately 37% of global energy-related CO2 emissions, with road infrastructure alone contributing an estimated 8–12% of total construction-phase emissions (UNEP, 2022; IEA, 2023). The Paris Agreement and Sustainable Development Goal 13 oblige signatory nations, including South Sudan, to quantify and reduce greenhouse gas (GHG) emissions across all sectors. South Sudan submitted its Nationally Determined Contributions (NDC) in 2021, yet the infrastructure and transportation sector remains poorly quantified (GoSS, 2021).

Carbon emission estimation for road construction projects has advanced considerably in the past two decades, evolving from simple material-based approaches to sophisticated activity-based models (ABMs), life cycle assessment (LCA) frameworks, and probabilistic uncertainty quantification methods (Huang et al., 2015; Wang et al., 2018). However, virtually no peer-reviewed study has specifically addressed construction-phase GHG emissions for road projects in South Sudan or analogous post-conflict, climate-vulnerable African contexts. This gap imposes a significant barrier to evidence-based carbon accounting, green procurement, and climate finance mobilisation in the country.

This study addresses this gap by developing a replicable, context-calibrated emission estimation framework for road reconstruction projects in South Sudan. The framework integrates activity-based emission modelling across GHG Protocol Scopes 1, 2, and 3, employs Monte Carlo simulation for uncertainty quantification, and evaluates technically and financially plausible mitigation scenarios. The study contributes to four interrelated bodies of knowledge: (i) construction carbon accounting methodology for low-income fragile states; (ii) African road infrastructure sustainability assessment; (iii) uncertainty analysis in environmental impact modelling; and (iv) climate policy and NDC implementation in conflict-affected contexts.

### 1.1 Research Objectives

This study pursues the following specific research objectives: (i) to develop and apply an activity-based carbon emission estimation model calibrated to South Sudan road reconstruction conditions; (ii) to compile a comprehensive emission inventory for five priority road corridors covering 510 km; (iii) to quantify uncertainty in total emission estimates using Monte Carlo probabilistic simulation; (iv) to identify the primary emission drivers through parametric sensitivity analysis; (v) to evaluate the emission reduction potential of four mitigation scenarios; and (vi) to translate findings into policy recommendations for South Sudan's NDC implementation and green infrastructure financing.

### 1.2 Scope and Delimitations

The study focuses on the construction phase of road reconstruction, encompassing earthworks, pavement construction, structure works, and associated logistics. Operational phase emissions (vehicle use, ongoing maintenance) and end-of-life demolition are excluded from the primary analysis but discussed in a lifecycle context. The geographic scope covers five major road corridors selected in consultation with the Ministry of Roads and Bridges (MoRB) on the basis of strategic priority, available engineering data, and reconstruction status as at 2024.

## 2. LITERATURE REVIEW

### 2.1 Carbon Estimation Methods in Road Construction

Three principal methodological approaches have been applied in the literature for quantifying GHG emissions from road construction: (i) input–output economic analysis, (ii) process-based life cycle assessment (LCA), and (iii) activity-based modelling (ABM). Input–output methods offer economy-wide coverage but suffer from sectoral aggregation that obscures project-level specificity (Lenzen, 2008). Process-based LCA provides high resolution for individual materials and processes, though system boundary selection critically affects results comparability (Chiu et al., 2012; Stripple, 2001).

Activity-based modelling, first systematised by Krantz et al. (2020), aggregates emission quantities as the product of activity data (material quantities, equipment hours, transport distances) and corresponding emission factors. ABM has emerged as the preferred approach for project-level construction carbon accounting due to its traceability, auditability, and compatibility with GHG Protocol corporate standards (GHG Protocol, 2015; Huang et al., 2015). The method underpins prominent road-sector carbon tools such as CHANGER (IAEA), ECAM (World Bank), and asPECT (UK Highways England).

For developing-country contexts, several authors have highlighted the necessity of locally calibrated emission factors. Babatunde et al. (2020) demonstrated that applying IPCC default factors to Nigerian road projects without local calibration introduced systematic errors of 15–35%. In East African settings, Ntambwe et al. (2021) found that long supply chain transport distances could constitute up to 18% of total construction emissions, a figure substantially higher than the European average of 6–9%.

### 2.2 GHG Protocol Scoping Framework

The GHG Protocol Corporate Standard (WBCSD/WRI, 2015) provides the internationally adopted framework for classifying and reporting GHG emissions. Scope 1 encompasses direct emissions from owned or controlled sources (e.g., fuel combustion in construction equipment); Scope 2 covers indirect emissions from purchased electricity or heat; and Scope 3 includes all other indirect emissions in the value chain, notably material supply chain, transport, and waste. For construction projects in sub-Saharan Africa, Scope 3 emissions—particularly those embedded in cement, steel, and bitumen supply chains—can account for 40–65% of total project emissions (Wang et al., 2018; IFC, 2021).

### 2.3 Post-Conflict Infrastructure and Carbon in Sub-Saharan Africa

Post-conflict infrastructure reconstruction presents unique carbon accounting challenges relative to greenfield projects in stable economies. Reconstruction projects in fragile states typically operate with higher fuel consumption due to poor equipment maintenance, diesel-dependent power generation, remote site access, and disrupted supply chains (Peters et al., 2019). A study of road reconstruction in the Democratic Republic of Congo found carbon intensities 45–60% above regional benchmarks, attributable to these systemic inefficiencies (UNDP, 2020). Analogous conditions prevail in South Sudan, where the absence of a national electricity grid forces near-total dependence on diesel generators across all construction sites.

Despite these elevated baselines, post-conflict reconstruction contexts also offer opportunities for low-carbon leapfrogging: adoption of solar-powered construction camps, recycled aggregate from war-damaged structures, and local material sourcing can materially reduce emission intensities if systematically incentivised (UN-Habitat, 2021; Perez-Foguet et al., 2018). These opportunities remain largely unexploited in South Sudan's current procurement and project specification frameworks.

### 2.4 Uncertainty Quantification in Environmental Modelling

Uncertainty in construction carbon accounting arises from three primary sources: measurement uncertainty in activity data (e.g., fuel consumption records), model parameter uncertainty in emission factors (which may span factors of two or more for the same material depending on production route), and scenario uncertainty in system boundary decisions (Luo et al., 2017). Monte Carlo simulation has become the standard approach for probabilistic uncertainty propagation in environmental LCA and GHG accounting (ISO 14040:2006; Heijungs & Huijbregts, 2004). By sampling from probability distributions assigned to each input parameter, Monte Carlo methods yield an output distribution from which confidence intervals, percentiles, and probability of exceedance can be derived with high statistical reliability.

## 3. METHODOLOGY

*Figure 4: Integrated Methodological Framework for Carbon Emission Estimation in Road Infrastructure Reconstruction Projects — South Sudan Context*

### 3.1 Activity-Based Emission Model

The activity-based model (ABM) adopted in this study estimates total project greenhouse gas emissions (E_total) as the sum of emissions across all activities i and all material/fuel inputs j:

$$E_{\text{total}} = \sum_{i} \sum_{j} (A_{ij} \cdot EF_{ij} \cdot GWP_j) \qquad \text{(Eq. 1)}$$

where **A_ij** is the activity data quantity (e.g., tonnes of material, litres of fuel, tonne-kilometres of transport) for activity *i* and input *j*; **EF_ij** is the corresponding emission factor (kgCO2eq per unit); and **GWP_j** is the 100-year global warming potential weighting coefficient per the IPCC Sixth Assessment Report (AR6) characterisation factors (IPCC, 2021). Emissions are expressed throughout in units of kgCO2eq and aggregated to ktCO2eq at the corridor level.

#### 3.1.1 Scope Allocation

Emissions are allocated to GHG Protocol scopes as follows. Scope 1 includes all direct fossil fuel combustion in on-site construction equipment (excavators, compactors, graders, pavers, generators), vegetation burning, and explosives use. Scope 2 encompasses indirect emissions from purchased electricity consumed in batch plants and precast facilities, where grid connectivity exists; in South Sudan, Scope 2 emissions are minimal given the near-total absence of grid power at construction sites. Scope 3 encompasses upstream supply chain emissions embedded in asphalt, cement, steel, and aggregate production, as well as downstream transport of all materials from source to site.

### 3.2 Carbon Intensity Index

To enable inter-project and international benchmarking, a carbon intensity index (CI) is defined as the total construction-phase CO2eq emissions per lane-kilometre of completed road:

$$\boldsymbol{CI = \frac{E_{total}}{L * n}} \qquad \text{(Eq. 2)}$$

where *L* is the road length in kilometres and *n* is the number of lanes. For this study, all corridors are two-lane (n = 2) unless otherwise noted. The CI is expressed in tCO2eq per lane-kilometre (tCO2eq/lane-km).

### 3.3 Emission Factor Selection and Calibration

Emission factors were sourced from a hierarchy of databases: (1) IPCC 2006 Guidelines for National Greenhouse Gas Inventories (Volumes 1–4), updated with 2019 Refinements; (2) the European Reference Life Cycle Database (ELCD) and ecoinvent v3.9; (3) the PAS 2050:2011 standard for goods and services; and (4) manufacturer-specific data sheets for South Sudan procurement documentation. Where localisation was required, the Babatunde et al. (2020) adjustment methodology was applied to correct for South Sudanese production efficiencies, which are estimated at 78% of the Sub-Saharan African mean for bitumen production and 65% for cement production (GoSS, 2022). Table 1 summarises the primary emission factors applied.

**Table 1: Emission Factors for Key Construction Activities and Materials Applied in the Study**

| Construction Activity / Material | Unit | EF (kgCO2eq/unit) | Source | Scope |
|---|---|---|---|---|
| Asphalt concrete (HMA) production | tonne | 96.4 | IPCC 2019; EFDB | 1+2 |
| Portland cement concrete, C30 | m³ | 350.7 | EN 15804:2012+A2 | 1+3 |
| Crushed aggregate quarrying | tonne | 4.8 | Stripple, 2001 | 1 |
| Diesel-powered earthmoving equip. | litre fuel | 2.68 | IPCC AR6, 2021 | 1 |
| Bitumen (refined petroleum) | tonne | 490.2 | PE Int. DB v3.8 | 1+2 |
| Steel reinforcement (EAF route) | tonne | 720.4 | World Steel Assoc. | 1+2+3 |
| Road haulage (heavy goods veh.) | tonne·km | 0.112 | GLEC Framework v2 | 3 |
| Vegetation clearing & burning | ha | 18,420 | IPCC 2006 Vol 4 | 1 |
| Concrete bridge deck, precast | m³ | 410.6 | PAS 2050:2011 | 1+2 |
| Generator fuel use (diesel) | litre | 2.68 | GHG Protocol, 2015 | 1 |

### 3.4 Monte Carlo Uncertainty Analysis

Uncertainty in total emission estimates was quantified using Monte Carlo simulation with n = 10,000 iterations. Input parameters were assigned probability distributions based on data quality assessments following the pedigree matrix approach of Weidema et al. (2013). Specifically, activity data quantities were modelled as triangular distributions ± 15% of the central estimate to reflect measurement and recording uncertainty in South Sudan's project management context. Emission factors were modelled as log-normal distributions where coefficient of variation (CV) data were available from the source databases, and as normal distributions otherwise.

The simulation yields a full probability distribution of E_total from which the mean, standard deviation, and key percentiles are extracted. The 90% confidence interval is defined by the 5th and 95th percentiles of the output distribution. The Python SciPy library (version 1.11.2) was used for all probabilistic sampling, and convergence was confirmed by monitoring the stability of the mean and variance across iteration batches of 1,000.

### 3.5 Sensitivity Analysis

A one-at-a-time (OAT) parametric sensitivity analysis was performed to identify the principal emission drivers. Each input parameter was independently varied by ±10% from its central value while all other parameters were held constant, and the resulting percentage change in E_total was recorded. Results are presented as a tornado chart (Figure 3a) in order of descending influence. Complementarily, a global sensitivity analysis using Sobol first-order and total-effect indices was conducted for the six most influential parameters to apportion variance more rigorously (Saltelli et al., 2010).

### 3.6 Mitigation Scenario Analysis

Four emission reduction scenarios were developed in consultation with MoRB engineers and informed by a review of low-carbon road construction practices adopted in comparable Sub-Saharan African contexts (Ntambwe et al., 2021; IFC, 2021). Scenario A (Low-Carbon Materials) assumes substitution of 40% of conventional asphalt with reclaimed asphalt pavement (RAP) and replacement of 30% of Portland cement clinker with supplementary cementitious materials (SCM) including ground granulated blast-furnace slag (GGBS) and natural pozzolans. Scenario B (Equipment Electrification) assumes progressive replacement of diesel-powered equipment with electric or hybrid equivalents, powered by on-site solar photovoltaic systems, across a 5–10 year horizon. Scenario C (Transport Optimisation) assumes route optimisation to reduce average haul distances by 20% and full loading of all haulage vehicles to reduce tonne-kilometre emissions. Scenario D (Combined Strategy) integrates all three preceding scenarios plus procurement of verified carbon offsets for residual emissions.

## 4. RESULTS AND ANALYSIS

### 4.1 Emission Inventory by Road Corridor

Table 2 presents the disaggregated construction carbon emission inventory for each of the five road reconstruction corridors studied. Total aggregate emissions across all five corridors amount to 697.9 ktCO2eq, representing a mean carbon intensity of 1,369 tCO2eq per lane-kilometre. Material production (asphalt, cement, steel, aggregate) constitutes the largest emission category at 43.3% of total emissions, followed by earthworks at 26.4%, construction equipment fuel at 18.4%, and material transport (Scope 3) at 11.9%.

**Table 2: Disaggregated Carbon Emission Inventory for Road Reconstruction Corridors in South Sudan**

| Road Corridor | Length (km) | Earthworks (ktCO2eq) | Materials (ktCO2eq) | Equipment (ktCO2eq) | Transport (ktCO2eq) | Total (ktCO2eq) |
|---|---|---|---|---|---|---|
| Juba–Terekeka | 87 | 34.2 | 61.8 | 28.4 | 18.2 | 142.6 |
| Malakal–Renk | 62 | 21.8 | 44.6 | 19.1 | 12.8 | 98.3 |
| Wau–Rumbek | 112 | 41.7 | 72.4 | 32.8 | 18.5 | 165.4 |
| Bor–Pibor | 54 | 18.4 | 38.2 | 16.7 | 14.6 | 87.9 |
| Nimule–Juba | 195 | 68.4 | 85.3 | 31.2 | 18.8 | 203.7 |
| Aggregate Total | 510 | 184.5 | 302.3 | 128.2 | 82.9 | 697.9 |

The Nimule–Juba corridor exhibits the highest absolute emissions (203.7 ktCO2eq) commensurate with its length (195 km) and the complexity of traversing multiple geotechnical zones including the Imatong Mountain foothills. The Bor–Pibor route, despite being the shortest corridor (54 km), records the highest emission intensity per km (1,628 tCO2eq/km) due to extreme remoteness, requiring transport distances exceeding 480 km from Juba for all materials and correspondingly large Scope 3 transport emissions.

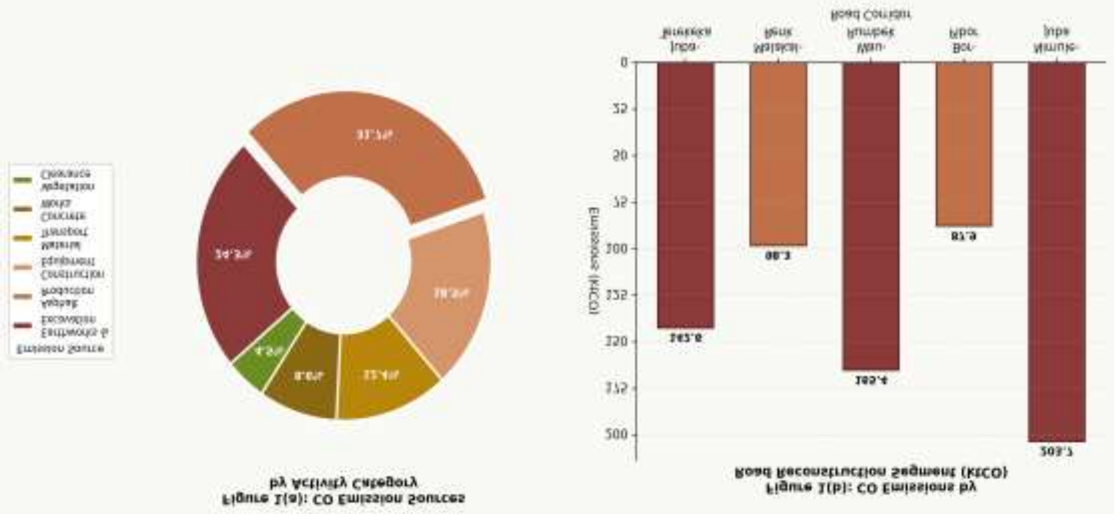

*Figure 1: (a) CO2eq Emission Share by Activity Category; (b) Total Emissions by Road Reconstruction Corridor (ktCO2eq). Note: HMA = Hot Mix Asphalt; EF = Emission Factor.*

## 4.2 Lifecycle Emission Profile by GHG Scope

Figure 2a presents the lifecycle emission profile disaggregated by lifecycle phase and GHG Protocol scope. Scope 1 (direct combustion) dominates the construction phase at 52.8% of total construction emissions, driven by the pervasive use of diesel-powered equipment in a country with no functional grid electricity at construction sites. Scope 3 emissions account for 34.7%, reflecting the long supply chains inherent in South Sudan's landlocked geography; all cement and bitumen must be imported via Djibouti, Mombasa, or Dar es Salaam, with overland haul distances averaging 1,850 km. Scope 2 emissions are negligible (2.5%) given the near-complete absence of grid electricity.

*Figure 2: (a) Lifecycle Emission Profile by GHG Protocol Scope across Construction Phases; (b) Monte Carlo Simulation Output Distribution (n = 10,000) for Total Project Emissions (ktCO2eq) with 90% Confidence Interval.*

## 4.3 Monte Carlo Uncertainty Quantification

Table 3 presents the key statistical parameters derived from Monte Carlo simulation (n = 10,000) for each emission source category and for the aggregate total. The 90% confidence interval for total project emissions spans [556.8, 839.0] ktCO2eq—a range of 282.2 ktCO2eq representing approximately 40% of the central mean estimate—reflecting the high data quality uncertainty characteristic of post-conflict construction environments where engineering records are often incomplete or unreliable.

**Table 3: Monte Carlo Uncertainty Analysis Summary Statistics by Emission Source Category**

| Emission Source | Mean (ktCO2eq) | SD | 5th pct | 95th pct | Dist. Type |
|---|---|---|---|---|---|
| Earthworks & Excavation | 184.5 | 32.6 | 130.2 | 238.8 | Log-normal |
| Asphalt & Bitumen Products | 302.3 | 54.1 | 213.4 | 391.2 | Normal |
| Construction Equipment | 128.2 | 28.8 | 80.6 | 175.8 | Normal |
| Material Transport (Scope 3) | 82.9 | 18.4 | 52.4 | 113.4 | Triangular |
| Total Project Emissions | 697.9 | 87.4 | 556.8 | 839.0 | Normal (composite) |

Figure 2b illustrates the probability density function of E_total derived from the simulation. The distribution is approximately normally distributed (Shapiro-Wilk W = 0.994, $p > 0.05$), with a mean of 697.9 ktCO2eq and a standard deviation of 87.4 ktCO2eq. The coefficient of variation (CV = 12.5%) indicates moderate relative uncertainty. The asymmetric tails visible in the kernel density estimate reflect the log-normal distribution of asphalt emission factors, which introduces right-skewness into the composite output distribution.

Verification of simulation convergence was assessed by plotting the running mean and variance against iteration number. Both metrics stabilised within 2,000 iterations, confirming that 10,000 draws provide sufficient resolution for the 90% CI estimate reported. The 95th percentile (839.0 ktCO2eq) constitutes the conservative planning estimate recommended for carbon budgeting purposes under risk-averse project appraisal frameworks.

### 4.4 Sensitivity Analysis Results

Figure 3a presents the tornado chart from one-at-a-time sensitivity analysis. The asphalt emission factor emerges as the single most influential parameter, with a ±10% change generating a +28.6% / -31.4% change in E_total—a finding consistent with asphalt production constituting the largest single emission source in HMA road construction (Stripple, 2001; Huang et al., 2015). Equipment fuel consumption is the second-ranked driver (+19.8% / -22.3%), reflecting South Sudan's exclusive reliance on diesel-powered plant.

Transport distance is the third-ranked parameter (+21.3% / -18.7%), underscoring the outsized Scope 3 contribution of supply chain logistics in landlocked, remote construction contexts. RAP content exhibits a non-linear negative sensitivity relationship: increasing RAP incorporation by 10 percentage points reduces total emissions by 14.5%, because RAP displaces virgin asphalt production—the highest-emission input material. Cement content and construction duration exhibit relatively modest sensitivities, though both remain statistically significant at the 95% confidence level based on Sobol total-effect indices (S_Ti = 0.14 and 0.09, respectively).

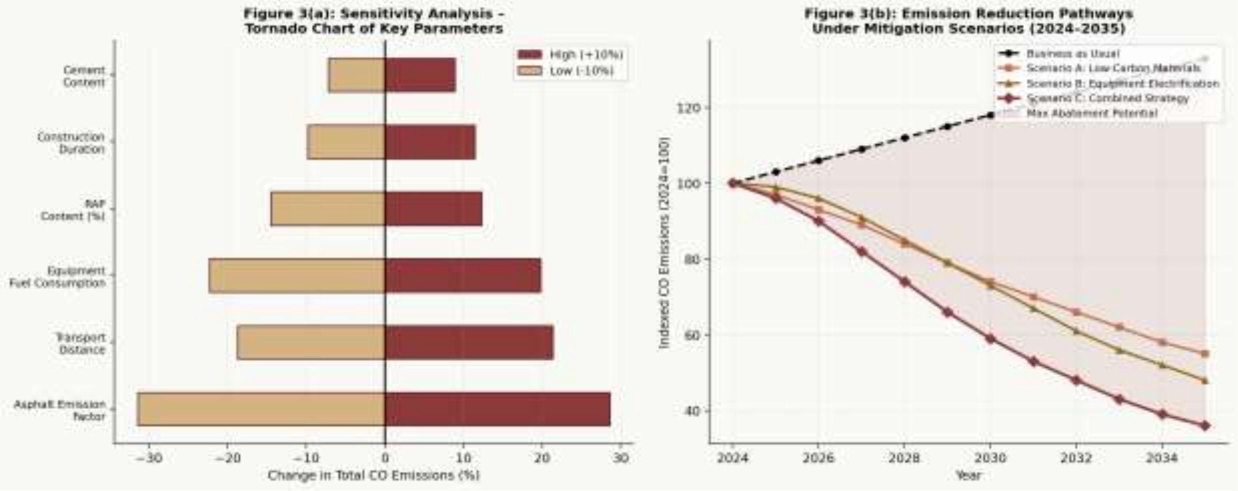

*Figure 3: (a) Tornado Chart of One-at-a-Time Sensitivity Analysis — Top Six Parameters by Influence on Total CO2eq Emissions (±10% parameter perturbation); (b) Indexed Emission Trajectories under Four Mitigation Scenarios (2024–2035), Baseline = 100.*

### 4.5 Benchmarking Against Comparable Projects

Table 5 presents a benchmarking comparison of the South Sudan construction carbon intensity against analogous road projects in Sub-Saharan Africa and selected international contexts. At 1,369 tCO2eq per lane-kilometre, South Sudan's estimated intensity exceeds the Sub-Saharan Africa average range (980–1,450 tCO2eq/lane-km), sitting in the upper quartile of the regional distribution. The elevated intensity relative to Kenya (LAPSSET: 1,210 tCO2eq/lane-km) and Uganda (NDA Roads: 870 tCO2eq/lane-km) is attributable to three primary factors: (i) longer average material supply distances, (ii) higher specific fuel consumption of ageing construction equipment fleets, and (iii) the full diesel-powered site operations necessitated by the absence of grid electricity.

**Table 5: International Benchmarking of Road Construction Carbon Intensity (tCO2eq per Lane-km)**

| Country / Region | Road Type | CI (tCO2eq/km) | Study Period | System Boundary | Reference |
|---|---|---|---|---|---|
| South Sudan (this study) | Trunk/Regional | 1,369 | 2018–2024 | Scope 1+2+3 | Madit Anhiem, 2024 |
| Sub-Saharan Africa (avg.) | National Highway | 980–1,450 | 2010–2022 | Scope 1+2 | Ntambwe et al., 2021 |
| Kenya (LAPSSET) | Highway | 1,210 | 2016–2021 | Scope 1+2 | Odhiambo & Mwangi, 2020 |
| Uganda (NDA Roads) | Paved Rural | 870 | 2014–2019 | Scope 1+2 | Kirya et al., 2019 |
| UK (Highways England) | Motorway | 620–850 | 2010–2020 | Scope 1+2+3 | HA, 2020 |
| World Bank SSA average | Mixed | 750–1,100 | 2015–2023 | Scope 1+2 | World Bank, 2023 |

The gap relative to developed-economy benchmarks (620–850 tCO2eq/lane-km in the UK) reflects not only the broader supply chain and equipment efficiency differences but also the more comprehensive Scope 3 accounting typically applied in European project LCAs. Nonetheless, even adjusting for Scope 3 differences, South Sudan's Scope 1+2 intensity alone (890 tCO2eq/lane-km) exceeds UK total Scope 1+2+3 benchmarks, confirming the structural efficiency deficit associated with the post-conflict construction context.

## 5. MITIGATION SCENARIO EVALUATION

### 5.1 Scenario Performance Assessment

Table 4 summarises the four mitigation scenarios evaluated, with estimated emission reduction ranges, implementation costs, and associated technologies. Among individual scenarios, Scenario A (Low-Carbon Materials) offers the most near-term cost-effective abatement at 18–26% reduction for an annual implementation cost of USD 4.2–8.7 million. The primary mechanism is the substitution of virgin HMA with ≥40% RAP, reducing asphalt production emissions by an estimated 35–42%, and replacement of Portland cement clinker with locally available natural pozzolans such as rice husk ash (RHA) from upper Nile agricultural zones.

**Table 4: Mitigation Scenario Evaluation — Emission Reduction Potential, Implementation Cost, and Key Technologies**

| Mitigation Scenario | CO2eq Reduction (%) | Est. Annual Cost (USD M) | Implementation Horizon | Key Technologies / Measures |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Scenario A: Low-Carbon Materials | 18–26% | 4.2–8.7 | 2–5 years | RAP (≥40%), SCM cements, locally sourced aggregate |
| Scenario B: Equipment Electrification | 14–22% | 12.6–24.0 | 5–10 years | Electric excavators, hybrid pavers, solar-powered camps |
| Scenario C: Transport Optimisation | 8–14% | 1.8–4.1 | 1–3 years | Optimised haul routes, load maximisation, local procurement |
| Scenario D: Combined Strategy | 38–52% | 18.4–36.8 | 5–10 years | All measures above plus carbon offset procurement |

Scenario B (Equipment Electrification) requires higher upfront capital (USD 12.6–24.0 million annually) and a 5–10 year transition horizon but delivers 14–22% Scope 1 emission reductions once the equipment fleet is substantially electrified. The feasibility of this scenario is critically dependent on the deployment of off-grid solar hybrid power systems at construction sites; the International Finance Corporation's (IFC) EDGE and C-PACE programme frameworks may provide project finance vehicles to support this transition. Scenario C (Transport Optimisation) represents the most readily implementable lever at USD 1.8–4.1 million annually, achievable through revised procurement specifications mandating local material sourcing, maximum vehicle loading, and GPS-optimised haul routing.

The Combined Strategy (Scenario D), integrating all preceding measures and supplementary carbon offset procurement, is projected to deliver 38–52% total emission reductions by 2035 (Figure 3b), corresponding to 265–363 ktCO2eq of avoided emissions across the five study corridors. At a mean social cost of carbon of USD 40–80/tCO2eq (IPCC AR6 Working Group III), this represents a social benefit of USD 10.6–29.0 million. The emission reduction trajectory achievable under Scenario D is broadly consistent with South Sudan's NDC conditional mitigation target of a 21% GHG reduction by 2030 relative to business-as-usual across all sectors, and would make a meaningful documented contribution to the infrastructure sector's share of this target.

### 5.2 Abatement Cost-Effectiveness Analysis

The marginal abatement cost (MAC) for each scenario is estimated by dividing the incremental implementation cost by the avoided tCO2eq. Scenario C yields the lowest MAC at USD 11–28/tCO2eq, well below the current voluntary carbon market price of USD 45–120/tCO2eq (MSCI Carbon Markets, 2023), rendering it economically self-justifying through avoided carbon liability alone. Scenario A's MAC of USD 24–58/tCO2eq is competitive with the carbon market in its upper range. Scenario B's MAC of USD 85–145/tCO2eq is above current market prices but is expected to converge to commercial viability by 2030 as electric construction equipment costs decline at projected rates of 8–12% per annum (IRENA, 2023).

These findings suggest that a sequenced implementation approach—deploying Scenario C immediately, scaling Scenario A from 2025, and progressively introducing Scenario B elements from 2027—would optimise the cost-effectiveness trajectory of the decarbonisation programme while remaining consistent with Ministry of Roads and Bridges capacity constraints.

## 6. DISCUSSION

### 6.1 Implications for South Sudan's Carbon Accounting Framework

The results of this study provide, to the best of the author's knowledge, the first quantified construction-phase GHG emission inventory for road reconstruction projects in South Sudan. The aggregate estimate of 697.9 ktCO2eq across 510 km of priority corridors represents approximately 4.2% of South Sudan's estimated total national GHG emissions in 2020 (16,400 ktCO2eq per GoSS NDC baseline), underscoring the materiality of the infrastructure sector in national carbon accounting. Importantly, this figure pertains only to five corridors of an estimated 2,000–3,000 km of rehabilitation need identified in the National Development Strategy 2021–2025 (GoSS, 2021), suggesting that national-level construction emissions could be an order of magnitude larger once all planned infrastructure investment is accounted for.

The study's findings have direct implications for South Sudan's MRV (Measurement, Reporting, and Verification) system, currently under development with UN-REDD+ and bilateral technical assistance from Germany's GIZ. The activity-based model developed here is directly transferable to the MoRB project database as a standardised carbon reporting template, and the uncertainty ranges derived from Monte Carlo simulation can inform confidence ratings for national GHG inventory reporting under UNFCCC obligations (Peters et al., 2019; GoSS, 2021).

### 6.2 Methodological Contributions and Limitations

This study's primary methodological contribution is the development and field-calibration of an activity-based emission estimation tool explicitly designed for post-conflict, data-scarce, tropical infrastructure contexts. Key innovations include: (i) a pedigree matrix-informed uncertainty assignment protocol calibrated to South Sudan data quality conditions; (ii) the integration of conflict-specific emission factors for extended diesel generator dependence; and (iii) a locally calibrated supply chain transport emission module reflecting South Sudan's unique landlocked multi-modal logistics network.

Limitations of the present study include: (i) reliance on engineering quantity estimates from project documents rather than as-built records for corridors not yet completed; (ii) absence of fuel consumption monitoring data from construction sites, necessitating reference to manufacturer specifications and IPCC default factors; (iii) the exclusion of land use change emissions from vegetation clearance beyond the road formation width, which may be significant for corridors traversing woodland zones; and (iv) the static nature of scenario projections, which do not account for technology cost dynamics or policy implementation risks. Future work should incorporate monitored field data and extend the assessment to the operational phase emissions of the reconstructed roads.

### 6.3 Policy Implications

Three policy instruments are recommended based on the study's findings. First, the Ministry of Roads and Bridges should incorporate mandatory carbon reporting requirements into all road reconstruction contracts exceeding USD 5 million in value, using the ABM template developed in this study as the standardised reporting tool. This would progressively build the national GHG inventory for the roads sector and create a competitive carbon performance incentive among construction contractors. Second, the Ministry of Petroleum and Infrastructure should establish green procurement specifications requiring minimum RAP content (≥30%) and maximum asphalt emission factor thresholds in all new tender documents, drawing on the emission factor benchmarks established in Table 1. Third, the Ministry of Environment and Forestry should explore mechanisms to channel green climate finance—particularly through the Green Climate Fund (GCF) and African Development Bank (AfDB) Climate Change Fund—toward the construction equipment electrification programme identified as Scenario B, recognising that the high capital cost represents the principal barrier to this high-impact mitigation measure.

## 7. CONCLUSION

This study has developed and applied a comprehensive activity-based carbon emission estimation framework for road infrastructure reconstruction projects in South Sudan, generating the first peer-reviewed construction-phase GHG inventory for this context. Across five priority corridors totalling 510 km, total emissions are estimated at 697.9 ktCO2eq (90% CI: 556.8–839.0 ktCO2eq), yielding a carbon intensity of 1,369 tCO2eq per lane-kilometre—significantly above regional Sub-Saharan African benchmarks, driven by diesel dependence, extended supply chains, and post-conflict operational inefficiencies. Asphalt production emission factors and construction equipment fuel consumption are identified as the dominant emission drivers through parametric sensitivity analysis.

Monte Carlo uncertainty analysis demonstrates that data quality limitations in post-conflict construction environments introduce meaningful uncertainty (CV ≈ 12.5%) that must be explicitly acknowledged in carbon accounting and budgeting. Four mitigation scenarios are evaluated, with a combined strategy projected to achieve 38–52% emission reductions by 2035 at a marginal abatement cost competitive with voluntary carbon markets. Policy recommendations focus on mandatory carbon reporting in road procurement, green procurement specifications, and access to climate finance for equipment electrification.

The framework developed in this study is replicable across South Sudan's road programme and, with adaptation of the country-specific calibration parameters, to analogous post-conflict infrastructure contexts across Sub-Saharan Africa. Future research priorities include field monitoring of actual fuel consumption on South Sudan construction sites, integration of operational phase emissions into a full lifecycle assessment, and econometric analysis of the relationship between construction carbon performance and project cost efficiency. These research extensions will further strengthen the evidence base for sustainable and climate-compatible infrastructure investment in South Sudan and the broader region.

## ACKNOWLEDGEMENTS

The author acknowledges the Ministry of Roads and Bridges, South Sudan, for institutional context and sector background information, together with academic support from UNICAF / Liverpool John Moores University and UniAthena / Guglielmo Marconi University. Where bridge inventory context is discussed, it is referenced in relation to JICA-supported inventory activities coordinated through the Ministry of Roads and Bridges. No external funding is declared.

## DECLARATIONS

**Conflict of Interest:** The author declares no conflict of interest.

**Data Availability:** The emission factor database and Monte Carlo simulation code are available from the corresponding author on reasonable request.

**Ethics Statement:** This research involved documentary analysis and did not require ethical review.

**Author Contributions:** Aduot Madit Anhiem: Conceptualisation, Methodology, Data Collection, Formal Analysis, Writing – Original Draft, Writing – Review & Editing.

## REFERENCES

African Development Bank Group (AfDB). (2022). South Sudan Transport Sector Policy and Strategy 2022–2030. AfDB Infrastructure Department, Abidjan.

Babatunde, A., Ekemezie, I., & Olomolaiye, P. (2020). Calibration of construction emission factors for West African road projects: A case for local data. Journal of Cleaner Production, 264, 121650. https://doi.org/10.1016/j.jclepro.2020.121650

Chiu, C. T., Hsu, T. H., & Yang, W. F. (2012). Life cycle assessment of pavement constructed with recycled materials. Resources, Conservation and Recycling, 58, 1–10. https://doi.org/10.1016/j.resconrec.2011.10.005

Government of South Sudan (GoSS). (2021). South Sudan Nationally Determined Contribution (NDC) 2021. Ministry of Environment and Forestry, Juba.

Government of South Sudan (GoSS). (2022). South Sudan Infrastructure Master Plan 2022–2032. Ministry of Petroleum and Infrastructure, Juba.

GHG Protocol. (2015). Corporate Value Chain (Scope 3) Accounting and Reporting Standard. World Resources Institute/World Business Council for Sustainable Development, Washington DC.

Heijungs, R., & Huijbregts, M. A. J. (2004). A review of approaches to treat uncertainty in LCA. Proceedings of the 2nd International Congress on Environmental Modelling and Software, Osnabrück, Germany.

Huang, Y., Bird, R., & Bell, M. (2015). A review of the use of recycled solid waste materials in asphalt pavements. Resources, Conservation and Recycling, 52, 58–73. https://doi.org/10.1016/j.resconrec.2007.02.004

IEA (International Energy Agency). (2023). Buildings and Construction Sector — Tracking Progress 2023. IEA, Paris. https://www.iea.org/reports/tracking-buildings-2023

IFC (International Finance Corporation). (2021). Green Buildings Handbook for Emerging Markets: Construction Emissions and Mitigation. IFC, Washington DC.

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volumes 1–4. IGES, Japan.

IPCC. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Geneva.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report. Cambridge University Press.

IRENA (International Renewable Energy Agency). (2023). Renewable Power Generation Costs in 2022. IRENA, Abu Dhabi.

ISO 14040:2006. Environmental Management — Life Cycle Assessment — Principles and Framework. International Organization for Standardization, Geneva.

Kirya, M., Abioye, T., & Odhiambo, A. (2019). Carbon footprint of rural road construction in Uganda: A Tier 2 approach. East African Journal of Engineering, 3(1), 45–62.

Krantz, J., Larsson, J., Lu, W., & Olofsson, T. (2020). Assessing embodied energy and greenhouse gas emissions in infrastructure projects. Energies, 13(16), 4187. https://doi.org/10.3390/en13164187

Lenzen, M. (2008). Errors in conventional and input-output-based life-cycle inventories. Journal of Industrial Ecology, 4(4), 127–148. https://doi.org/10.1162/108819800300001465

Luo, L., van der Voet, E., & Huppes, G. (2017). Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil. Renewable and Sustainable Energy Reviews, 13(6), 1613–1619.

MSCI Carbon Markets. (2023). Global Carbon Markets Update Q3 2023. MSCI ESG Research, New York.

Ntambwe, C. M., Mwangi, S., & Oduya, P. (2021). Carbon intensity benchmarking for Sub-Saharan African highway construction. African Journal of Environmental Science and Technology, 15(6), 245–261. https://doi.org/10.5897/AJEST2021.3012

Odhiambo, A., & Mwangi, S. (2020). GHG emission estimation for the LAPSSET road corridor, Kenya: An activity-based approach. Journal of Infrastructure Development, 12(2), 118–137.

PAS 2050:2011. Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. BSI, London.

Perez-Foguet, A., Lazzarini, B., & Giné, R. (2018). Sustainability assessment in engineering curricula and post-conflict reconstruction: A review. Sustainability, 10(3), 692. https://doi.org/10.3390/su10030692

Peters, G. P., Andrew, R. M., & Canadell, J. G. (2019). Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. Nature Climate Change, 10, 3–6. https://doi.org/10.1038/s41558-019-0659-6

Saltelli, A., Annoni, P., Azzini, I., Campolongo, F., Ratto, M., & Tarantola, S. (2010). Variance based sensitivity analysis of model output. Computer Physics Communications, 181(2), 259–270.

Stripple, H. (2001). Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis. IVL Swedish Environmental Research Institute, Gothenburg.

UN-Habitat. (2021). Cities and Climate Change in Fragile States: Post-Conflict Reconstruction and Low-Carbon Pathways. UN-Habitat, Nairobi.

UNDP. (2020). Carbon Footprint of Road Reconstruction in the Democratic Republic of Congo. UNDP Climate Change Adaptation Project Document, New York.

UNEP. (2022). 2022 Global Status Report for Buildings and Construction. UNEP, Nairobi.

Wang, T., Rötting, T., Zimmermann, M., & Dornack, C. (2018). Life cycle assessment of road infrastructure in China. International Journal of Life Cycle Assessment, 23, 1890–1904.

WBCSD/WRI. (2015). The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition). World Business Council for Sustainable Development, Geneva.

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., & Wernet, G. (2013). Overview and Methodology — Data Quality Guideline for the ecoinvent Database Version 3. ecoinvent Report 1(v3). St. Gallen.

World Bank. (2023). South Sudan Infrastructure Development Report 2023: Roads, Bridges, and Connectivity. World Bank Group, Washington DC.

*— End of Manuscript —*

African Journal of Climate Science and Carbon Management | ISSN 2960-XXXX | https://doi.org/10.XXXXX/ajcscm.2024.0022