

Life cycle assessment of the Garissa solar PV plant: evaluating the environmental sustainability of utility-scale solar in Kenya

Diana Asiko Eshibukho

asikidiana@gmail.com

Article

Keywords: Lifecycle assessment, Utility-scale solar, Green-house gas emissions, Garissa End-of-life, Kenya

Posted Date: October 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11341527/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

1 Life cycle assessment of the Garissa solar PV plant: evaluating the
2 environmental sustainability of utility-scale solar in Kenya

3 Diana A. Eshibukho¹

4

5 ¹ School of Geosciences, University of Edinburgh, Edinburgh, EH8 9YL, United Kingdom

6 * Correspondence: asikidiana@gmail.com

7

Abstract

Kenya's transition to low-carbon energy systems has accelerated the deployment of utility-scale solar photovoltaic projects, yet questions remain about their long-term environmental sustainability. This study presents a cradle-to-grave life cycle assessment of the Garissa Solar PV Plant, the largest grid-connected solar facility in East and Central Africa, to quantify its greenhouse gas emissions and identify environmental hotspots. Using an attributional LCA framework and a custom Excel-based model and region appropriate inventories, the study assessed emissions across manufacturing, transportation, operation, and end-of-life management under current national conditions.

The results indicate the plant's lifecycle intensity is 23.6 g CO₂-eq kWh⁻¹, substantially lower than fossil-based electricity generation (coal: 780-1095 g CO₂-eq kWh⁻¹; natural gas: 400-726 g CO₂-eq kWh⁻¹), and consistent with international benchmarks for utility-scale PV systems (typically 20-60 g CO₂-eq kWh⁻¹, depending on the technology, geography, and system boundaries). Lifecycle contributions are dominated by upstream stages: manufacturing, 17.27 g CO₂-eq kWh⁻¹ and balance of components, 5.85 g CO₂-eq kWh⁻¹; transport, 0.47 g CO₂-eq kWh⁻¹; and end-of-life, 0.0237 g CO₂-eq kWh⁻¹ under a conservative 100% landfill baseline.

Although Garissa's carbon profile aligns with international benchmarks, it reveals Kenya's reliance on carbon-intensive global supply chains remains a key driver in upstream emissions. The study underscores the need for lifecycle-aligned policy reforms, including solar-specific recycling protocols, localised manufacturing strategies, and water-efficient maintenance practices in arid regions. It also anticipates future challenges posed by BESS, which could significantly increase lifecycle emissions. By providing Kenya's first utility-

31 scale solar LCA, this research offers critical insights for policymakers, developers, and
32 researchers aiming to align solar expansion with climate and sustainability goals.

33 **Key words:** Lifecycle assessment, Utility-scale solar, Green-house gas emissions, Garissa
34 End-of-life, Kenya

35

1 Introduction

The global energy landscape is undergoing a transformative shift driven by climate change imperatives and the pursuit of universal energy access. In line with the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), countries are increasingly transitioning towards low-carbon energy systems. Kenya, like many nations in sub-Saharan Africa, faces a dual challenge: expanding reliable electricity access to underserved populations while simultaneously reducing greenhouse gas (GHG) emissions. Within this context, the rapid scaling of renewable energy technologies, particularly solar photovoltaic (PV) systems, has gained strategic significance.

Among renewable energy options, utility-scale solar energy (USSE) systems have emerged as a key pillar of global decarbonisation strategies due to their scalability, declining costs, and alignment with energy access goals [1]. These large installations typically exceed 1 MW and are connected directly to the transmission grid. However, while solar PV is widely recognised for its low operational emissions, concerns persist regarding the upstream and downstream environmental impacts across the technology's life cycle, including material extraction, manufacturing, transportation, and end-of-life disposal [2].

According to the International Energy Agency, solar PV is expected to drive nearly 80% of the projected 5,500 GW increase in global renewable capacity between 2024 and 2030 [1]. This marks a 2.6-fold increase over the previous six years. The surge is driven by falling equipment costs, faster permitting, and strong public support.

In sub-Saharan Africa (SSA), including Kenya, the adoption of USSE is accelerating, yet comprehensive environmental assessments remain limited. Most policy and investment decisions continue to prioritise generation capacity and cost-effectiveness, often overlooking

upstream and downstream sustainability implications. This gap poses a risk to long-term environmental objectives if solar deployment proceeds without due consideration of life cycle impacts such as e-waste, land-use trade-offs, and embedded emissions.

To address this gap, this dissertation investigates the life cycle environmental performance of the Garissa Solar PV Plant, commissioned in 2018 as the largest grid-connected solar project in East and Central Africa. Through a life cycle assessment (LCA) approach, the study evaluates the sustainability of utility-scale PV in the Kenyan context and contributes to the growing body of evidence needed to support environmentally responsible energy planning in the Global South.

1.1 Background and context

1.1.1 Kenya's renewable energy profile

Kenya has made significant strides in decarbonizing its electricity sector, positioning itself as a regional leader in renewable energy. As of 2024, renewables account for approximately 83% of the country's electricity generation, a result of strong natural resource endowments and supportive government policy [3]. The national installed capacity stands at around 3.7 GW, led by geothermal energy (26.4%), followed by hydropower (24.4%), thermal (17.8%), wind (12.2%), and solar (12.4%) [3].

In terms of actual electricity output, geothermal remains the dominant source, supplying 41.7% of the total generation. Hydropower (24.7%), wind (13.1%), and solar PV (3.5%) follow, while thermal sources contribute 8.2%, and electricity imports account for 8.8%, as illustrated in **Figure 1**. Despite the country's strong renewable energy base, fossil fuel reliance and energy access disparities persist, particularly in rural and underserved areas [3].

1.1.2 Utility-scale solar PV in Kenya: status, vision and challenges

Kenya's geographic position along the equator grants it excellent solar potential, with most regions receiving 5–7 peak sun hours per day. Annual solar irradiance ranges from 700 kWh/m² in highland regions to over 2,600 kWh/m² in arid and semi-arid lands (ASALs), which remain among the least electrified parts of the country [4]. These areas present a significant opportunity for equitable energy access through the deployment of USSE systems, particularly in underserved regions with high solar irradiance [4]. This spatial variation in solar potential is illustrated in **Figure 2**, which maps the distribution of annual global horizontal irradiation (GHI) and PV potential across Kenya.

As of 2024, Kenya's grid-connected solar PV capacity totalled 210.3 MW, representing approximately 6.5% of total installed capacity and contributing 3.5% to national electricity generation [3]. Notable installations include the 54.65 MW Garissa Solar Plant, developed by the Rural Electrification and Renewable Energy Corporation (REREC), and three 40 MW independent power producer (IPP) projects in Malindi, Eldoret, and Selenke [5]. While these projects are important milestones, they fall significantly short of the country's vast technical and economic solar potential [4].

To address this gap, the government has set ambitious expansion targets: 8 GW of installed solar capacity by 2040 and 140 GW by 2050, as part of its broader strategy to achieve net-zero emissions by mid-century [3,6]. These goals are embedded within Kenya's national energy planning frameworks and align with its aspirations for green industrialization, regional energy leadership, and universal electricity access [3].

Despite this strong policy intent and abundant solar resource base, several structural and operational barriers continue to constrain the pace and scale of utility-scale solar deployment. These include limited transmission infrastructure in high-insolation areas, land

acquisition challenges, intermittency management, and a lack of long-term investment certainty [3].

One critical technical limitation is the absence of integrated battery energy storage systems (BESS). Currently, solar electricity is fed directly into the national grid without dedicated storage support [3]. While this has been manageable under the existing generation mix, the growing share of intermittent solar energy highlights the need for flexible storage solutions to maintain grid reliability and manage peak demand. The Least Cost Power Development Plan (2022–2043) acknowledges the strategic role of BESS and outlines plans for their phased integration into the national grid to support renewable energy expansion [5]. However, deployment remains limited due to high capital costs, regulatory gaps, and environmental concerns related to battery production and disposal [7].

1.1.3 Policy and regulatory framework gaps

Kenya’s political commitment to renewable energy expansion is reflected in an ambitious policy landscape that emphasizes deployment incentives, tariff frameworks, and grid integration. However, this strong emphasis on scaling installed capacity has not been matched by equivalent attention to the environmental sustainability of solar PV systems across their entire life cycle.

The Energy Act (2019) and the National Energy Policy (2025-2034) set ambitious targets for renewable energy expansion, yet they lack substantive provisions related to upstream impacts (e.g., material sourcing), midstream issues (e.g., land-use management and civil infrastructure), and downstream challenges such as end-of-life disposal, decommissioning, and solar e-waste governance [7]. The Least Cost Power Development Plan (2024-2043) further underscores the country's generation targets but offers limited guidance on environmental safeguards beyond initial Environmental Impact Assessments

(EIAs), which often exclude life cycle considerations [5].

Notably, while Kenya has enacted broader sustainability laws such as the Sustainable Waste Management Act (2022) and the Extended Producer Responsibility (EPR) Regulations (2024), these instruments remain generic and insufficiently tailored to the specific risks associated with solar PV. Although EPR regulations include electrical equipment, solar PV modules are not explicitly listed in the First schedule, suggesting they may be implicitly covered but not in a targeted enforceable way [7]. As a result, there are no solar-specific provisions regarding hazardous substance management (e.g., cadmium in CdTe panels), producer take-back obligations for end-of-life modules, dedicated recycling infrastructure and standards for PV components, or traceability systems to monitor solar e-waste streams, particularly in informal settings.

This regulatory vacuum is particularly problematic given that most utility-scale projects are being rolled out in ecologically sensitive and infrastructurally weak regions, such as Kenya's ASALs. Without a lifecycle-aligned regulatory approach, there is a risk of shifting environmental burdens downstream, undermining the sustainability credentials of solar energy itself. Furthermore, institutional fragmentation adds to implementation challenges. Responsibilities for environmental oversight are scattered across agencies such as the National Environmental Management Authority (NEMA), the Ministry of Energy and Petroleum (MoEP), and the Energy and Petroleum Regulatory Authority (EPRA), with limited inter-agency coordination or enforcement capacity specific to solar infrastructure. A comprehensive summary of Kenya's solar-relevant policy landscape and its coverage across lifecycle stages is provided in supplementary information, section S7.

1.2 Problem statement

Despite Kenya's commendable progress in scaling renewable energy, particularly solar PV, critical concerns persist regarding the long-term environmental sustainability of utility-scale solar projects. Current national energy planning frameworks largely prioritize rapid capacity expansion, cost competitiveness, and universal access. However, they offer limited attention to the full life cycle impacts of solar PV technologies, including embedded carbon emissions, material extraction, land use, and end-of-life waste management.

As Kenya accelerates solar deployment, especially in ecologically sensitive and infrastructurally underserved regions, these overlooked environmental dimensions are becoming increasingly relevant. Without integrated planning and robust regulatory oversight, there is a growing risk that solar energy systems may inadvertently introduce new environmental externalities, thereby undermining their sustainability credentials.

The policy landscape, while ambitious in deployment targets, remains weak in enforcing life cycle environmental accountability. Regulatory gaps around hazardous materials, recycling infrastructure, and solar-specific EoL governance exacerbate this challenge. Moreover, institutional fragmentation has hindered coordinated environmental oversight for solar infrastructure.

In this context, empirical LCAs are urgently needed to inform evidence-based policy and environmentally responsible project development. Yet, such assessments remain scarce in the Kenyan and broader sub-Saharan African context. The Garissa Solar PV Plant, Kenya's largest grid-connected solar facility, offers a strategic case study for evaluating the environmental trade-offs associated with utility-scale solar deployment in the Global South. This dissertation, therefore, addresses a critical gap in both research and policy by evaluating

the life cycle GHG emissions of the Garissa Solar Plant. It contributes to a growing body of scholarship aimed at integrating life cycle thinking into national renewable energy strategies.

1.3 Research aim

This study aims to evaluate the life cycle GHG emissions of the Garissa Solar PV Plant in Kenya, to inform more environmentally sustainable solar energy planning and deployment strategies.

1.4 Research questions

This study is guided by the following primary and subsidiary research questions:

Primary research question:

- What is the life cycle GHG emissions associated with the Garissa Solar PV Plant?

Sub-questions:

- i. Which life cycle phases (e.g., manufacturing, transportation, installation, operation, decommissioning) contribute most significantly to the plant's overall GHG emissions?
- ii. How does the plant's life cycle GHG emissions compare with international benchmarks for utility-scale solar PV systems?
- iii. What are the methodological limitations, assumptions, and data constraints involved in conducting a LCA for solar PV in the Kenyan context?
- iv. What best practices can be drawn from this case study to enhance the environmental sustainability of future solar PV projects in Kenya and similar sub-Saharan African settings?

2 Literature review

2.1 Environmental impacts of USSE

The global transition towards renewable energy sources, initially driven by climate change mitigation goals, has increasingly been reinforced by economic incentives, particularly as PV technology has become more cost-competitive than traditional energy sources such as diesel generators [1]. This shift has contributed to the rapid expansion of USSE systems worldwide [8]. However, this growth introduces a complex set of environmental trade-offs that extend beyond carbon mitigation. Unlike rooftop solar, USSE projects require large tracts of land and centralized infrastructure, often situated in ecologically sensitive or water-stressed regions. These systems interact with local environments across multiple dimensions, altering land use, affecting biodiversity, drawing on water resources, contributing to upstream emissions, and generating waste at end-of-life [9].

This section critically examines the major environmental impacts associated with USSE through five interconnected lenses: land use, biodiversity, water consumption, air pollution, and end-of-life management. Together, these dimensions provide a holistic understanding of USSE's sustainability profile and identify key areas where policy, planning, and technological innovation must intervene to ensure responsible solar development.

2.1.1 Land use

USSE systems, particularly ground-mounted PV and concentrating solar power (CSP) installations, are often frequently scrutinized for their relatively large land footprints. Multiple studies have found that these technologies generally exhibit higher land-use

intensity (measured in m^2/MWh) compared to some renewable alternatives such as nuclear, natural gas, and offshore wind [8].

This spatial requirement can give rise to land-use conflicts, particularly when PV installations are sited on or near land used for agriculture, forestry, conservation, or urban development [8]. However, it is important to recognize that this competition is not a fixed outcome of the technology itself. Rather, it stems from site management practices. The perception of “direct competition” typically applies to fenced-off installations that exclude other uses.

A growing body of research highlights the potential to co-locate solar infrastructure with other land uses, thereby reducing or even reversing these conflicts. Agrivoltaics, for instance, enables the simultaneous production of crops and solar electricity, while biodiversity-sensitive siting can support pollinator habitats or native vegetation [9]. These integrative strategies can soften land-use trade-offs and create multifunctional landscapes that serve both energy and ecological objectives.

Still, the extent and severity of land-use competition vary by region. In regions with high humidity, the expansion of PV installations can intensify land-use conflicts by competing directly with food production and forest conservation goals, potentially leading to long-term instability in land-use patterns [10]. Yet, compared to traditional fossil fuel systems, USSE projects also offer distinct environmental advantages. For example, PV arrays can reduce soil surface temperatures and water evaporation, which may increase local drought resilience and plant water-use efficiency [9].

Moreover, a strategic solution lies in deploying solar infrastructure on degraded or marginal lands, such as brownfields, landfills, and former mining sites. These disturbed landscapes typically offer low ecological or agricultural value and present opportunities to

deliver environmental co-benefits through reclamation and native landscaping efforts [8,9]. When well-planned, such siting approaches can help minimize displacement effects while maximizing solar energy output in a land-constrained world.

2.1.2 Biodiversity

The transformation of land through solar energy infrastructure doesn't only affect human land-use priorities, it may also alter ecological systems. Increasingly, researchers are evaluating the impacts of solar energy development on biodiversity and ecosystem functions, though critical knowledge gaps persist [9]. The construction and operation of utility-scale solar installations often require extensive land clearing, leading to habitat loss, fragmentation, and ecological degradation [8]. This disruption leads to habitat destruction and fragmentation, forcing displacement or loss of native flora and fauna, thereby reducing species richness and abundance. Arid ecosystems are particularly vulnerable due to their slow ecological recovery rates and high specialization of species [9].

Despite these general trends, ecological responses to solar PV installations are not uniform and depend heavily on regional biophysical conditions. Xiao et al., (2025) note that some arid and semi-arid zones may demonstrate relatively higher resilience, particularly in areas where vegetation is already sparse or where previous land uses have led to ecological degradation. In such contexts, the marginal ecological cost of solar deployment may be lower, and carefully designed installations can even offer opportunities for habitat restoration.

Beyond direct biodiversity metrics, large-scale PV installations also affect broader ecosystem functions. Tawalbeh et al., (2021) highlights that while utility-scale solar contributes to local climate regulation,

it compromises local services such as erosion control, groundwater recharge, and forage production.

Despite the potential negative outcomes, several studies propose integrative solutions to harmonize energy development with ecological goals. Sinha et al., (2018) recommend biodiversity-enhancing practices like vegetative buffer zones, adaptive land management, and pollinator-friendly plantings. Their case study at the Topaz Solar Farm in California reported improved habitat quality and increased avian and invertebrate abundance.

Multiple scholars emphasize that site selection is critical. Xiao et al., (2025) advocate for integrating ecological modelling and species-specific forecasting into solar energy planning, suggesting that proactive strategies can avert long-term ecological damage.

Despite growing interest, there remains a lack of standardized methodologies and geographic diversity in the literature. Lafitte et al., (2023) highlight that most empirical studies are limited to North America, with few longitudinal datasets or consistent biodiversity indicators. They call for expanded research in underrepresented regions such as, Africa, Asia and Latin America, and more rigorous ecological monitoring to inform policy and best practices globally.

2.1.3 Water consumption

Beyond terrestrial impacts, USSE projects also interact with water resources; an especially pressing concern in arid and semi-arid environments where solar potential is high. PV systems are widely recognized for their low operational water footprint, primarily due to their non-thermal nature[8]. Operational water demand is confined to mainly cleaning and, in some cases, cooling panels [8,11].

Yet, the narrative is more nuanced. Water-stressed regions, especially those in arid and semi-arid zones, remain highly sensitive to even marginal increases in water demand

[9]. Tawalbeh et al., (2021) caution that the deployment of USSE in these environments can amplify competition for limited water sources, particularly when sited near areas where other critical uses such as domestic supply or agriculture are present, even at the local scale.

Moreover, although often overlooked, water consumption during the construction phase of PV plants can be considerably higher than during operation. Water use at this stage ranges from 0.0367 to 0.7488 m³/MWh for consumption and up to 6.0112 m³/MWh for withdrawal [11]. In 2016, PV installations accounted for nearly 29% of water consumed and 27% withdrawn across all non-hydro renewable plant constructions in Africa, owing to their relatively larger deployment compared to other renewables like wind or CSP. While CSP technologies have higher per-unit construction water use, their limited installed capacity means their absolute water demand remains smaller than that of PV [11].

Furthermore, upstream processes such as mineral extraction, silicon purification, and module fabrication are considerably more water intensive [11]. Wastewater generated during these processes necessitates effective treatment and reuse to minimize environmental harm, with various technologies such as biological treatment, adsorption, and membrane separation being employed.

2.1.4 Air pollution

While USSE is widely praised for producing zero air emissions during operation, it still has indirect air pollution impacts associated with its lifecycle. Unlike fossil fuel-based power plants, PV systems do not release air pollutants such as carbon dioxide (CO₂), methane (CH₄), nitrogen oxides (NO_x), or sulphur oxides (SO_x) during operation [8]. This characteristic makes them highly valuable in efforts to mitigate air pollution and improve public health outcomes associated with poor air quality.

Although PV systems are emission-free during their active lifetime, emissions are associated with upstream and downstream processes, particularly during the manufacturing phase. Key sources include the energy-intensive production of materials such as aluminium, steel, and high-purity silicon, as well as the fabrication of glass and module assembly [8]. Studies indicate that manufacturing accounts for the overwhelming majority, up to 90–95%, of the life cycle GHG emissions of PV systems. Transport-related emissions are minimal, contributing less than 1% to the total. This is because PV modules, though often shipped over long distances, involve minimal fossil fuel consumption relative to the emissions embedded in their production.

The extent of manufacturing emissions is largely influenced by the energy mix used in module production. For instance, PV panels manufactured in regions with coal-dominant grids tend to have higher embodied emissions than those produced using renewable or low-carbon electricity [8].

To reduce the air pollution and carbon intensity of PV deployment, several strategies are being explored. These include using low-carbon or renewable-powered manufacturing, increasing the lifespan and efficiency of PV systems, and deploying alternative technologies such as cadmium telluride (CdTe) and cadmium selenide (CdSe) quantum dot thin-film modules, which typically require less material and energy to produce. Ground-mounted installations in high-irradiance regions like deserts can further optimize performance and minimize per-kWh emissions. Additionally, improved system design, including larger capacities and scalable configurations, contributes to more favourable emission profiles over time [8].

2.1.5 End of life (EoL)

As USSE systems approach the end of their operational lives, concerns shift from environmental impacts during use to those associated with disposal and recycling. This final subsection explores the growing challenge of solar waste and the global response to managing PV system end-of-life impacts.

As one of the most environmentally sustainable sources of electricity, PV systems are witnessing rapid deployment worldwide [12]. However, their typical operational lifespan of approximately 30 years, will eventually raise pressing concerns about the handling of EoL modules, particularly in utility-scale projects where the volume of decommissioned panels will be substantial. According to projections by the IEA PVPS and IRENA, cumulative global PV waste could reach 8 million tonnes by 2030 and up to 78 million tonnes by 2050 [12].

Improper EoL management can undermine the climate and environmental benefits gained during the operational phase. Landfilling, for example, remains a common but unsustainable practice [13]. Many PV modules contain hazardous substances such as lead, cadmium, and antimony, which can leach into soil and groundwater if not properly managed. Sharma et al., (2021) demonstrated that aged polycrystalline panels exposed to acidic conditions released lead at levels exceeding safe environmental limits. However, modules with intact glass-laminate layers exhibited significantly reduced leaching potential, indicating that controlled disposal conditions can mitigate risks.

To address these environmental concerns, recycling of EoL PV modules is increasingly recognized as both an economically viable and ecologically necessary solution [12,13]. In response, numerous jurisdictions have adopted EPR frameworks. The European Union set a precedent by including PV modules in its Waste Electrical and Electronic

Equipment (WEEE) Directive in 2012, mandating material recovery and depollution standards [14].

Despite growing attention to solar panel recycling, significant gaps remain in the end-of-life management of PV modules. Current recycling practices are often energy-intensive and economically unviable, with low recovery rates for valuable materials such as silver, indium, and tellurium. Moreover, regulatory and infrastructural gaps persist, especially in developing nations [13]. These limitations are compounded by the absence of harmonized global regulations and the inconsistent classification of PV panels as hazardous waste, particularly in developing countries. Without robust policy frameworks and investment in recycling innovation, the environmental risks associated with PV waste are likely to escalate as deployment scales up.

2.2 LCA of USSE systems

The preceding sections have outlined the key environmental dimensions of USSE, from land and water impacts to biodiversity disruption, air pollution, and end-of-life management. However, to systematically assess these, LCA is the globally recognized framework for evaluating environmental impacts across a system's entire life, from raw material extraction (cradle) to end-of-life management (grave) [15].

Although the global deployment of USSE systems has accelerated, LCA research in this domain has not evolved at the same pace. Much of the existing literature prioritizes economic or technical feasibility, often overlooking comprehensive life cycle environmental considerations. Where environmental LCAs have been conducted, they predominantly focus on small- or medium-scale monofacial PV systems, often omitting the unique characteristics of utility-scale infrastructure [16]. Most studies focus narrowly on PV modules, particularly

during manufacturing and recycling phases [2]. Limited attention has been given to utility-scale systems, especially in relation to the Balance of System (BOS) components such as inverters, transformers, support structures, and electrical infrastructure [17].

Moreover, scholars emphasize that large-scale solar PV systems are not directly comparable to smaller systems due to their structural complexity, land use intensity, and greater civil works [10]. Additionally, inconsistency in Life Cycle Impact Assessment (LCIA) methodologies across studies hinders comparability, underscoring the need for harmonized LCA protocols in the solar sector.

Table 1 summarizes selected international studies and highlights several key gaps. GHG emissions vary widely, from 27.4 to 149.3 g CO₂-eq/kWh, due to factors like solar irradiance, module efficiency, system design, and methodological choices such as system boundaries and LCI database. While PV module production remains the dominant emissions source, BOS and storage systems (e.g., lithium-ion batteries) also contribute significantly. For instance, Mehedi et al., (2022) found that lithium-ion batteries contributed over 50% of total GHG emissions in hybrid configurations.

A notable insight from this review is the severe underrepresentation of SSA in the LCA literature. Only one study, by [16], based on a 33.7 MW project in Zagtouli, Burkina Faso, focuses on the region. Despite the project's high solar irradiance (2,140 kWh/m²/year), it reports moderate GHG emissions of 37–48 g CO₂-eq/kWh. This suggests that while high irradiance can reduce life cycle emissions per unit of energy, other regional factors; such as the use of imported components, limited BOS optimization, or nascent infrastructure for recycling and maintenance, may elevate environmental impacts relative to global best practice [18].

Kenya, despite its renewable energy leadership and high solar irradiance, lacks any published environmental LCA for utility-scale PV. This dissertation addresses that gap by providing the first localized LCA of the Garissa Solar PV plant. The analysis incorporates Kenyan-specific factors where possible and aims to inform more sustainable and regionally relevant planning.

3 Methodology

3.1 Research design

This study uses a LCA method to evaluate the environmental performance of the Garissa Solar PV Plant. It focuses on GHG emissions throughout its entire operational lifespan. LCA is a well-known analytical tool that measures environmental impacts from start to finish, covering raw material extraction, manufacturing, transportation, operation, and disposal at the end of life [15].

There are two main types of LCA: Attributional LCA (ALCA) and Consequential LCA (CLCA). ALCA assigns environmental burdens based on average material and energy flows within a set system boundary [19]. It is used to quantify the emissions that arise from the physical processes in the system's current life cycle, rather than estimating the overall change in emissions that would result from choosing to build or operate the system. In contrast, CLCA looks at the wider consequences of decisions, such as market changes, policy actions, or shifts in behaviour. It is often used for scenario analysis and strategic planning [19].

Since the study aims to assess the fixed environmental footprint of a utility-scale solar installation under current technology and infrastructure, an ALCA framework was adopted. This approach aligns with the goal of generating empirical evidence for Kenya's solar infrastructure as it is now. Nonetheless, the importance of CLCA is acknowledged in interpreting the results, especially regarding policy implications and end-of-life management. For instance, while ALCA highlights the end-of-life phase as a major source of emissions, analysing the long-term impact of introducing solar-specific recycling systems or enforcing EPR regulations would need CLCA thinking.

By recognizing the strengths and weaknesses of both approaches, this study provides a more complete understanding of the environmental sustainability of utility-scale solar PV systems in Kenya. It helps support better decision-making for future energy planning.

To guide the modelling process, a narrative literature review of peer-reviewed LCAs was conducted on utility-scale PV systems in Africa. Although not systematic, the review shaped core methodological parameters. It informed the definition of system boundaries, selection of the functional unit, identification of impact categories, and establishment of performance benchmarks for similar technologies in comparable climatic and operational settings [16,17,20]. This integration enhances transparency and consistency of modelling assumptions and aligns with best practices in PV-related LCA research.

3.2 Software used

Due to budget and accessibility constraints, a custom Excel-based model was used to calculate emissions instead of relying on proprietary platforms like SimaPro or Sphera. This decision came from the need for complete transparency and flexibility in changing emission factors and region-specific assumptions.

The model was designed to calculate emissions using mass-normalized inputs, Ecoinvent v3.10 data, and confirmed emission factors from recent studies on PV in Africa and China [2,17]. These factors were modified to suit the regional context of East Africa, taking into account transportation distances, grid emission intensities, and the lack of formal recycling infrastructure. Electricity grid emission factors for upstream manufacturing were based on China's 2017 grid mix, aligning with the procurement timeline of the Garissa plant. A complete breakdown is provided in supplementary information, section S3

.

3.3 Case study description: Garissa Solar PV plant

The case study selected for this assessment is the Garissa Solar PV Plant, a USSE facility located in Garissa County, Kenya. Commissioned in 2018, the plant represents a landmark in the region's renewable energy development, with an installed capacity of 54.65 MW, making it the largest grid-connected solar facility in East and Central Africa [21]. The plant is overseen by the Rural Electrification and Renewable energy Corporation (REREC, formerly REA), which leads renewable energy and rural electrification initiatives in Kenya.

The facility is situated in an arid region characterised by high solar irradiance (approximately 2000 kWh/m² annually), low precipitation (below 400 mm/year), and wide diurnal temperature variations [22].

Figure 3 provides a partial aerial view of the plant, showing the layout of the 85-acre site. It hosts 206,232 polycrystalline PV modules (265 Wp each) and 1,172 inverters. Electricity is transmitted through a 5.23 km; 132 kV line connected to a 132/33/11 kV substation managed by Kenya Electricity Transmission Company (KETRACO). The electrical system includes a 50 MVA transformer, 33 smaller step-up transformers (0.415/33 kV), an indoor 33 kV switch room, and a central control room with real-time monitoring and CCTV systems [21].

Most plant components were sourced internationally. PV modules came from Jinko Solar, and inverters from BYD, both based in China. Additional electrical parts, including transformers and cables, were also imported. The EPC contract was awarded to China Jiangxi International Economic and Technical Cooperation Co. (CJIC), which subcontracted civil and design work to two other Chinese firms [21]. This international sourcing is critical to LCA due to the embodied carbon from long-distance manufacturing and transport.

The Garissa Solar PV Plant was selected as a case study due to its operational status, scale, data availability, and policy significance within Kenya's renewable energy framework. It offers a representative model for assessing the life cycle environmental performance of utility-scale PV installations in the East African context. The plant's reliance on imported materials and technologies presents an opportunity to examine embedded emissions across its life cycle, including manufacturing, transportation, and disposal stages, core components of this research. Additionally, the case highlights sustainability trade-offs in project localisation, supply chain design, and infrastructure resilience, thereby enriching the LCA's interpretative value

3.4 LCA framework

The LCA was carried out in accordance with the principles, framework, and methodological requirements outlined by the International Organization for Standardization, as well as the recommendations provided by the International Energy Agency's PV Power Systems Programme [15,20].

The LCA process follows a systematic approach across four key phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation, as shown in **Figure 4**. The subsequent sections provide a detailed discussion of each phase of the LCA process.

3.4.1 Goal and scope definition

The primary goal of this LCA is to quantify the environmental impacts, particularly GHG emissions, associated with the operation of the Garissa Solar PV Plant, a 54.6 MW grid-connected facility in Kenya. The LCA aims to support evidence-based policy decisions,

aid in energy infrastructure planning, and contribute to sustainability evaluations for large-scale solar power projects.

The system boundary for this study includes the entire life cycle of the solar power system, from raw material extraction (cradle) through manufacturing, installation, operation, and eventual decommissioning (grave). This is illustrated in **Figure 5**.

Key system components analysed in this study included:

- 206,232 polycrystalline silicon modules (265 Wp each)
- 1,172 inverters
- 33 x Transformers, cabling, and mounting structures

A 25-year operational lifetime was applied for modules, with shorter lifespans for inverters (10 years) and longer lifespans for mounting structures (30 years), based on [20].

3.4.1.1 Functional unit

A dual-functional unit approach was adopted:

- 1 kWp installed solar capacity (for equipment-level mass normalization)
- 1 kWh electricity delivered (for emissions performance benchmarking)

This method allows for integration of component-level inventory data while supporting broader policy and sustainability comparisons in terms of energy output per unit of climate impact. The use of output-normalized metrics is particularly relevant given Kenya's solar resource variability and the importance of comparability in LCA [20].

3.4.2 Life cycle inventory (LCI) data

The LCI analysis involved systemically compiling and quantifying all material, and emissions flows associated with the Garissa Solar PV Plant throughout its life cycle. A

bottom-up modelling approach that combined empirical assumptions with mass and energy balance equations to estimate equipment amounts and their resource needs.

To ensure contextual relevance and credibility, data was sourced from a manufacturer specification sheets [23], peer-reviewed academic literature [24], and industry reports. Inventory data were categorised into foreground processes, which reflect site-specific or system-specific data (e.g., installation practices, transportation logistics), and background processes, which were derived from global datasets and represent upstream manufacturing or extraction activities.

Technical parameters for the PV modules and inverters were derived from manufacturer datasheets and are summarised in supplementary information, section S1. A complete breakdown of raw materials used for PV modules, inverters, and mounting structures, including quantities of silicon, aluminium, copper, and steel, is presented in supplementary information, section S2. This data supports all subsequent emission calculations in the Life Cycle Impact Assessment (LCIA) phase.

3.4.2.1 Manufacturing

Solar Panels: The impacts of solar panel manufacturing were modelled using inventory data gathered from several recent and reliable sources. For the extraction and processing of silica sand into metallurgical-grade silicon (mg-silicon), updated inventories from Heidari and Anctil. (2022) and Méndez et al. (2021) were used to reflect current industrial practices. The subsequent stages including, polysilicon production, wafering, and solar cell manufacturing, were mainly informed by Antonanzas et al. (2019). Their data closely matches the comprehensive inventory published by Xie et al. (2018). Xie's study is particularly robust, drawing from facilities responsible for 66% of China's national PV production as of 2013, making it a credible benchmark for monocrystalline silicon (m-Si)

panel manufacturing. Module assembly was modelled using estimates from Antonanzas et al. (2019), which align with other recent sources such as Frischknecht et al. (2020), thereby ensuring consistency and reliability across the full panel production chain.

Mounting Structures: The mounting structures were modelled based on a fixed, horizontal (0° tilt) configuration, consistent with the actual plant design. Drawing from recent real-world installations, a unitary material intensity of 38.02 kg/kW was adopted, as reported by Antonanzas et al. (2019). This value corresponds to a double-post steel structure, where rows of flat-mounted PV panels are supported by galvanized steel posts, rafters, and purlins.

Inverters: Inventory for inverters were derived from Badza et al. (2023), which provide a detailed LCI for central inverters with specifications comparable to those used in this system. Although the actual inverters in the 54.65 MWp system may vary in capacity, the proxy data were considered technically suitable for this analysis. Material and energy inputs were normalized per kilowatt of inverter capacity to ensure consistency with the system's scale.

Transformers: Due to the lack of detailed manufacturer information, a proxy LCI for a 2330 kVA, 420 V oil-immersed transformer, as reported by Badza et al. (2023), was employed. Although the actual transformers used in the 54.65 MW system are 415/33 kV units with an estimated capacity of 1656 kW each and manufactured in China, the proxy was considered technically comparable. To account for the capacity difference, all material and energy inputs were normalized per kilowatt of transformer capacity. The manufacturing impacts of 24 proxy transformers were modelled to represent the system's total transformer capacity. This number aligns closely with the system's installed DC capacity of 54,650 kWp, thereby avoiding fractional scaling while maintaining a reasonable approximation. Regional

manufacturing differences were not modelled, and results should therefore be interpreted with caution. Sensitivity analyses are recommended to assess the robustness of assumptions related to transformer impacts.

Other BOS elements: The inventory for “electrical installation” was based on the work of Méndez et al. (2021), which provides recent empirical data from a large-scale ground-mounted solar system. This source primarily covers components such as cables, conduits, and other electrical connection elements.

3.4.2.2 Transportation modelling

Transport emissions were calculated based on the distances between major supply chain nodes and the project site. These are summarized in **Table 2**.

These distances were applied in emissions modelling for both upstream logistics and end-of-life disposal. Full emission factors and transport assumptions are presented in supplementary information, section S5.

3.4.2.3 Decommissioning

Due to the absence of dedicated solar PV recycling infrastructure and the lack of a formal solar specific end-of-life pathways in Kenya, landfilling was assumed as the default disposal method for major system components at the end of their service life. Although the 2024 EPR regulations now categorise solar equipment under general e-waste, implementation remains limited, and no tailored solar recycling streams currently exist [7]. In practice, components may also enter informal e-waste channels, where dismantling and disposal practices are unregulated and data availability is scarce.

Given that solar PV modules typically have an operational lifespan of 25–35 years, [20] and that Kenya’s utility-scale PV deployment accelerated in the early 2010s [27] most systems in the country are projected to reach their end-of-life phase in the early 2030s.

Accordingly, the decommissioning phase was modelled conservatively, assuming no material recovery or reuse, under the premise that infrastructure and data remain insufficient, while recognising that these conditions may improve by the 2030s as policy and industry capacity develop. All major components, including PV modules, inverters, and mounting structures, were assumed to be transported approximately 350 kilometres to the nearest appropriate landfill, such as the Dandora dumpsite. A detailed dismantling or refurbishment phase was not included, in line with established LCA practice and guidance, which recommend conservative, transparently documented end-of-life assumptions when waste management systems are nascent or undocumented [15].

3.4.3 Lifecycle impact assessment (LCIA)

The LCIA phase translated the inventory data developed in Section 3.4.2 into quantified environmental impacts. This study focused on one impact category: Lifecycle GHG emissions. The GHG flows were identified and calculated in the LCI. The LCIA stage then converted these flows into CO₂-equivalent values by applying the relevant global warming potentials. The assessment was implemented using a bottom-up Excel-based model, which applied emission-factor data to the material and process flows captured in the inventory.

In accordance with ISO 14044 and IEA PVPS guidance, all impacts are normalised to the functional unit of 1 kilowatt-hour (kWh) of electricity delivered to the grid over the system's 25-year operational lifetime [20]. The LCIA model incorporated impacts from module manufacturing, BOS components, transport logistics, and end-of-life processing.

3.4.3.1 GHG calculations

The GHG emissions associated with each life cycle stage were derived by scaling the total emissions from materials and processes to the total electricity generated over the system

lifetime. The following equations were applied to estimate emissions per kilowatt-hour for various life cycle phases.

PV module and BOS emissions:

$$GHG_{PV} = (LCI_{panel} \times A_{panel} \times N_{panels}) / (E_{annual} \times 25) \quad \text{Eq. (1)}$$

$$GHG_{BOS} = (LCI_{BOS} \times A_{BOS} \times N_{BOS}) / (E_{annual} \times 25) \quad \text{Eq. (2)}$$

Where:

- GHG_{PV} , GHG_{BOS} : GHG emissions from PV manufacturing and BOS respectively (kg CO₂-eq kWh⁻¹),
- LCI_{panel} , LCI_{BOS} : Life cycle inventory impact of panel and BOS respectively (kg CO₂-eq m⁻²),
- A_{panel} : Area of one panel (m²),
- N_{panels} : Number of panels,
- E_{annual} : Annual electricity production (kWh/year),
- 25: System lifetime in years

Transportation emissions:

Transportation emissions accounted for both maritime and road-based logistics involved in delivering components from manufacturing locations (primarily China) to the Garissa site. The calculation was expressed as:

$$GHG_{Transport} = (LCI_{road} \times D_{road} \times LCI_{ocean} \times M \times D_{ocean}) / (E_{annual} \times 25 \times 1000) \quad \text{Eq. (3)}$$

Where:

- LCI_{road} : Emission factor for road transport (kg CO₂-eq/ton-km),
- LCI_{ocean} : Emission factor for ocean transport (kg CO₂-eq/ton-km),
- M : Mass of panels, and BOS system (kg),
- D_{road} : Road transport distance (km),

- D_{ocean} : Ocean transport distance (km),
- E_{annual} : Annual electricity production (kWh/year),
- 25: System lifetime in years,
- 1000: Conversion factor from kg to tons

End of life (EoL) emissions:

EoL emissions were calculated based on the environmental impacts of transporting and landfilling PV modules, with recycling excluded due to the absence of formal infrastructure. All components are assumed to be disposed of 350 km from the site. Detailed calculations are provided in supplementary information, section S6.

$$GHG_{\text{EOL}} = (LCI_{\text{landfilling}} \times A_{\text{panel}}) / (E_{\text{lifetime}}) \quad \text{Eq. (4)}$$

Where:

- GHG_{EOL} : GHG emissions from end-of-life treatment (kg CO₂-eq kWh⁻¹),
- $LCI_{\text{landfilling}}$: Landfilling impact per m² (kg CO₂-eq m⁻²),
- A_{panel} : Area of one panel (m²),
- E_{lifetime} : Total electricity produced over system lifetime (kWh/panel)

3.5 Study limitations and assumptions

The life cycle inventory for this study was developed using secondary data, as no primary operational data were available from the Garissa Solar PV Plant. Although this approach reduced the accuracy for this specific site, using secondary data is an accepted method in LCA research, especially when data is limited. Peer-reviewed studies like Badza et al., (2023), Mehedi et al., (2022), and Hou et al., (2016) have effectively used secondary datasets to evaluate the environmental performance of large-scale solar PV systems. These examples demonstrate that, when carefully selected and adjusted, secondary data can provide

trustworthy insights that have remained viable for policymaking. To improve the relevance of the context, emission factors and inventory inputs were modified using regionally suitable sources and checked against international standards. Nevertheless, the results should be interpreted carefully. Future research would benefit from having access to primary operational data and site-specific measurements.

Energy generation and component performance were modelled as fixed averages over a 25-year lifespan, even though degradation is known to occur. The assessment only looks at GHG emissions because of the limits of Excel-based models, leaving out other impact categories like water use, land transformation, and toxicity.

End-of-life modelling assumed non-recyclability of materials, reflecting the absence of formal solar recycling systems in Kenya. In practice, however, some components may enter informal e-waste streams, where unregulated recovery could reduce landfill volumes but introduces uncertainty in environmental outcomes. Informal recovery was excluded from the model due to unreliable data and the absence of standardized accounting methods, even though such practices could contribute to material reuse. Future studies would benefit from exploring mixed end-of-life scenarios that incorporate both formal and informal recovery pathways.

Moreover, the findings of this study are specific to the Garissa Solar PV Plant and should not be overgeneralised to all Kenyan PV projects, as differences in irradiance, logistics, and balance-of-system designs may alter lifecycle impacts. Future assessments could be improved by adding more environmental indicators, socio-economic factors, and sensitivity analyses, which would enhance the usefulness and policy relevance of LCA applications in Kenya.

4 Results and discussion

4.1 Overview of lifecycle GHG emissions

This study estimates the cradle-to-grave GHG emission intensity of the Garissa Solar PV plant based on a projected system output of 2.19 TWh over 25 years and an average annual solar irradiance of 2000 kWh/m². The findings indicate that the total lifecycle GHG emissions amount to 23.6 g CO₂-eq kWh⁻¹ of electricity delivered to the grid. This result aligns with global lifecycle estimates for PV systems situated in high-emission supply chains, which typically range between 20 and 60 g CO₂-eq kWh⁻¹, depending on technology type, geography, and system boundaries [28]. Notably, the high solar irradiance at Garissa substantially enhances the plant's annual energy yield, thereby reducing the GHG emissions per kilowatt-hour of electricity generated. This inverse relationship between solar resource availability and emission intensity is consistent with findings from similarly irradiated regions [2,16].

However, this seemingly moderate emission figure should not be interpreted as an inherently “clean” outcome. Rather, it reflects a composite of structural advantages and analytical exclusions. For example, this assessment omits key components often included in more expansive LCAs, such as BESS, land-use transformation, site infrastructure, and operational water use. As shown in studies like Mehedi et al. (2022) and Antonanzas et al. (2019), inclusion of such parameters can significantly increase lifecycle emissions. Compared to global fossil-fuel-based electricity generation, the plant exhibits a 90–95% reduction in lifecycle GHG emissions, as shown in **Table 3**.

Thus, while Garissa demonstrates strong carbon efficiency, its 27.73 g CO₂-eq kWh⁻¹ should be seen as a baseline under current infrastructure and supply chains, not a universal

benchmark. This observation underscores a central paradox: although Kenya is a regional renewable energy leader, it imports a significant portion of the environmental cost embedded in its solar infrastructure. As Kenya scales up USSE, greater scrutiny of upstream emissions and supply chain sustainability will be essential.

4.1.1 Emissions breakdown by lifecycle stage

Figure 6 and **Figure 7** present the proportional and normalized breakdown of GHG emissions across the plant's lifecycle stages. The most carbon-intensive phase is manufacturing, which contributes 73.1% of the total emissions ($17.27 \text{ g CO}_2\text{-eq kWh}^{-1}$). This is followed by BOS production, which accounts for 24.8% of total emissions ($5.85 \text{ g CO}_2\text{-eq kWh}^{-1}$). Transportation contributes marginally to overall emissions, at just 2.0% ($0.47 \text{ g CO}_2\text{-eq kWh}^{-1}$), with end-of-life impacts remaining below 0.1% of total emissions.

4.1.1.1 Manufacturing

PV module manufacturing is a major source of emissions in Garissa's lifecycle, contributing $17.27 \text{ g CO}_2\text{-eq kWh}^{-1}$. The most carbon-intensive processes are solar-grade silicon purification ($9.81 \text{ g CO}_2\text{-eq kWh}^{-1}$) and wafer production ($3.03 \text{ g CO}_2\text{-eq kWh}^{-1}$), reflecting the fossil-fuel-heavy energy mix in China, where the modules are produced [2]. Additional contributions arise from solar cell processing and panel assembly, which together add roughly $2.81 \text{ g CO}_2\text{-eq kWh}^{-1}$ to manufacturing-stage emissions.

This figure aligns with global estimates for multi-Si modules of 15–17% efficiency, which report module-related emissions between $13\text{--}17 \text{ g CO}_2\text{-eq kWh}^{-1}$ [28]. However, manufacturing emissions depend more on the regional electricity mix than module efficiency. Processes like silicon purification, ingot casting, and aluminium frame production are particularly carbon-intensive when powered by coal [17].

The BOS phase contributes 5.85 g CO₂-eq kWh⁻¹, making it the third-largest contributor. Mounting structures, primarily steel, account for 4.58 g CO₂-eq kWh⁻¹ (nearly 80% of BOS emissions), while the rest (~1.27 g CO₂-eq kWh⁻¹) comes from inverters, cabling, and transformers, which rely on energy-intensive materials like copper and plastics [26,28].

These figures are consistent with international benchmark. [28] reports show that steel-intensive racking systems can contribute up to 20–25% of total lifecycle emissions in utility-scale PV projects. Similarly, regional case studies in Latin America and Asia report BOS emissions in the range of 5–7 g CO₂-eq kWh⁻¹, depending on material sourcing and structural design [28].

4.1.1.2 Transportation

Transport-related emissions for the Garissa Solar PV Plant are estimated at 0.47 g CO₂-eq kWh⁻¹, accounting for approximately 2% of total lifecycle emissions. This minor contribution is consistent with wider empirical findings, which place transport as a relatively small emitter compared to energy-intensive manufacturing and end-of-life processing stages. For instance, Ito et al. (2016) found that transporting PV modules contributes only 0.5 t CO₂-eq per MW, compared to 1,491 t CO₂-eq per MW for production and 37 t CO₂-eq per MW for waste treatment. Similarly, Mukoro et al. (2021) notes that transport emissions across African utility-scale solar projects remain relatively low, especially when supply chains are dominated by carbon-intensive production and undeveloped waste infrastructure.

Nonetheless, this modest footprint reveals deeper structural dependencies. The Garissa project sources all core system components—including PV modules, inverters, and mounting structures—from Asia, requiring long maritime and inland transport. While sea

freight is generally energy-efficient, the inland leg from the port of Mombasa to Garissa spans over 500 km and reflects the logistical complexity of deploying infrastructure in remote, under-resourced regions. Moreover, as Mukoro et al. (2021) emphasizes, transport impacts vary with mode, distance, and vehicle fuel efficiency, suggesting scope for emissions reductions via better logistics and procurement strategies.

Therefore, transportation, though low in emissions, is analytically significant for two reasons. First, it reflects the outsourcing of manufacturing emissions to distant economies, tying Kenya's renewable energy transition to the decarbonisation of exporting nations. Second, it highlights the PV sector's limited localisation, reducing potential industrial spillovers and exposing vulnerabilities to rising shipping costs, geopolitical risks, and carbon border adjustment policies.

4.1.1.3 Decommissioning

The EoL stage emerges as the least carbon-intensive phase in Garissa's lifecycle, contributing 0.1% ($0.0237 \text{ g CO}_2\text{-eq kWh}^{-1}$) of total emissions. This very small figure reflects the current modelling assumption of complete landfilling and a 350 km haul to disposal sites, which mirrors Kenya's present lack of formal PV recycling infrastructure. In other words, the number is low because landfilling is a low-energy treatment and the model does not include any recycling credits for recovered materials.

This framing is consistent with international LCA work. When landfill is the endpoint, EoL GHG burdens are typically very small compared with manufacturing. EoL only becomes more visible when studies include energy-intensive recycling processes and apply avoided-burden credits for recovered materials. In regions with mature waste systems, such as those operating under the EU's WEEE framework, policy requires structured collection and treatment of PV waste. As a result, EoL is discussed more prominently in

those contexts, even though its GHG share still remains modest relative to upstream manufacturing [20].

However, the assumption of zero recycling likely overstates long-term emissions. Kenya, like many developing economies, hosts a vibrant informal sector that engages in the recovery of valuable materials such as aluminium, copper, and steel. While these practices are often environmentally unsafe, they do contribute to material circularity and should not be overlooked in emissions accounting.

Recent studies underscore the emission-reduction potential of formalised recycling. Badza et al. (2023) estimate that end-of-life recycling can lower lifecycle emissions by 17–38%, primarily through the substitution of virgin materials with recycled inputs.

Importantly, Kenya’s 2024 EPR regulations offer a policy framework to formalise EoL practices [7]. These regulations could enable a transition from informal, unregulated recovery to hybrid systems that integrate informal actors into formal recycling networks. Such a shift would not only improve environmental outcomes but also enhance social equity by recognising the role of informal workers as stakeholders rather than obstacles.

In this context, the current LCA serves as a baseline: a conservative, present-day scenario that usefully highlights where infrastructure and governance will have the greatest leverage. Future assessments should adopt mixed EoL scenarios that reflect both informal recovery and emerging formal systems. This would yield more accurate emissions estimates and provide policy-relevant insights for sustainable PV deployment in Kenya and similar contexts.

4.2 Broader environmental and social externalities

4.2.1 BESS: A forward-looking challenge for lifecycle thinking in Kenya

As Kenya accelerates its transition toward a renewables-led energy system, the deployment of BESS is no longer a question of if, but of when. While the Garissa Solar PV plant currently operates without integrated storage, future utility-scale projects, especially in solar-dominant grids of ASALs, will increasingly require BESS to manage intermittency, enhance dispatchability, and stabilize grid operations. This shift is already embedded in national energy planning, with the 2024–2043 LCPDP and EPRA’s 2050 strategy documents identifying large-scale storage as a critical enabler of Kenya’s clean energy future [6,27].

However, this transition introduces a critical oversight in current LCAs. BESS, especially those using nickel manganese cobalt (NMC) lithium-ion chemistries, carry substantial environmental and social burdens that are often excluded from planning frameworks(Raugei et al., 2020). Studies suggest that incorporating lithium-ion storage can increase lifecycle GHG emissions by 30–60% (e.g., from 23.6 g CO₂-eq kWh⁻¹ to 31–38 g CO₂-eq kWh⁻¹).

Beyond emissions, BESS technologies introduce complex resource and toxicity trade-offs. Cobalt and lithium mining, required for most high-density battery chemistries, has been linked to water depletion, habitat loss, and hazardous waste generation during both extraction and disposal [30]. The social dimension is equally troubling. Over 70% of the global cobalt supply originates from the Democratic Republic of Congo, where systemic human rights violations, including child labour and dangerous artisanal mining practices, have been widely documented. These impacts are not abstract; they are embedded in the upstream supply chains Kenya will increasingly depend on as it scales battery procurement.

To ensure a more holistic sustainability approach, future LCAs must treat BESS as a core component of high-renewables systems rather than an optional add-on. Assessment frameworks should expand to include indicators for resource scarcity, toxicity, and social equity.

4.2.2 *Water use*

Although PV systems have a relatively low water footprint compared to thermal power plants, water use remains a critical sustainability concern in arid regions such as Garissa. While PV technology avoids the large cooling water requirements typical of thermoelectric generation, it still depends on water during construction and operation [31].

At the operational phase, water is primarily needed for cleaning panels to mitigate dust accumulation, which can reduce efficiency by up to 30% [31]. Garissa's design, horizontal 0° tilt panels, exacerbates this issue by trapping more dust and retaining water, leading to cementation that degrades performance. While such mounting reduces capital costs, it raises long-term operational inefficiencies. Design improvements such as, increasing tilt angles to $\geq 15^\circ$, and applying anti-soiling coatings, can reduce cleaning frequency by 30-40% [31].

Based on African benchmarks, operational cleaning typically requires 1 and 5 L/MWh [11]. Applying this to Garissa's annual generation of about 76,000 MWh suggests a cleaning demand of between 76,000 and 380,000 litres per year. Comparable studies in the Middle East report up to 0.5 litres/m² per cleaning cycle is required [32], suggesting that local water stress could be exacerbated if similar practices are adopted.

On the other hand, construction-phase water use is considerably higher. Estimates for PV projects in Africa indicate consumption between 0.0367 and 0.7488 m³/MWh and withdrawals up to 6.0112 m³/MWh, largely due to concrete mixing, dust suppression, and

component manufacturing. In 2016, PV installations accounted for nearly 29% of water consumed and 27% withdrawn across all non-hydro renewable plant constructions in Africa, reflecting their scale of deployment [11]. Although CSP technologies have higher per-unit construction water intensity, their limited installed capacity means their absolute water demand remains smaller than PV. Moreover, upstream processes such as silicon purification are even more water-intensive requiring up to 470 kg of water per kilogram of silicon produced.

Globally, PV systems exhibit one of the lowest water footprints (75–190 L/MWh) compared to coal, nuclear, or natural gas (>1, 000 L/MWh). Nevertheless, localized impacts in arid regions remain non-trivial.

Therefore, there is a need for mitigation strategies such as robotic dry-cleaning, electrostatic dust removal, or rainwater harvesting. However, while automated dry-cleaning technologies are available, they may be cost-prohibitive and technically demanding for decentralised rural systems [33]. In this regard, emerging solutions from similar environments could offer valuable insights. For instance, countries like Jordan and Morocco have integrated rainwater harvesting systems into PV farms, where tilted panels serve as catchment surfaces. Even in low-rainfall regions, intermittent harvesting paired with basic filtration and storage can meet panel cleaning needs during dry periods [32].

Moreover, construction-phase water use highlights the importance of integrating water considerations into Environmental Impact Assessments and planning frameworks to ensure that upstream demands do not undermine the sustainability of solar deployment.

4.3 Advancing sustainable solar: Global lessons for Kenya's PV transition

Kenya's rapid expansion of PV infrastructure presents a critical opportunity to advance both climate mitigation and energy equity. However, achieving sustainability at scale requires a holistic approach that goes beyond clean electricity generation. This section synthesizes global best practices and contextualizes them for Kenya, with a focus on environmental resilience and infrastructural realities in arid counties such as Garissa.

4.3.1 Rethinking end-of-life management from emissions to circularity

4.3.1.1 Regulatory foundations (EPR)

The European Union has established a comprehensive regulatory framework to manage electronic and electrical waste, guided by the WEEE directives [14]. This framework aims to ensure effective waste handling across all 28 EU member states by clearly defining the responsibilities of various stakeholders. Under the WEEE directives, manufacturers of electrical and electronic products are legally obligated to manage the end-of-life treatment of their products, regardless of where the items were produced. The directives provide detailed requirements covering the collection, recovery, and recycling of waste, with a strong emphasis on environmental protection and public health. Kenya's 2024 EPR policy offers a foundation to establish a similar formal recovery system. Adopting a PV-specific EPR approach could significantly reduce end-of-life emissions and landfill reliance.

4.3.1.2 Innovation pathways (circular solar ecosystems)

While formal EPR systems address the regulatory dimension of EoL management, emerging circular economy strategies offer complementary opportunities to extend the value of PV systems. Although large-scale reuse and industrial symbiosis for PV modules are not

yet widely implemented, they are increasingly recognised in academic and policy discourse as viable components of a sustainable solar economy.

For instance, the U.S. National Institute of Standards and Technology has identified the potential for secondary feedstocks and industrial symbiosis in solar PV manufacturing and recycling systems [34]. Pilot studies and conceptual frameworks suggest that decommissioned PV modules, particularly those with partial functionality, can be repurposed for low-demand applications such as rural lighting, agricultural pumping, or educational infrastructure. These second-life applications can delay waste generation and reduce the demand for virgin materials.

In Kenya, circularity efforts remain nascent but promising initiatives are emerging at grassroot level. For instance, Solibrium-Solar, a Kenyan solar company, launched the Resource Efficiency and Waste Management for Off-grid Solar Products (REWMOS). The project aims to identify best recycling practices and develop business models that make solar waste management commercially viable [35]. Nevertheless, these efforts remain insufficient to meet the large-scale recycling demands associated with utility-scale facilities, such as the Garissa Solar Power Plant.

Despite these challenges, Kenya is well-positioned to pioneer such circular approaches. By integrating reuse markets and co-located recycling facilities within industrial zones such as Konza Technopolis, the country could foster a circular solar ecosystem that supports decentralised energy access and green industrialisation. Notably, mounting structures and metal supports-being durable and widely usable-are highly likely to be repurposed locally, even in informal settings. This potential for reuse underscores the importance of designing PV systems with disassembly and material recovery in mind.

4.3.2 *Enabling local value chains in PV system manufacturing*

Reducing upstream emissions while maximising socio-economic benefits requires Kenya to strategically localise aspects of its solar PV value chain. Full-scale manufacturing of solar cells and modules may be capital-intensive and technologically demanding for an emerging industrial economy. However, selective local assembly and component manufacturing offer a more feasible and impactful entry point.

Currently, Kenya relies almost entirely on imported PV modules and components, primarily from China. This dependence is shaped by limited industrial capacity, high production costs, and weak policy incentives for domestic manufacturing [36]. In contrast, India has pursued a more interventionist approach combining import substitution strategies with partnerships involving transnational firms to build local capacity. Measures such as high import tariffs on solar panels and equipment and targeted industrial policies have been introduced to protect and nurture India's fledgling solar industry [37]. Moreover, India's Production Linked Incentive (PLI) scheme illustrates how targeted public investment can attract solar manufacturing, but it also highlights the importance of scale and vertical integration, challenges Kenya may struggle to overcome in the short term [37].

As such, for Kenya, a phased localisation strategy is both pragmatic and aligned with national industrial ambitions (Vision 2030). Initial focus should be on assembling imported PV cells, and domestic production of mounting systems, electrical wiring, and inverter housings, which together represent a significant share of a PV system's embodied emissions. These activities require lower capital investment and can be anchored in industrial zones such as Konza Technopolis, or Export Processing Zones (EPZs), leveraging existing infrastructure and workforce.

Localisation must also extend beyond materials. A detailed case study by Elder et al. (2022) on Solinc East Africa Ltd, Kenya's only operational solar module assembler, reveals that successful localisation depends on intricate upstream and downstream linkages, including reliable input supply and access to off-take markets. The study finds that Solinc's viability was supported by proximity to the Naivasha Industrial Park and participation in regional energy access programmes. Crucially, the author argues that Kenya's comparative advantage may lie not in full-scale manufacturing, but in the localisation of high-value service chains: system design, installation, monitoring, and maintenance.

4.3.3 Site management and biodiversity

The Garissa Solar PV plant exemplifies the environmental and social tensions that can arise when clean energy infrastructure displaces traditional land uses without adequate safeguards. Local accounts from Raya village suggest unfulfilled development promises and exclusion from former grazing lands, reflecting deeper concerns around procedural injustice and benefit-sharing in Kenya's energy transition [39].

Ecologically, land conversion in arid zones risks habitat fragmentation, reduced species richness, and disruption of key ecosystem functions such as carbon cycling and erosion control [8]. These risks are magnified in ecosystems like Garissa's, where recovery is slow and biodiversity highly specialized.

Yet multifunctional solar design offers a path forward. Agrivoltaics, vegetative buffers, and pollinator-friendly groundcover can reduce trade-offs between energy and ecology [40]. To ensure justice and resilience, Kenya must embed ecological modelling and community consultation into site selection, particularly in ASAL regions. Without these safeguards, utility-scale PV may solve one crisis while deepening others.

4.4 Policy implications

The findings of this study point to several strategic policy interventions necessary for improving the environmental sustainability of utility-scale solar in Kenya. The reliance on imported PV modules and balance-of-system components contributes significantly to lifecycle emissions, indicating the need for targeted support for regional manufacturing to reduce upstream carbon intensity. End-of-life emissions are currently small (0.1%) under a landfill-only baseline, which reflects missing recovery systems. Establishing PV-specific EPR and recycling would convert ‘missing’ EoL benefits into upstream reductions.

Kenya's 2024 EPR regulations offer a timely opportunity to establish solar-specific circular economy systems. In arid regions, operational water use for panel cleaning remains an overlooked factor; integrating water-efficient technologies and rainwater harvesting into system design is essential. Finally, the future integration of BESS could substantially increase lifecycle emissions. National energy plans must incorporate battery-related environmental risks, ethical sourcing, and alternative storage technologies to ensure long-term sustainability.

5 Conclusion

This dissertation has undertaken a comprehensive LCA of the Garissa Solar PV Plant, Kenya’s largest grid-connected solar facility (54.65 MW), to evaluate its environmental sustainability and inform future utility-scale solar deployment. The findings reveal a nuanced picture: while solar PV offers substantial climate benefits compared to fossil-based electricity generation, its environmental footprint is shaped by upstream manufacturing emissions, limited local value chains, and the absence of end-of-life (EoL) infrastructure.

The results indicated a total lifecycle GHG intensity of approximately 23.6 g CO₂-eq kWh⁻¹, placing it within the lower-emission tier of global utility-scale solar systems. This performance is largely attributable to Kenya's high solar irradiance, which enhances energy yield and reduces per-kWh emissions. However, the profile masks significant structural dependencies: upstream manufacturing dominates the footprint (73.1% from PV module manufacturing and 24.8% from BOS components). This underscores a critical insight: Kenya's solar transition, while locally clean, is globally carbon-intensive due to supply chain externalities.

Under a conservative landfill-only baseline, EoL accounts for 0.1% (0.0237 g CO₂-eq kWh⁻¹) of total emissions. This small share follows directly from the modelling choices: landfilling is a low-energy treatment, and the model applies no avoided-burden credits for materials that would be recovered under recycling. Read in context, it signals an absence of circularity infrastructure rather than an insignificant phase. Kenya's new EPR framework provides the basis for a PV-specific scheme. The next step is to adopt PV-specific rules that mandate collection, accredited treatment, and verified material recovery.

Transportation emissions were found to be minimal (2%), yet analytically significant. They reveal Kenya's reliance on long-distance imports and the logistical challenges of deploying infrastructure in remote regions. While sea freight is relatively efficient, inland transport from Mombasa to Garissa adds complexity and cost. These dependencies also expose Kenya to geopolitical risks and carbon border adjustment mechanisms, reinforcing the case for localized manufacturing and assembly.

Beyond emissions, the study identifies several broader environmental and social externalities. Operational water use, though excluded from the LCA, is a critical concern in arid regions like Garissa. Horizontal panel designs exacerbate dust accumulation, increasing

cleaning frequency and water demand. Emerging solutions such as rainwater harvesting and dry-cleaning technologies offer promising adaptations but require integration into project planning and design.

The anticipated integration of BESS presents a forward-looking challenge. While essential for grid stability and renewable integration, BESS could increase lifecycle emissions by 30–60%, depending on battery chemistry and usage patterns. Moreover, the social and environmental costs of lithium and cobalt mining, often borne by vulnerable communities in the Global South, must be internalized in Kenya’s energy planning. Lifecycle sustainability must evolve into lifecycle justice, encompassing both environmental and ethical dimensions.

Policy analysis reveals that Kenya’s regulatory framework is ambitious in deployment targets but fragmented in lifecycle oversight. Existing policies prioritize capacity expansion and grid integration, with limited attention to upstream sourcing, land-use impacts, and EoL governance. The 2024 EPR regulations offer a foundation for reform but lack solar-specific provisions. Strengthening inter-agency coordination and integrating lifecycle thinking into energy planning documents such as the Least Cost Power Development Plan and Kenya Energy Transition and Investment Plan will be essential.

Methodologically, this study demonstrates that LCAs are feasible in data-scarce contexts using custom Excel-based models. While limited in impact categories, the approach is replicable. Future work should expand system boundaries to include water, land, and socio-economic factors. Scenario modelling and Kenya-specific LCI databases will enhance accuracy and policy utility.

In conclusion, the Garissa Solar PV Plant offers both a benchmark and a cautionary tale. It exemplifies the climate potential of solar energy in high irradiance regions but also

reveals the hidden environmental costs of globalized supply chains and infrastructural gaps. As Kenya scales up solar deployment, it must move beyond carbon-centric metrics to embrace holistic sustainability. This includes investing in circular economy systems, local manufacturing, adaptive site management, and ethical procurement frameworks.

The next phase of Kenya's solar journey must be guided by integrated planning, lifecycle accountability, and inclusive governance. By embedding these principles into national energy strategies, Kenya can not only meet its climate goals but also lead the way in sustainable and equitable energy transitions across sub-Saharan Africa.

5.1 Recommendations for future studies

Scenario modelling and sensitivity analysis

Future LCAs should use probabilistic techniques, such as Monte Carlo simulations, to better characterize uncertainty in key parameters. These include module degradation rates, transportation emissions, and recycling efficiencies. Including a scenario-based framework would allow for the evaluation of different system configurations, such as partial recycling, mixed end-of-life pathways, and local manufacturing of BOS components. This would provide stronger evidence to guide policy development and investment planning for Kenya's solar sector.

Expand system boundaries

This study focused only on GHG emissions. Future research should integrate additional impact categories such as water consumption, land-use change, biodiversity loss, and supporting infrastructure (e.g., office structures, control building, fencing). Using more comprehensive tools such as OpenLCA or SimaPro would support multi-impact assessment and provide a richer understanding of the broader sustainability implications of USSE plants.

Develop Kenya specific EOL model

Since there are no established PV recycling systems in Kenya, future research should design hybrid EoL pathways that consider both formal recycling potential and informal material recovery practices. These models should examine recovery rates, logistical needs, and the environmental trade-offs tied to each pathway. This research would address important knowledge gaps as Kenya gets ready for the first wave of PV waste expected in the 2030s.

Strengthen local life cycle inventory data

To reduce reliance on global default datasets, future research should collaborate with EPRA, KETIP, the Ministry of Energy, and local academic institutions to create a Kenya-specific LCI database. This would enable the inclusion of local material characteristics, transport distances, manufacturing conditions, and grid emission factors. In the end, this would improve the accuracy, relevance, and usefulness of LCAs conducted in the region.

Declarations

Availability of data and materials

All data generated or analysed during this study can be obtained from the corresponding author upon request.

Competing interests

The author declares she has no competing interests.

Funding

The author received no specific funding for this work.

Author's contributions

Diana A. Eshibukho conceived the study, carried out the analysis, and prepared the manuscript. The author read and approved the final manuscript.

Acknowledgements

The author would like to thank Prof. Dan van der Horst for his invaluable guidance and constructive feedback, which significantly shaped the direction and depth of this research. Appreciation is also extended to Dr. Mathew Brander for his insightful review of the methodology. Finally, the author thanks Brian Robert Ngunyi for his assistance with editing the manuscript.

1088 **Author's information**

1089 Diana A. Eshibukho is a MSc Environmental Sustainability graduate (2025) from the
1090 University of Edinburgh. Her research focuses on life cycle assessment, circular economy
1091 policy, and low-carbon power systems in sub-Saharan Africa. She has a particular interest in
1092 sustainable infrastructure planning.

References

- [1] IEA. Renewables 2024 – Electricity. Paris: International Energy Agency (IEA); 2024.
- [2] Hou G, Sun H, Jiang Z, Pan Z, Wang Y, Zhang X, et al. Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. JApenergy 2016;164:882–90. <https://doi.org/10.1016/j.apenergy.2015.11.023>.
- [3] EPRA. Energy and Petroleum Statistics Report. For the Financial Year Ended 30th June 2024 2024.
- [4] Kimutai SK, Kimutai IK, Kiplagat KM. East Africa’s Renewable Energy Diversity Landscape: A case of Kenya’s Potential, Progress and Future Prospects. Journal of Energy Research and REviews 2024;16:13–27. <https://doi.org/10.9734/jenrr/2024/v16i9369>.
- [5] Ministry of Energy and Petroleum. Least Cost Power Development Plan (LCPDP) 2024-2043 2020.
- [6] KETIP. Kenya Energy Transition and Investment Plan 2050 - Full Document 2023.
- [7] Government of Kenya. Sustainable Waste Management (Extended Producer Responsibility) Regulations, 2024. Legal Notice No. 176 of 2024. 2024.
- [8] Tawalbeh M, Al-Othman A, Kafiah F, Abdelsalam E, Almomani F, Alkasrawi M. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. Science of Total Environment 2021;759. <https://doi.org/10.1016/j.scitotenv.2020.143528>.

- 1113 [9] Xiao J, He P, Li Y, Shi M, Li Y, Ma J. Ecological dichotomies of solar energy expansion:
1114 resilience in arid regions versus fragility in humid ecosystems. *Front plant Sci* 2025;16.
1115 <https://doi.org/10.3389/fpls.2025.1549519>.
- 1116 [10] Hernandez, Hoffacker MK, Field CB. Land-Use Efficiency of Big Solar. *Environ Sci*
1117 *Technol* 2014;48:1315–23. <https://doi.org/dx.doi.org/10.1021/es4043726>.
- 1118 [11] Sanchez RG, Seliger R, Fahl F, Felice LD, Ouarda TBMJ, Farinosi F. Freshwater use
1119 of the energy sector in Africa. *Applied Energy* 2020;270.
1120 <https://doi.org/10.1016/j.apenergy.2020.115171>.
- 1121 [12] IEA-PVPS. End-of-Life Management of Photovoltaic Panels: Trends in PV Module
1122 Recycling Technologies. International Energy Agency Photovoltaic Power Systems
1123 Programme.; 2018.
- 1124 [13] Sharma HB, Vanapalli KR, Barnwal VK, Dubey BK, Bhattacharya J. Evaluation of
1125 heavy metal leaching under simulated disposal conditions and formulation of strategies
1126 for handling solar panel waste. *Scitotenv* 2021;780.
1127 <https://doi.org/10.1016/j.scitotenv.2021.146645>.
- 1128 [14] CENELEC. EN 50625-2-4:2017 – Collection, logistics & treatment requirements for
1129 WEEE – Part 2-4: Treatment-related requirements for photovoltaic panels. European
1130 Committee for Electrotechnical Standardization (CENELEC); 2017.
- 1131 [15] ISO. ISO 14040:2006 Environmental management — Life cycle assessment —
1132 Principles and framework. Geneva: International Organization for Standardization
1133 (ISO); 2006.

1134 [16] Badza K, Sawadogo M, Soro YM. Life cycle assessment of a 33.7 MW solar
 1135 photovoltaic power plant in the context of a developing country. *Sustain Environ Res*
 1136 2023;33. <https://doi.org/10.1186/s42834-023-00201-x>.

1137 [17] Mehedi TH, Gemechu E, Kumar A. Life cycle greenhouse gas emissions and energy
 1138 footprints of utility-scale solar energy systems. *JApenergy* 2022;314.
 1139 <https://doi.org/10.1016/j.apenergy.2022.118918>.

1140 [18] Mukoro V, Gallego-Schmid A, Sharmina M. Life cycle assessment of renewable energy
 1141 in Africa. *Sustainable Production and Consumption* 2021;28:1314–32.
 1142 <https://doi.org/10.1016/j.spc.2021.08.006>.

1143 [19] Schaubroeck T, Schaubroeck S, Heijungs R, Zamagni A, Brandão M, Benetto E.
 1144 Attributional & Consequential Life Cycle Assessment: Definitions, Conceptual
 1145 Characteristics and Modelling Restrictions. *Sustainability* 2021;13.
 1146 <https://doi.org/10.3390/su13137386>.

1147 [20] Frischknecht R, Stolz P, Heath G, Raugei M, Sinha P, Wild-Scholten M de.
 1148 Methodology Guidelines on Life Cycle Assessment of Photovoltaic. International
 1149 Energy Agency Photovoltaic Power Systems Programme; 2020.

1150 [21] REREC. REREC Newsletter: January–March (Quarter 3). Kenya: Rural Electrification
 1151 and Renewable Energy Corporation; 2021.

1152 [22] Solargis;The World Bank Group. Global Solar Atlas 2.0: Kenya 2025.

1153 [23] JinkoSolar. Eagle JKM265-285PP-60(V) Polycrystalline Solar Module Datasheet n.d.

1154 [24] Heidari SM, Anctil A. Country-specific carbon footprint and cumulative energy
 1155 demand of metallurgical grade silicon production for silicon photovoltaics. *RResconrec*
 1156 2022;180:106171. <https://doi.org/10.1016/j.resconrec.2022.106171>.

- 1157 [25] Méndez L, Forniés E, Garrain D, Vázquez AP, Souto A, Vlasenko T. Upgraded
1158 metallurgical grade silicon and polysilicon for solar electricity production: A
1159 comparative life cycle assessment Author links open overlay panel. *Scitotenv*
1160 2021;789. <https://doi.org/10.1016/j.scitotenv.2021.147969>.
- 1161 [26] Antonanzas J, Arbeloa-Ibero M, Quinn JC. Comparative life cycle assessment of fixed
1162 and single axis tracking systems for photovoltaics. *JJclepro* 2019;240.
1163 <https://doi.org/10.1016/j.jclepro.2019.118016>.
- 1164 [27] Ministry of Energy and Petroleum. The National Energy Policy 2025-2034 2025.
- 1165 [28] IEA-PVPS. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic
1166 Systems. 2020.
- 1167 [29] Ito M, Lespinats S, Merten J, Malbranche P, Kurokawa K. Life cycle assessment and
1168 cost analysis of very large-scale PV systems and suitable locations in the world. *Pip*
1169 2016;24:159–74. <https://doi.org/10.1002/pip.2650>.
- 1170 [30] Rauei M, Leccisi E, Fthenakis VM. What Are the Energy and Environmental Impacts
1171 of Adding Battery Storage to Photovoltaics? A Generalized Life Cycle Assessment.
1172 *Energy Technology* 2020;8. <https://doi.org/10.1002/ente.201901146>.
- 1173 [31] Khalid HM, Rafique Z, Muyeen SM, Raqeeb A, Said Z, Saidur R, et al. Dust
1174 accumulation and aggregation on PV panels: An integrated survey on impacts,
1175 mathematical models, cleaning mechanisms, and possible sustainable solution.
1176 *JSolener* 2023;251:261–85. <https://doi.org/10.1016/j.solener.2023.01.010>.
- 1177 [32] Myyas RN, Al-Dabbas MA, Tostado-Véliz M, Jurado F. A novel solar panel cleaning
1178 mechanism to improve performance and harvesting rainwater. *JSolener* 2022;237.
1179 <https://doi.org/10.1016/j.solener.2022.03.068>.

- 1180 [33] Aidara MC, Ndiaye ML, Mbaye A, Mamadou S. Study of the performance of a system
1181 for dry cleaning dust deposited on the surface of solar photovoltaic panels. *International*
1182 *Journal of the Physical Sciences* 2018;13:16–23.
1183 <https://doi.org/10.5897/IJPS2017.4701>.
- 1184 [34] Mathur N. Decarbonizing the Economy: Circularizing Solar Photovoltaics.
1185 *Encyclopedia of Sustainable Technologies*. 2nd ed., Berkeley, CA: Elsevier; 2024.
- 1186 [35] Solibrium-Solar. REWMOS. Solibrium-Solar 2020. [https://www.solibrium-](https://www.solibrium-solar.com/rewmos-2)
1187 [solar.com/rewmos-2](https://www.solibrium-solar.com/rewmos-2) (accessed December 8, 2025).
- 1188 [36] KIPPRA. Promoting the Use of Solar Energy in the Manufacturing Sector in Kenya
1189 2022. Promoting the Use of Solar Energy in the Manufacturing Sector in Kenya
1190 (accessed December 5, 2025).
- 1191 [37] Galan M. Governing the scalar politics of solar energy: Global production and national
1192 regulation in Kenyan and Indian off-grid solar markets. *Energy Research & Social*
1193 *Science* 2022;90.
1194 <https://doi.org/10.1016/j.erss.2022.102607>.
- 1195 [38] Elder D, Elmer HU, Ivan N. Localising the solar value chain in Kenya? *Innovation and*
1196 *Development* 2022;14:217–40. <https://doi.org/10.1080/2157930X.2022.2121306>.
- 1197 [39] Mbugua S, Langat W. Discontent Shadows Kenya’s Biggest Chinese-Funded Solar
1198 Power Project. *The China-Global South Project* 2024.
1199 [https://chinaglobalsouth.com/analysis/discontent-shadows-kenyas-biggest-chinese-](https://chinaglobalsouth.com/analysis/discontent-shadows-kenyas-biggest-chinese-funded-solar-power-project/)
1200 [funded-solar-power-project/](https://chinaglobalsouth.com/analysis/discontent-shadows-kenyas-biggest-chinese-funded-solar-power-project/) (accessed July 18, 2025).

- 1201 [40] Sinha P, Althouse L, Hoffman B, Sakers J. Best Practices in Responsible Land Use for
 1202 Improving Biodiversity at a Utility-Scale Solar Facility. *Cse* 2018;2:1–12.
 1203 <https://doi.org/10.1525/cse.2018.001123>.
- 1204 [41] Nordin AHM, Sulaiman SI, Shaari S, Mustapa RF. Energy and environmental impacts
 1205 of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: A life-
 1206 cycle approach. *JClepro* 2022;335. <https://doi.org/10.1016/j.jclepro.2021.130326>.
- 1207 [42] Soler D, Rigamonti L, Gazbour N, Fuentealba E. Environmental performance of a 1
 1208 MW photovoltaic plant in the Atacama Desert: A life cycle assessment study. *JSolener*
 1209 2025;292. <https://doi.org/10.1016/j.solener.2025.113454>.
- 1210 [43] UNECE. Life Cycle Assessment of Electricity Generation Options. United Nations
 1211 Economic Commission for Europe (UNECE); 2021.

1212 **Table 1** Summary of Selected Studies on LCA of Ground Mounted Utility Scale PV Systems (2016 – 2025)

Study Reference	Project Location	Solar Irradiance (kWh/m ² /year)	System Size (MW)	Module Type(s)	Module Efficiency (%)	Design Life (yrs)	GHG Emissions (g CO ₂ -eq/kWh)
[29]	Morocco, France	2,344 / 1,737	1,000	Mono-Si, Multi-Si, CdTe, CIS	13.0–21.2	30	27.4–48.8
[17]	Alberta, Canada		5	Multi-Si	16.72	25	98.3-149.3
[16]	Zagtouli, Burkina Faso	2,140	33.7	Multi-Si, Mono-Si, CdTe	17.2	25	37-48
[41]	Bidor, Malaysia	1,958	33.5	Multi-Si	17.1	30	30.95
[42]	Atacama Desert, Chile	2,624	1	Multi-Si	13	30	33.1

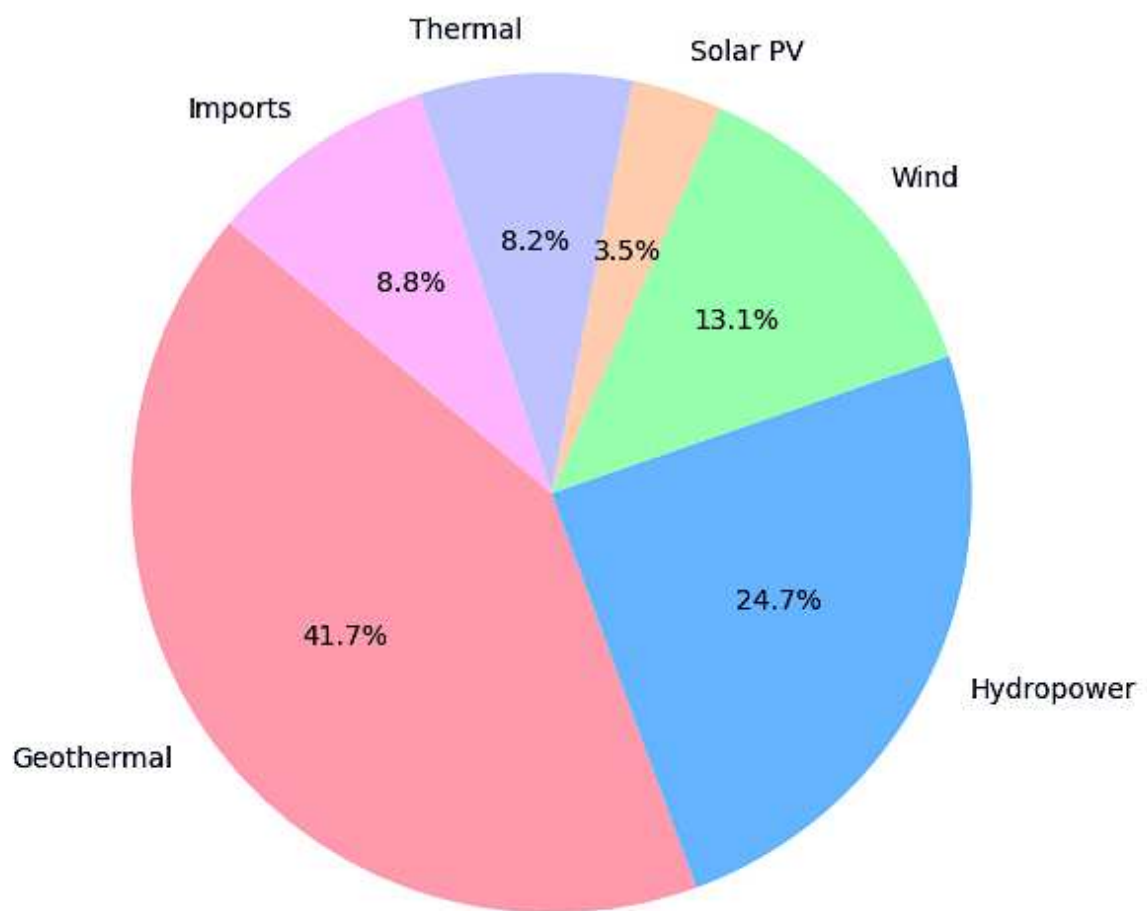
1213

Table 2 Transport routes and distances considered

Route	Distance (km)
Marine transportation (factory in Shanghai China to Mombasa port)	10,800
Land transportation (Mombasa Port to Garissa Site)	470
Land transportation (Garissa Site to Landfill)	350

Table 3 Life cycle GHG emissions of selected electricity generation technologies

Technology	GHG (g CO ₂ -eq/kWh)	Reference
Coal-fired	780–1095	[43]
Natural gas	400–725.75	[43]
Nuclear	22.2–24.2	[17]
Hydropower	0.5–152	[43]
Wind (Onshore)	3 - 45	[43]
Garissa PV	23.6	This study



1219

1220 **Figure 1** Kenya Electricity Generation Mix [3]

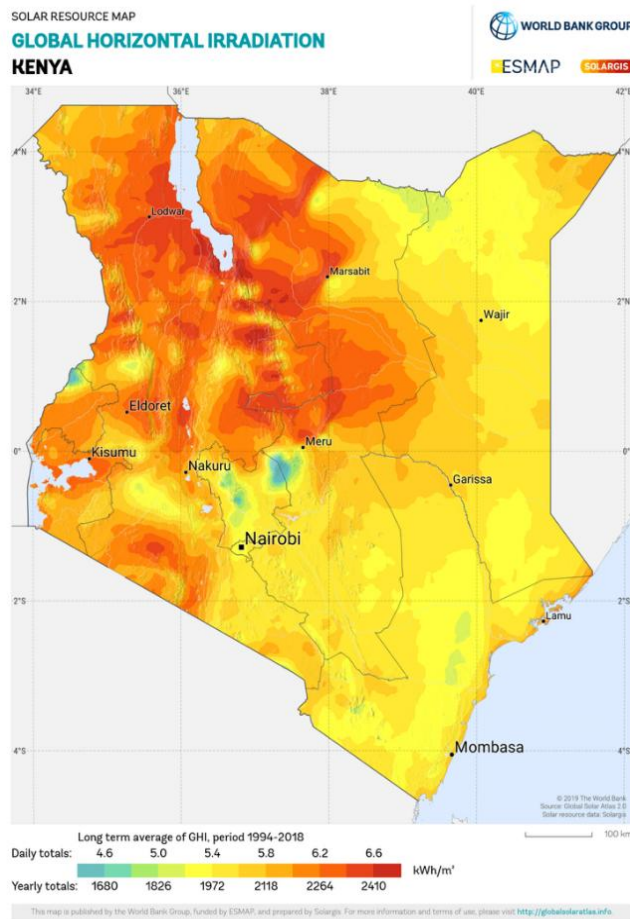
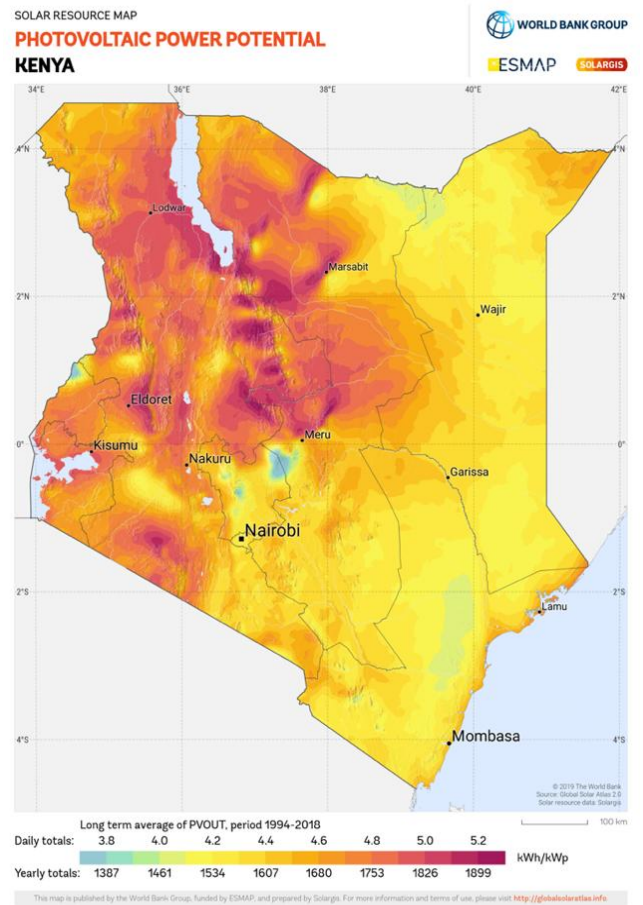


Figure 2 Annual GHI Distribution and PV Potential Across Kenya [22]



Figure 3 Aerial view of the Garissa Solar Power Plant [39]

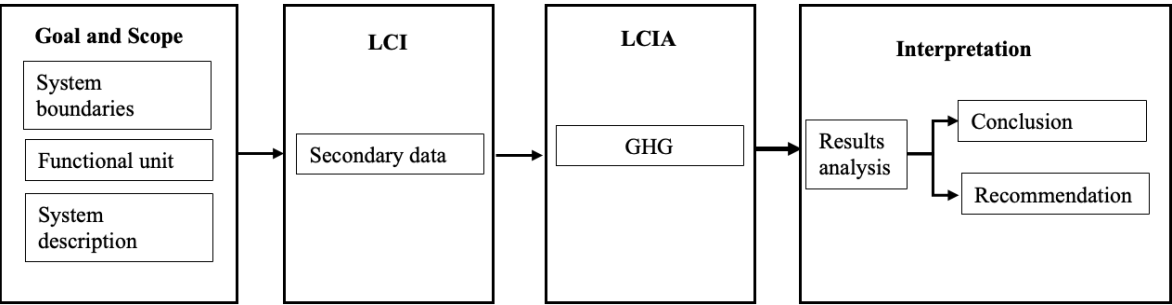


Figure 4 Life-Cycle Assessment Framework Modified from the ISO 14040 Standard [15]

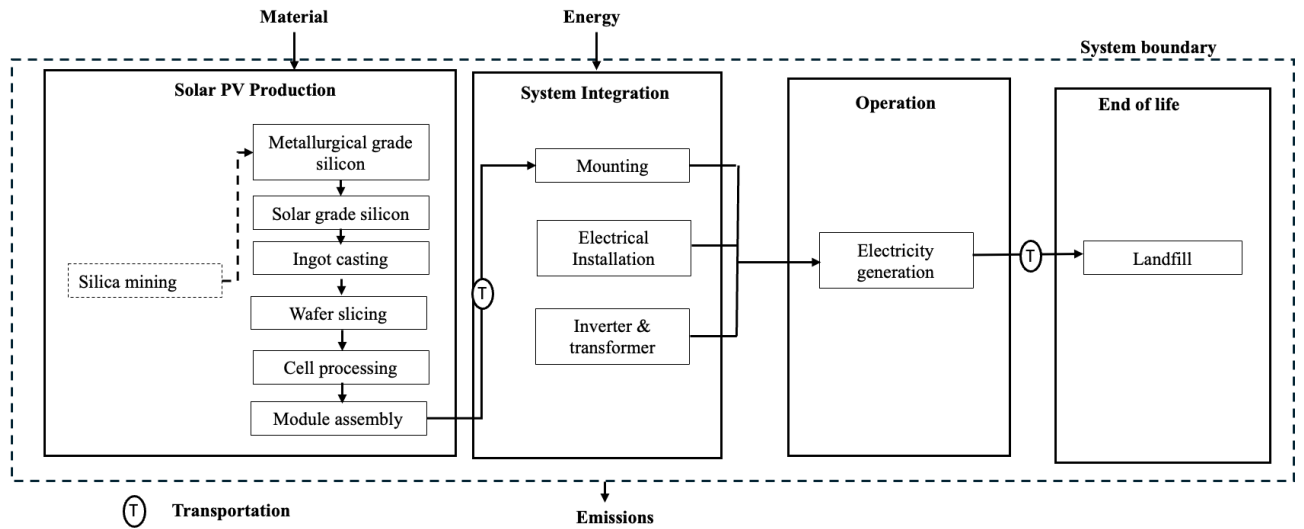


Figure 5 The assessment considers all relevant stages of the PV system's life cycle (Adapted from [17])

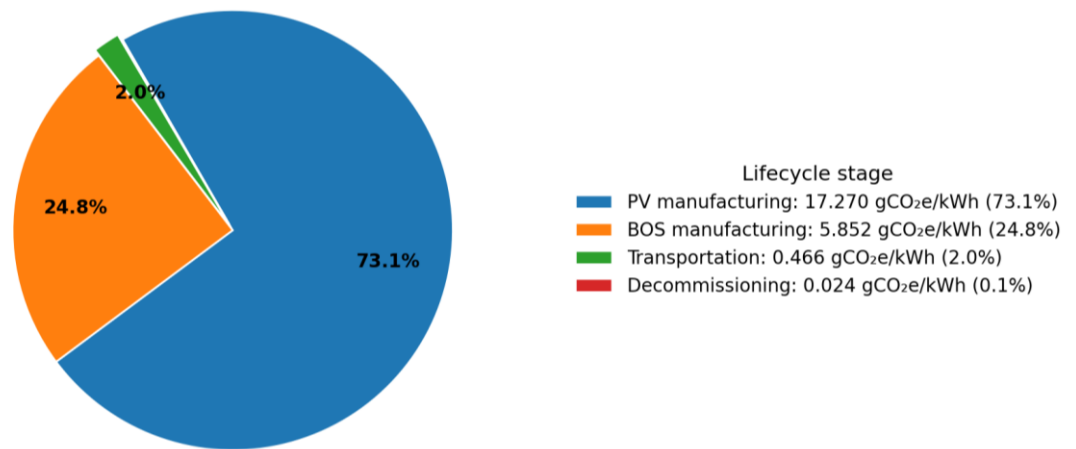


Figure 6 Proportional GHG emissions by lifecycle stage

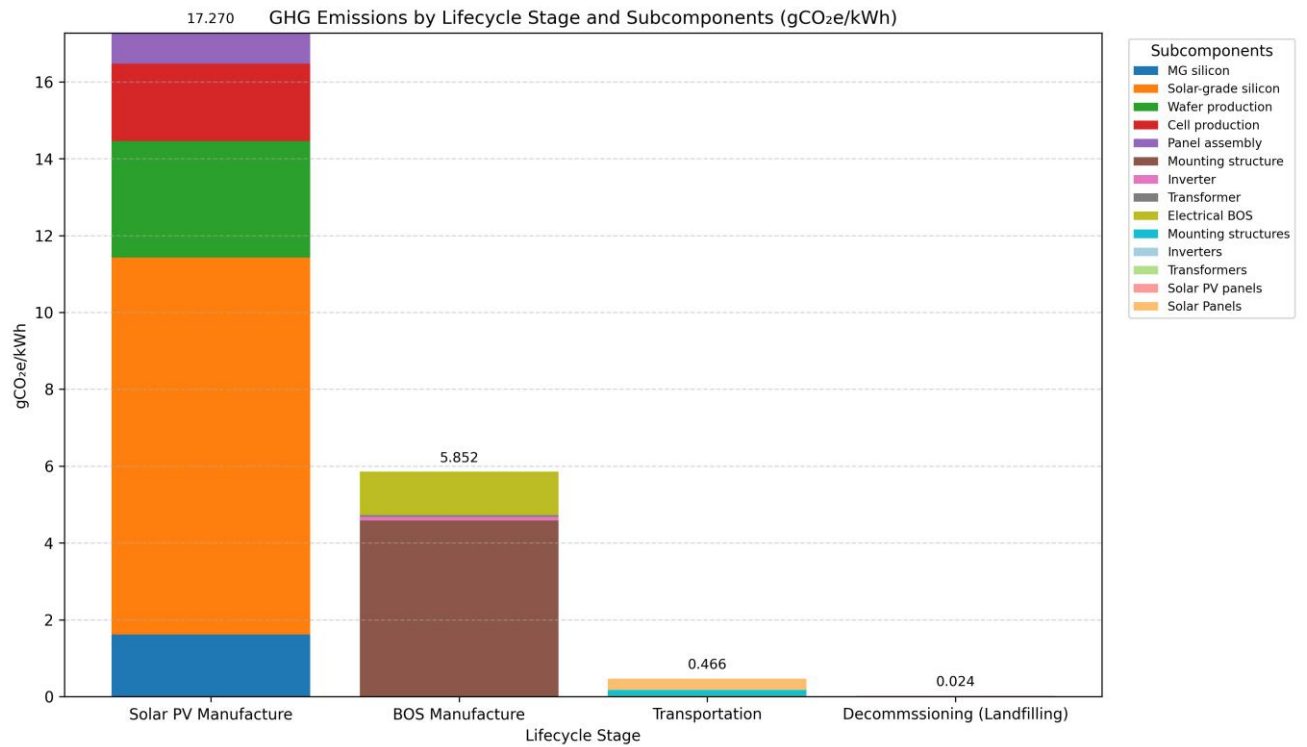


Figure 7 Lifecycle GHG Emission by stage, normalized to the system’s total energy output (2.19 TWh) over its 25-year lifespan.

Supplementary information

S1: PV modules and inverter specifications

Table 4 Assumed characteristics of the PV module examined, sourced from the manufacturer’s datasheet [23]

Parameter	Value	Unit
Nominal maximum power (Pmax)	265	Wp
Maximum power voltage (vmp)	31.4	V
Maximum power current (imp)	8.44	A
Open circuit voltage (VOC)	38.6	V
Short circuit current (isc)	9.03	A
Efficiency	16.19%	%
Operating temperature	−40 ≈ +85	°C
Cell type	Poly-crystalline	
Cell arrangement	60 (6 x 10)	
Dimensions	1650 x 992 x 35	mm
Area	1.64	m ²
Weight	19	kg
Lifetime	25	years

Table 5 Assumed characteristics of Inverter specifications, sourced from the manufacturer's (Huawei Technologies) datasheet

Input Parameter (DC)	Value	Unit
Max PV input power	44	KW

Voltage Range MPP (T)	200 ~ 1000	V
Maximum DC voltage	1100	V
Maximum DC Current	108 (4 MPPT × 27)	A
DC input	8 inputs, 4 MPPTs	
Output Parameters (AC)		
Nominal AC output power	40	KW
Max AC Current	63.8	A
Nominal Output voltage	400	V
Output frequency	50/60	Hz
Efficiency	98.7	%
Own power consumption	≤5.5	W
Physical Parameters		
Dimensions	640 × 530 × 270	mm
Weight	43	kg
Lifetime	10	years
Temperature range	-20 to +65	°C

S2: Lifecycle inventory data

The inventory uses most current and relevant data to represent industry practices for solar panel manufacturing, balance-of-system components, and end-of-life management. Material and input flows are summarized in **Table 6**.

Table 6 Lifecycle inventory data

MG Silicon	Value (for 1 kW)	Unit	Source
Output: MG Silicon	6.37593	kg	Inputs from
Materials			
Charcoal	1.0839	kg	
Coke	147.4746	MJ	
Graphite	0.6376	kg	
Petroleum coke	3.18797	kg	
Oxygen, liquid	0.1275	kg	
Silica sand	17.215	kg	
Wood chips (dry mass)	3.5049	kg	
Electric arc furnace converter	6.37593E-11	piece	
Energy			
Electricity (high voltage)	70.1352	kWh	
Solar Grade Silicon	Value (for 1 kW)	Unit	Source
Output: Solar Grade Silicon	4,587	kg	Closed loop Siemens process for solar grade

Silicon LCI. Inputs
from [26]

Materials

MG silicon	6.37593	kg
Chlorine, liquid	0.9174	kg
Hydrogen, liquid	0.24577146	kg
Sodium hydroxide	1.60545	kg
Quicklime	2.66046	kg
Water	4708.4	kg

Energy

Electricity	424.0429215	kWh
-------------	-------------	-----

Wafer	Value (for 1 kW)	Unit	
Output: Wafer	5.4696	M²	Inputs from [26]

Materials

SoG silicon	4.58671866	kg
Ceramic crucible	0.9731242	kg
Argon, liquid	1.7664564	kg
Steel	1.92085278	kg
Steel wire	1.92085278	kg
Silicon carbide	1.37271192	kg
Polyethylene glycol	5.94235034	kg
Adhesive (Acrylic binder)	0.01033804	kg
Sodium hydroxide	0.011237	kg

Hydrochloric acid, 36%	0.0269688	kg
Hydrogen fluoride	0.0539376	kg
Nitric acid, 50%	0.1752972	kg
Acetic acid	0.12113486	kg
Flat glass	0.25642834	kg
Water	475.02	kg

Energy

Electricity	131.0267911	kWh
-------------	-------------	-----

Solar cell	Value (for 1 kW)	Unit
------------	------------------	------

Output: solar cell	5.15613	m²	Inputs from [26]
---------------------------	----------------	----------------------	------------------

Materials

Silicon wafer	5.4696	m ²
Metallization paste, 90% Ag	0.02967	kg
Metallization paste, 85% Al	0.289992	kg
Ammonia, liquid	0.065016	kg
Phosphorus chloride	0.018576	kg
Silane	0.020124	kg
Sulphuric acid	0.514968	kg
Hydrochloric acid, 36%	0.20898	kg
Hydrogen fluoride	1.71828	kg
Nitric acid, 50%	2.71932	kg
Potassium hydroxide	0.106812	kg
Oxygen, liquid	0.0391644	kg

Water	637.389	kg	
Energy			
Electricity	87.044556	kWh	
PV panel	Value (for 1 kW)	Unit	
Output: PV panel	5.71	m²	Inputs from [20,26]
Material			
Silicon solar cell	5.15613	m ²	
Aluminium alloy	10.6206	Kg	
Solder, tin	0.134756	kg	
Solder, copper	0.539024	kg	
Glass	30.8911	kg	
Ethylvinylacetate, foil	4.53945	kg	
Back foil, PVDE	0.58242	kg	
Back foil, PET	1.96424	kg	
Corrugated board box	6.255876	kg	
Water	106.236	kg	
Energy			
Electricity	34.55692	kWh	
Mounting structure-Fixed and flat	Value (for 1 kW)	Unit	
			Horizontal 0°tilt.
Output: Mounting structure	5.71	m²	Inputs from [26]
Material			
Steel	38.01174596	kg	

Aluminum	0.009472141	kg
Aluminum extrusion	0.009472141	kg
Zinc coat	2.228790886	m2
Corrugated board box	0.49	kg
Polystyrene	0.02598	kg

Inverter	Value (for 1 kW)	Unit	
Output: Inverter	1	kW	Inputs from [16]
Material			
Aluminum. cast alloy	0.127	kg	
Copper	0.325	kg	
Electric connector. wire clamp	0.046	kg	
Glass fibre reinforced plastic.			
polyamide. injection moulded	0.069	kg	
Transformer	Value (for 1 kW)	Unit	
Output: Transformer	1	kWp	Inputs from [16],
Material			normalized, assuming
Aluminium primary. ingot	0.260944206	kg	2330KW
Reinforcing steel	1.945064378	kg	
Section bar extrusion Aluminium	0.260944206	kg	
Section bar rolling steel	1.945064378	kg	
Paraffin	0.469957082	kg	
Electricity (medium voltage)	1.909012876	kWh	

Electrical Installations	Value (for 1 kW)	Unit	
Output: Electrical BOS (Cables, Conduit, Other Electrical BoS)	6.19	m²	Estimated amount to produce 1kWp based on 265Wp panels.
Material			
Aluminium, wrought alloy	2.476	kg	Inputs from [25]
Epoxy resin, liquid	0.00030331	kg	
Nylon 6	0.039616	kg	
Polycarbonate	0.00037759	kg	
Polyvinylchloride, bulk polymerised	0.6809	kg	
Wire drawing, copper	2.476	kg	

1250

S3: Electricity mix

To maintain consistency in the LCI, electricity mix assumptions are based on 2017 data, aligning with the manufacturing period of the Garissa Solar PV Plant. This ensures upstream emissions reflect the grid carbon intensity during production in China.

In 2017, China’s grid was mainly coal (64.7%) and hydro (18.6%), with smaller shares from nuclear, gas, solar, and wind. A grid emission factor of 0.925 kgCO₂-eq/kWh was applied for module and inverter production. Details are shown in **Table 7**.

Table 7 Electricity generation mix (%) and corresponding CO₂ emission intensity for upstream manufacturing in China [26]

Coal	Oil	Gas	Nuclear	Solar	Wind	Geo-thermal	Hydro	Biomass	grid intensity (kg CO ₂ -eq kWh ⁻¹)
64.7	1.9	3.2	3.9	1.8	4.7	0	18.6	1.2	0.925

S4: Emission factors

Lifecycle GHG emission factors for key BoS materials used in the Garissa PV plant. The values are sourced from the GHG Protocol Life Cycle Database, based on recent LCA literature for global and Chinese supply chains. These factors support upstream emissions accounting for steel, aluminium, copper, and plastic composites. See **Table 8**.

Table 8 Emission factors

Material	Unit	EF (kg CO ₂ -eq unit ⁻¹)
Steel (primary)	kg	2.2–2.5
Steel bar	kg	2.4
Aluminum (cast/wrought)	kg	11.5–13.0
Corrugated board (packaging)	kg	1.0–1.5
Polystyrene	kg	2.7–3.2
Copper	kg	4.0–5.0
Electric connectors (plastic + metal)	kg	~6.5
GRP/polyamide (plastic composite)	kg	~6.0
Epoxy resin	kg	~6.0
Nylon 6	kg	~6.5
Polycarbonate	kg	~8.0
PVC (bulk polymerized)	kg	~2.2
Wire drawing, copper	kg	~5.0

S5: Transportation modelling inputs

The transport stages considered include:

- Inland transportation from Mombasa Port to the project site in Garissa County via road freight.
- Marine transportation from the manufacturing facility in Shanghai, China to Mombasa Port, Kenya via the Suez Canal.
- Inland Transportation from Garissa site to the Dandora Landfill

The lifecycle GHG emissions for each transport segment were estimated using a bottom-up modelling approach based on energy intensity, distance, fuel properties, vehicle/vessel specifications, and published emission factors. The values presented here are critical inputs to the overall lifecycle assessment of the project and directly inform the emissions reported in Section 3.3 of the main text.

Table 9 summarises the parameters used for inland road transport, including vehicle efficiency, payload characteristics, and diesel combustion emissions based on regional truck fleet data. Table 10 presents the marine transport modelling inputs, with vessel specifications, energy consumption per tonne-km, and associated emission factors for High Sulfur Fuel Oil (HSFO) as the primary marine fuel.

All parameters were obtained from credible sources including the IPCC 2006 Guidelines, International Energy Agency, DEFRA, Ecoinvent, and peer-reviewed literature.

These inputs were used to calculate both well-to-tank (WTT) and well-to-wheel (WTW) emissions associated with the transportation of materials. The results provide the emission intensities (in kg CO₂-eq) per tonne-km for both transport modes, which are aggregated in the lifecycle carbon footprint results in the main body.

1291 **Table 9** Inland Transportation Parameters

Parameter	Unit	Value	Notes
Lower Heating Value (LHV) of diesel	MJ/litre	46.3	IPCC 2006 Guidelines – Lower Heating Value of diesel
Fuel economy of heavy-duty truck	km/litre	2.76	Kenyan long-haul truck fleet; Ecoinvent and IEA datasets
Vehicle gross weight	tonnes (t)	40	Legal GVW per KeNHA regulations
Energy consumed per km	MJ/km	12.41	Based on measured performance of HD trucks in Kenya
Payload capacity	tonnes (t)	20	Effective payload (50% of GVW), per trip
WTW emission factor (combustion only)	g CO ₂ /MJ	94	Well-to-wheel emissions from diesel combustion
Diesel energy intensity	MJ/litre	36	Energy content of typical diesel fuel
Specific energy consumption	litre/tonne-km	0.034	Standard for rigid HD trucks used in regional freight
WTW GHG emission factor for diesel	kg CO ₂ /litre	3.24	Lifecycle emissions per litre of diesel

1292

1293 **Table 10** Marine Transportation Parameters

Parameter	Unit	Value	Notes
-----------	------	-------	-------

			Approximate maritime route (Shanghai to
Distance (origin to destination)	km	10,800	Mombasa via Suez Canal)
			Representative of medium-sized cargo
Ship deadweight (DWT)	tonnes	9,072	vessels
Average speed of ship	km/h	32.19	Typical cruising speed for container ships
Load factor	%	83	Cargo utilization efficiency
Lower Heating Value (LHV) of			
fuel	MJ/litre	49.2	LHV for High Sulfur Fuel Oil (HSFO)
Fuel density	kg/litre	0.99	Standard fuel density for HSFO
Energy consumption (engine)	MJ/kWh	5.15	Includes main engine and auxiliary power
Combustion emission factor	g CO ₂ /MJ	80.5	Tailpipe emissions per MJ of HSFO
			Well-to-tank emissions (refining +
WTT emissions (fuel life cycle)	g CO ₂ /MJ	12.5	transport)
			Average for ocean freight cargo per tonne-
Energy intensity	MJ/tonne-km	0.16	kilometre

1294

1295 **S6: Decommissioning**

1296 **Scenario: 100% landfilled at Dandora dumpsite**

1297 Given the absence of solar-specific EoL infrastructure in Kenya, a conservative landfill-
 1298 based disposal model was applied. Transport to Dandora landfill, located approximately 350
 1299 km from the site, was included in the emissions calculation, while recycling and material
 1300 recovery were excluded. Each component's mass was multiplied by the transport distance
 1301 and an emission factor of 0.11016 kg CO₂-eq per tonne-km to estimate transport emissions.

All components were assumed to be inert materials (e.g., metals, glass, and non-biodegradable plastics), which do not generate methane or other landfill gases. Therefore, a landfill emission factor of 8 kg CO₂-eq per metric tonne was applied. This value is consistent with conservative assumptions used in lifecycle assessments for inert waste, as supported by the GHG Protocol Product Life Cycle Standard and aligned with methodologies outlined in the EPA's Emission Factors for GHG Inventories.

These sources provide a credible basis for modelling end-of-life emissions in the absence of methane capture or material recovery, which reflects the current waste management conditions at Dandora. The total GHG emissions from transport and landfilling of all components amount to 301,698.71 kg CO₂-eq.

S7: Policy analysis of USSE systems in Kenya

Table 11 Policy frameworks for USSE systems in Kenya: Key provisions, impacts and gaps

Policy Document	Year	Key Provisions & Evolution	Impact on Solar PV	Shortcomings (Solar PV Focus)
National Energy Policy [27]	2025–2034	Sets 100% clean energy target by 2030; prioritizes renewables; aligns with climate goals	Drives investment and grid expansion for solar PV	Lacks detail on solar PV EOL, recycling, or hazardous waste
Energy Act	2019	Establishes legal/regulatory framework; mandates Integrated National Energy Plans (INEP); annual reporting; empowers EPRA to develop sector-specific regulations.	Regulatory certainty for solar projects; enables coordinated planning	No solar PV waste or circular economy provisions or recycling requirements
Energy (Solar PV) Regulations	2012	Sets technical standards for installations; licensing for technicians/installers; component quality control	Ensures quality, safety, and compliance for installations	No EOL, decommissioning, or recycling requirements

Draft Energy (Solar PV Systems) Regulations	2019/2020	Updates 2012 regs; new license categories; 10-year panel warranty; 3-year license validity	Improves quality assurance and technician competence	Still draft, not enforced; no EOL/recycling protocols
Least Cost Power Development Plan (LCPDP) [5]	2024–2043	10–20-year roadmap for generation/transmission; prioritizes renewables; grid integration; post-COVID recovery	Guides utility-scale solar expansion and sequencing	No integration of lifecycle emissions or material circularity
Feed-in Tariff (FiT) Policy	2021–Present	All solar projects to be procured under the Renewable Energy Auctions (REA) Policy (2021) instead of the FiT policy.	Moves suitable investors to a bespoke framework that addresses needs and concerns more specifically.	Largely dormant for solar as of 2025; Kenya shifting to auction-based procurement; no environmental or waste obligation
Renewable Energy Auctions (REA) Policy	2021–Present	Created a framework for investors to bid for contracts on solar project development and power supply to the grid.	Allows for a merit-based selection of solar power suppliers based on proof of capacity to deliver and cost efficiency, facilitating greater credibility.	Still has no prerequisite for environmental impact analyses and EoL activities.

Environmental Impact Assessment (EIA) Regulations	Ongoing	EIAs required for solar manufacturing and large-scale projects; environmental compliance for approval	Ensures environmental oversight for new facilities	No mandate for post-decommissioning plans or PV-specific waste guidance
Sustainable Waste Management Act & EPR Regulations [7]	2022, 2024	Mandates EPR for all electrical/electronic equipment; eco-design, take-back, recycling obligations; EPR registration	Legal basis for lifecycle management; potential for solar PV waste regulation	Not solar-specific; lacks PV/battery guidelines, collection/recycling systems, hazardous substance protocols, tracking of PV e-waste; informal sector not integrated; weak awareness/enforcement

1314