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ENERGICA



ENERGY ACCESS AND GREEN TRANSITION COLLABORATIVELY DEMONSTRATED IN URBAN AND RURAL AREAS IN AFRICA

D8.1

Life cycle assessment results

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PROJECT SUMMARY

The ENERGICA project has grouped 11 African-based partners and 17 European entities with offices or subsidiaries in Africa to enhance collaboration on energy access and sustainable energy development. The project's primary goal is to showcase the effective implementation of renewable energy technologies tailored to local needs.

Three demonstration sites have been established, each managed by local Energy Transition Boards overseeing community-scale Integrated Community Energy Systems (ICESs). Through these methodologies and innovative technologies, ENERGICA aims to demonstrate the positive social, environmental, technical, and economic impacts of high energy-efficiency and low carbon emission renewable energy technologies (RETs).

Specifically, the project will focus on:

- Developing innovative nano grids in rural Madagascar
- Implementing low-tech efficient biogas systems in peri-urban Sierra Leone
- Introducing solar-powered e-mobility solutions in urban Kenya

By doing so, ENERGICA will highlight the benefits of renewable energy in diverse contexts across Africa.

More information on the project can be found at https://cordis.europa.eu/project/id/101037428

OBJECTIVE AND EXECUTIVE SUMMARY

This report is part of the deliverables from the project "ENERGICA" which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101037428.

Background

Africa faces a dual challenge: accelerating decarbonization while meeting rising energy demand driven by population growth and industrialization. Heavy reliance on fossil fuels and limited renewable infrastructure hinder progress toward achieving climate goals. Existing research provides limited evidence on the comparative impact of emerging technologies versus existing technologies. This lack of direct comparison creates uncertainty in assessing their effectiveness and scalability. The work presented in this deliverable belongs to the three demonstrator sites. WP8 of the ENERGICA project focuses on the environmental and social impacts of demonstrators in WP4, 5, and 6 and the impacts of scaling up. Task 8.1 will focus specifically on the assessment of environmental impacts of innovative nano grids in rural Madagascar, innovative fertilizer products from biogas digester in Sierra Leone and innovative urban mobility systems in Kenya using ISO standards. The aim of this study is to compare existing technologies to emerging renewable technologies.

Objectives and Goals

- Assess environmental performance of decentralized renewable energy systems and electrified transport compared to fossil-based alternatives.
- Identify design and operational improvements to maximize sustainability benefits.
- Provide actionable insights for policy and investment decisions aligned with EU climate and circular economy objectives.

Methods

The assessment applies to the Center for **Environmental Science Leiden University - Impact Assessment** (**CML-IA)** and **Environmental Footprint (EF 3.0)** methodologies to quantify impacts across climate change, resource use, water consumption, and air pollution. Scenario analysis and sensitivity checks ensure robustness and capture variability in scale and design.

Results

Results from three demonstrator sites: solar-powered nanogrids in Madagascar, integrated biogas–water systems in Sierra Leone, and electric bus deployment in Kenya show that renewable and integrated technologies outperform conventional based solutions in terms of impact categories such as climate impact and resource efficiency. However, there are trade-offs in mineral and metal resource use for electrified transport due to battery use.

Implications

There is potential in reducing environmental burdens and accelerating progress toward sustainability goals. To enable implementation, financing and market development measures are essential. Robust monitoring and governance are needed to ensure continuous improvement

TABLE OF CONTENT

OBJECTIVE AND EXECUTIVE SUMMARY 4

TABLE OF CONTENT 5

FIGURES 6

TABLES 6

1. MADAGASCAR 7

1.1. INTRODUCTION 7
1.2. NANO GRIDS SYSTEM DESCRIPTION 7
1.3. MATERIALS AND METHOD 8
1.4. CONCLUSIONS 14

2. SIERRA LEONE 15

2.1. LCA FOR BIOGAS DIGESTER PRODUCTS 15
2.2. INTRODUCTION 15
2.3. MATERIALS AND METHOD 16
2.4. RESULTS 20
2.5. DISCUSSION 26
2.6. SENSITIVITY RESULTS 28
2.7. CONCLUSION 29

3. KENYA 30

3.1. LCA FOR SUSTAINABLE MOBILITY IN KENYA 30
3.2. INTRODUCTION AND CONTEXT 30
3.3. MATERIALS AND METHOD 31
3.4. RESULTS 36
3.5. DISCUSSION 39
3.6. CONCLUSION 40

EXECUTIVE CONCLUSION 42

REFERENCES 43

APPENDICES 47

FIGURES

Figure 1. System boundary and process flow of the nanogrid's food, water and energy solutions of Madagascar. The system boundary includes all relevant resource inputs, emissions, and infrastructures. 9
Figure 2. Environmental impact assessment of per ton of husked rice by solar-powered and conventional agri-processing systems. 12
Figure 3. Environmental impact assessment of per cubic water pumping by solar-powered and conventional diesel-powered systems. 13
Figure 4. Environmental impact assessment of daily cold services provided by solar-powered refrigerator and conventional diesel-powered (ice-cubes) systems. 14
Figure 5. System boundary and process flows for the combined biogas digestion and water purification system. Solid blue lines represent the baseline scenario, including anaerobic digestion, CHP generation, digestate separation, composting, and water purification using solar photocatalysis. Dashed blue lines indicate alternative scenarios, such as biogas upgrading, use of digestate as cooking gas, evaporation of the liquid fraction, and varying routes of nutrient recovery and valorisation. The system boundary includes all relevant resource inputs, emissions, and infrastructure. 18
Figure 6. Characterized Results for the 300 kg/day system. 21
Figure 7. Normalized results for the 1500 kg/day system. 22
Figure 8. Environmental Footprint results for 300 kg/day configuration (acidification, climate change, eutrophication, ozone depletion and water use). 24
Figure 9. Environmental Footprint results for 1500 kg/day configuration (acidification, climate change, eutrophication, ozone depletion and water use). 25
Figure 10. Normalized CML-IA results for Sierra Leone biogas system at 300 kg/day and 1500 kg/day. 27
Figure 11. Normalized Environmental Footprint (EF 3.0) results for Sierra Leone biogas system at 300 kg/day and 1500 kg/day. 28
Figure 12. Sensitivity results for Environmental Footprint method. 29
Figure 13. The flow of the chart of system boundary 33
Figure 14. Environmental impacts for the diesel and electric buses per passenger-kilometre pkm using Environmental Footprint 3.1 method (EC, 2022) 37
Figure 15. Environmental impacts for the diesel and electric buses per passenger-kilometre pkm using CML 2016 baseline method (University of Leiden, 2016). 38

TABLES

Table 1. Specifications of solar powered system of agri, water and cooling systems. 10
Table 2. Scenario analysis results of reduced solar panel size and battery weight. 14
Table 3. Scenarios of bus fleet in Kenya 32
Table 4. Bus specifications 32
Table 5. Bill of materials 32
Table 6. Weight of each component of the buses 33
Table 7. Fleet climate impact based on the emission factors from the composite bus using the current electricity mix in Kenya using Environmental Footprint 3.1 method (EC, 2022) 38
Table 8. Change in climate impact due to changes in grid intensity and fleet composition 39

1. Madagascar

1.1. Introduction

The immediate challenge of providing energy access involves quickly delivering basic and affordable electricity to the vast majority of the unelectrified population. In Madagascar, over 20 million people still lack access to modern and reliable electricity services. According to the energy inventory compiled by Praene and Rakotoson (2017), traditional fuel wood accounts for the largest share approximately 92% of Madagascar's total energy supply. Fossil fuels contribute around 7%, while less than 1% is provided by other renewable energy sources. The dominance of wood energy is primarily due to its accessibility and low cost for the population.

Madagascar faces significant challenges in electricity access, largely due to high costs and insufficient production capacity. The national electrification rate is only 4.7%, although this figure is higher in urban areas. The population growth in rural areas is expected to outpace the rate of electrification in the coming years. A significant proportion of unelectrified individuals live in remote rural areas, far from any existing national or local grid, with little hope of being connected to the national power grid in the near future. This lack of energy access has severe consequences on the living conditions of communities, who often rely on unhealthy, low-quality, and expensive alternatives to electricity, such as kerosene lighting or biomass cooking, both of which emit harmful fumes. Additionally, these alternatives pose a direct threat to the environment. Biomass cooking significantly contributes to the increasing deforestation in the country, and battery-powered small electrical appliances generate a substantial amount of toxic waste. Furthermore, basic health facilities cannot operate without a reliable electricity supply, and poor energy access directly impacts the life expectancy of unelectrified communities. The absence of electricity-powered devices and proper lighting makes many daily tasks time-consuming, negatively affecting the lives of many Malagasy, especially women and children.

The long-term challenge of enabling sustainable development involves progressively building decarbonized and decentralized sustainable power infrastructures, which could boost the economic and social development of the country. In Madagascar, informal work is very common, particularly among young people. More than two-thirds of the population is under 35 years old and often works in poor conditions, without a fixed and sufficient income or social security. Low energy access frequently traps rural Malagasy workers in inefficient, time-consuming tasks that do not help them improve their standard of living. Therefore, the youth of Madagascar should be seen as an opportunity to address energy access challenges. This highly motivated segment of the population should be relied upon to accelerate the energy revolution. Nearly one million young people enter the job market in Madagascar each year, and the responsibility of building lasting 21st-century electric infrastructures for their country should be placed in their hands. This would create local job markets and reduce unemployment. Despite the critical importance of addressing both short-term and long-term challenges through electrification initiatives, current practices in the energy sector in Madagascar and other African countries do not reflect this necessity.

1.2. Nano grids system description

The ENERGICA project aims to advance the Lateral Electrification concept by researching, developing, and pioneering the deployment of Nanogrids designed to support productive energy uses, particularly within the Water-Energy-Food (WEF) nexus. Nanoé has already successfully demonstrated the deployment and sustainable operation of nanogrids for domestic needs in over 200 villages in the Diana region. The Horizon H2020 LEAP-RE project has proven the feasibility and potential of

progressively interconnecting these nanogrids to form village-wide DC balancing microgrids capable of serving productive loads.

The concept of a nanogrid is relatively new and lacks a universally accepted definition. In this report, as well as in the overall ENERGICA project, nanogrids are defined as: "*Very low voltage direct current (i.e. < 120 V) power production, storage and distribution infrastructures providing access to electricity to a small number of neighbouring users (typically less than ten located in a perimeter of <100 meters)*".

This solution differs from Solar Home Systems or Kiosks in that it connects multiple users rather than just one system owner or user. It also differs from microgrids or minigrids in terms of voltage level and geographical extent. Notably, the very low voltage direct current nature of a nanogrid means that its power is produced, stored, and distributed at DC voltages < 50 V. If necessary, access to AC power is possible for some users, provided they are equipped with DC/AC converters.

Solar Nanogrid Definition

A solar nanogrid is a nanogrid whose power production capacity is entirely solar-based. In this context, the terms "solar nanogrid" and "nanogrid" will be used interchangeably, as all power grids considered for the demonstration site in Madagascar will be powered exclusively by solar energy. The tailored nanogrid solutions will specifically target the three main productive uses typically found in northern Madagascar, as outlined in Deliverable 2.1 on the Baseline Assessment and linked to the WEF nexus:

- **Agri-processing** - with a focus on the rice value chain (husking, hulling, milling, etc.) and wood transformation.
- **Water pumping** - with an emphasis on drinking water.
- **Cold management** - focusing on food refrigeration and ice production.

1.3. Materials and Method

The following subsections describe the methodological framework adopted for the life cycle assessment for nanogrid solutions in Madagascar, staring from the goal and scope, followed by the system boundaries, functional unit, life cycle inventory modelling, impact assessment, and scenario analysis approach to evaluate the environmental performance.

1.3.1. Goal and scope

The goal of this study is to evaluate the environmental performance of the Integrated nanogrid solar system solutions for the agri, water and cold system compared to their respective conventional systems. Life Cycle Assessment (LCA) is used for the identification of all processes for a product or service throughout their entire lifespan, from cradle to grave. It includes all production or/and process stages in order to identify and clarify which contribute to the highest environmental impact results.

The other aim is to identify which parts and processes of the PV system contribute to highest environmental impact. Such results clarify the production impacts and can thus be used to prioritise eventual improvements correctly. In life cycle impact assessment (LCIA), midpoint impact categories quantify specific environmental problem mechanisms (e.g., climate change, acidification) using characterization factors applied to inventory flows, whereas endpoint impact categories aggregate these midpoints into damage on the areas of protection, human health, ecosystems/biodiversity, and resource scarcity. This study focuses on mid-point impact categories and the environmental impact categories used are resource consumption, water use, global warming potential (GWP), acidification potential, eutrophication potential, ozone depletion potential, human toxicity potential and ionizing

radiation. Beyond the mentioned environmental impact categories, the study also presents the possible reduction of GWP by scenarios for 10-15% reduction of solar panel size and capacity of the battery.

1.3.2. System description

1.3.2.1. System boundary

The system boundary includes all relevant foreground and background activities from the raw material extraction through system operation and final use of the outputs, excluding end-of-life disposal processes. This encompasses resource extraction, construction, operation, and end-use processes. The overall system boundary is shown in Figure 1.

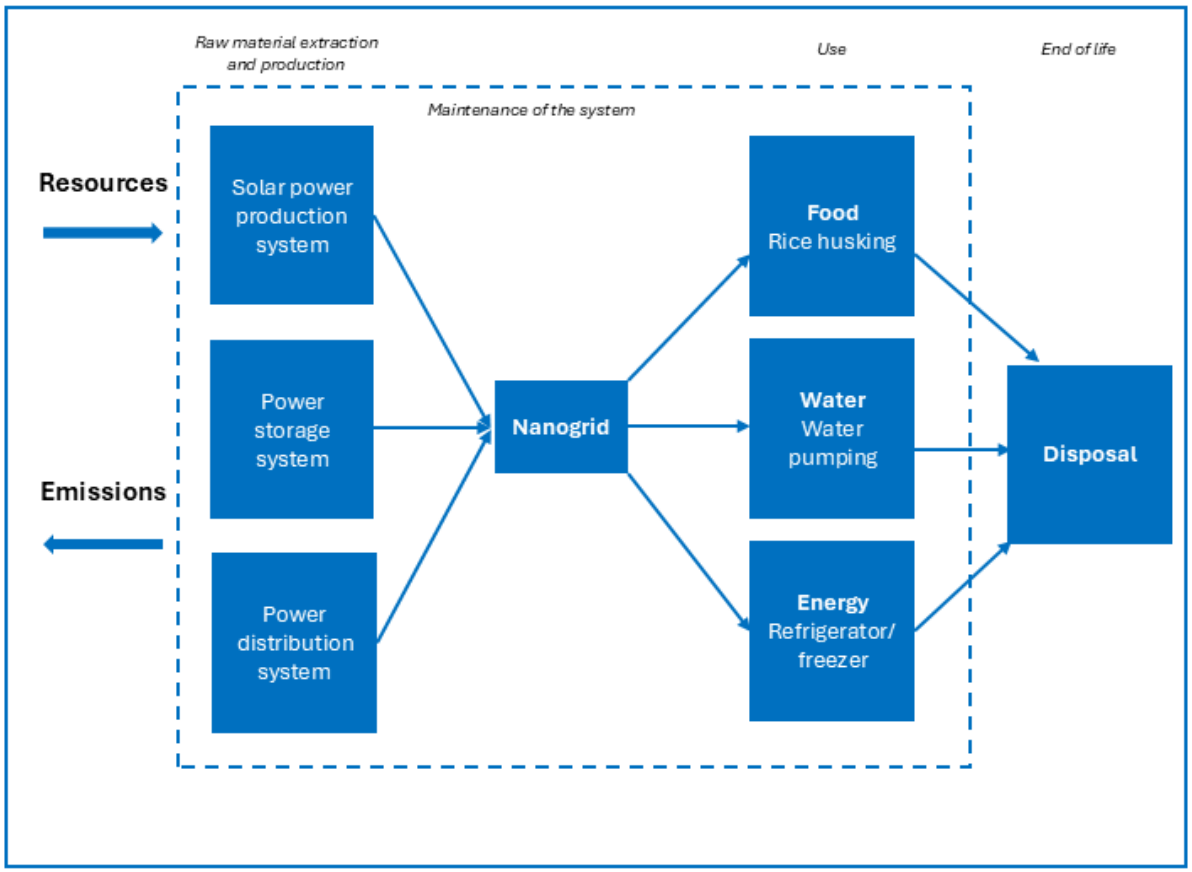


Figure 1. System boundary and process flow of the nanogrid's food, water and energy solutions of Madagascar. The system boundary includes all relevant resource inputs, emissions, and infrastructures.

1.3.2.2. Functional unit

The functional units for the analysis of environmental impacts were:

- Rice husking system of 1 ton of husked rice
- Water pumping system of 1 cubic water pumped
- Refrigerator/freezer system – impact of cooling consumption (0-4 °C) per year

1.3.3. Life cycle inventory

1.3.3.1. Specifications of solar powered system of agri, water and cooling systems

This section outlines the core parameters and criteria used to assess the environmental impact of the nanogrid's integrated food, water, and energy solutions in Madagascar. The main parameters are shown in Table 1. The LCA was conducted using data from Ecoinvent 3.8 and SimaPro 9.6.0.1 (Pre Sustainability, 2024) as the modelling software.

Table 1. Specifications of solar powered system of agri, water and cooling systems.

System materials	**Nano Agri (rice husking)**	**Nano water**	**Nano cold**
Photovoltaic panel	Type: Monocrystalline Dimension: 19.2 m2 Lifetime: 20 years	Type: Polycrystalline Total dimension: 1.99 m2 Lifetime: 20 years	Type: Plycrystalline Total dimension: 2.68 m2 Lifetime: 20 years
Battery	Weight: 45 kg Lifetime: 15 years	Weight: 76 kg Lifetime: 15 years	Weight: 152 kg Lifetime: 15 years
Inverter	Quantity: 1 Lifetime: 15 years		
Other electronics for the control unit	Weight 1.265 kg Lifetime: 10 years	Weight: 80 g Lifetime: 10 years	Weight: 80 g Lifetime: 10 years
Concrete	-	Weight: 31000 kg	
Cables	-	Type: Aluminium Length: 35 m	

1.3.3.2. Specification of conventional of agri, water and cooling systems

Conventional agri (rice husking): Rice is husked using diesel, mostly during the months of May-June-July and a bit between April, August, December and January. In the LCA, the average diesel quantity in a year is used by surveying 10 sites. Average rice husked in a year is 49 000 kg and average diesel used in a year is 430 litres. The average quality of lubricant used in the husking machine is also considered, which is 18.1 liter.

Conventional water pumping: Currently, villagers use buckets to fetch water. In towns, there are pumps connected to the town's electricity supply (like most cities in Europe). Electricity in the towns of Madagascar is generated by diesel generators. To estimate the power consumption to pump 1 m^3 water is not straight forward because it depends on many parameters such as the model of pump, its flow rate, the height of the tank, etc.

Assuming an average city pump flow rate of 170 m^3/hour (Q), a head of 10 meters (H), pump efficiency of 70% (η), water density of 1,000 kg/m^3 (ρ), and gravitational acceleration g = 9.81 m/s^2, the hydraulic power requirement can be calculated using the formula (Zang, 2020):

$$P = \frac{Q \times H \times \rho \times g}{\eta}$$

Substituting the values:

$$P = \frac{0.0472 \times 10 \times 1000 \times 9.81}{0.7} \approx 6.62 \text{ kW}$$

This means approximately 6.62 kW is needed to pump 170 m^3 of water to a height of 10 m per hour. For 1 m^3, the energy requirement is about 39 W per hour.

Over one year, a solar-powered system could pump 365 m^3 of water. To pump the same amount using a conventional system would require:

$$39 \times 365 = 14{,}235 \text{ Wh } (14.2 \text{ kWh})$$

This calculation does not account for the lifetime electricity cost. However, lifetimes for the pump (10 years) and concrete infrastructure (40 years) have been considered.

Conventional cold system:

In this area, most households have freezers that are not connected to the electricity grid. Instead, they purchase ice blocks from the city, which are typically delivered by bike in insulated coolers. Each household usually buys one to two ice blocks per day. These ice blocks are produced in towns using the Jirama thermal power grid.

The volume of a single ice block is approximately 13,500 cm^3. Based on the datasheet (see appendix) for a similar machine used in Madagascar, the machine operates at 4 kW and requires 5 hours to produce 16 blocks. This means:

$$\text{Energy consumption} = 4\ \text{kW} \times 5\ \text{h} = 20\ \text{kWh for 16 blocks}$$

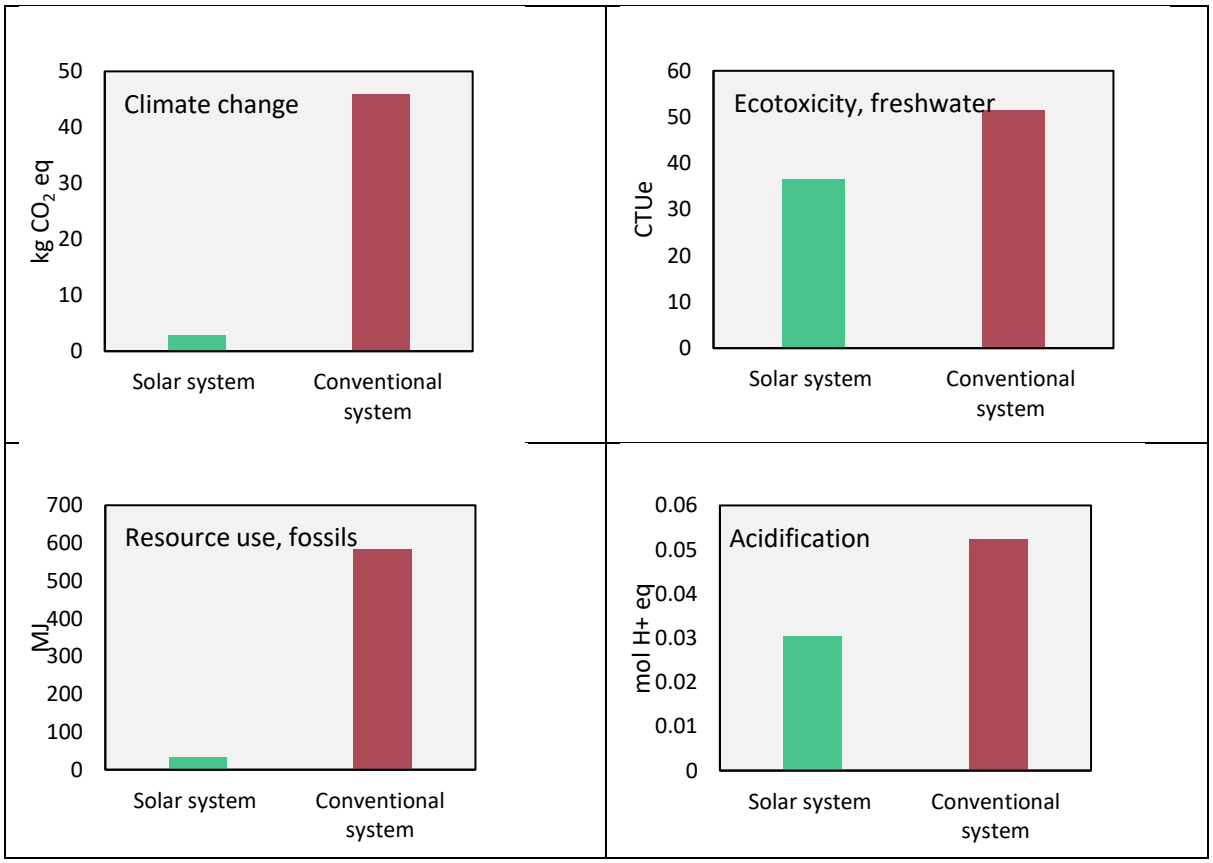
Therefore, the energy required per ice block is:

$$\frac{20\ \text{kWh}}{16} = 1.25\ \text{kWh per block (or 1250 Wh per block)}$$

1.3.4. Impact assessment results

1.3.4.1. Environmental impact assessment of solar-powered and conventional agri-processing

The Results section focuses exclusively on the most critical and impactful outcomes. As a comparison with conventional diesel-powered rice husking, the environmental impact per ton of husked rice by solar-powered rice husking reduced the climate impact by 93%, freshwater ecotoxicity by 28%, fossil resource use by 94%, acidification by 42% and photochemical ozone formation by 92% (Figure 2).



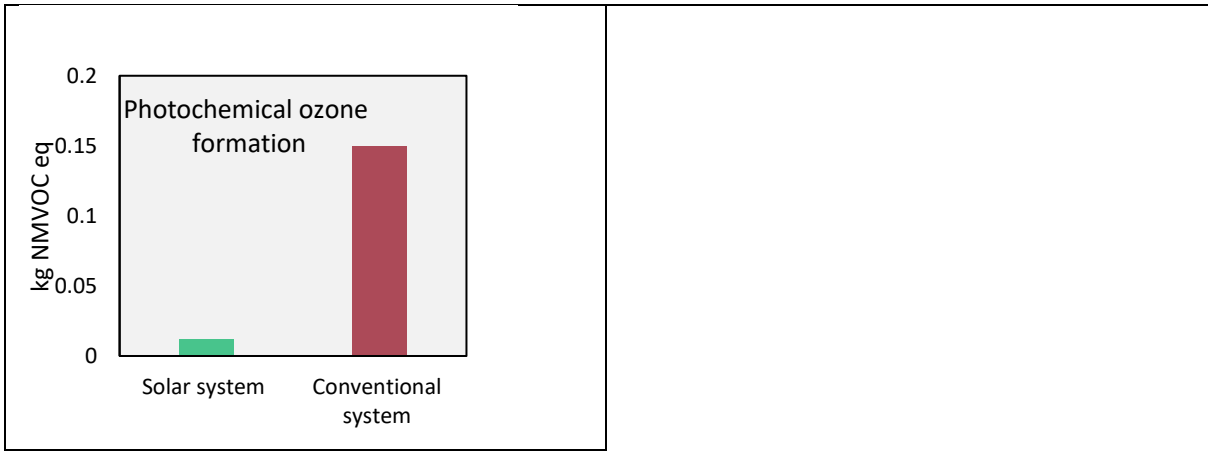
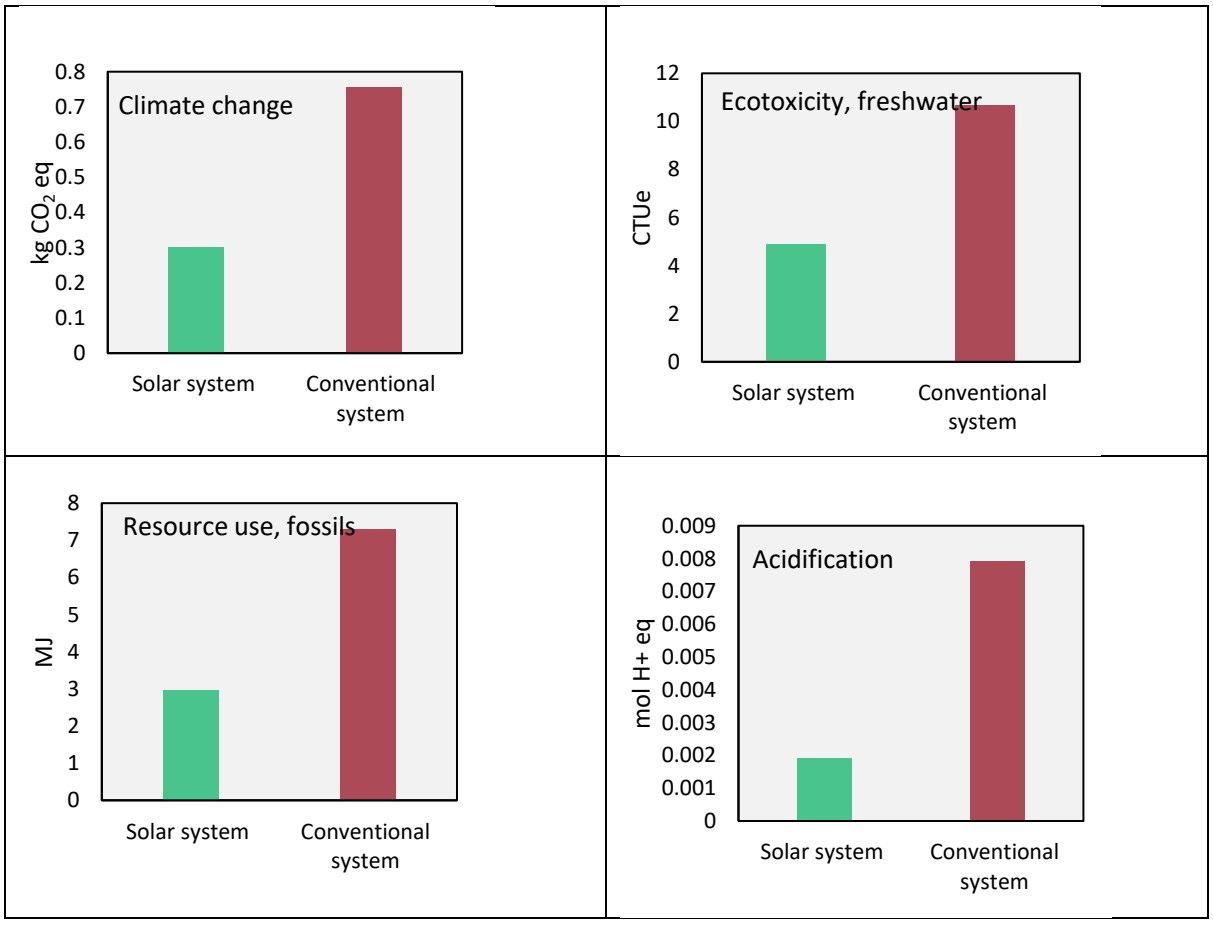


Figure 2. Environmental impact assessment of per ton of husked rice by solar-powered and conventional agri-processing systems.

1.3.4.2. Environmental impact assessment of solar-powered and conventional water supply system

As a comparison with conventional diesel-powered water pumping, the environmental impact of per cubic water pumping by a solar-powered pump reduced the climate impact by 60%, freshwater ecotoxicity by 54%, fossil resource use by 59%, acidification by 75% and photochemical ozone formation by 64% (Figure 3).



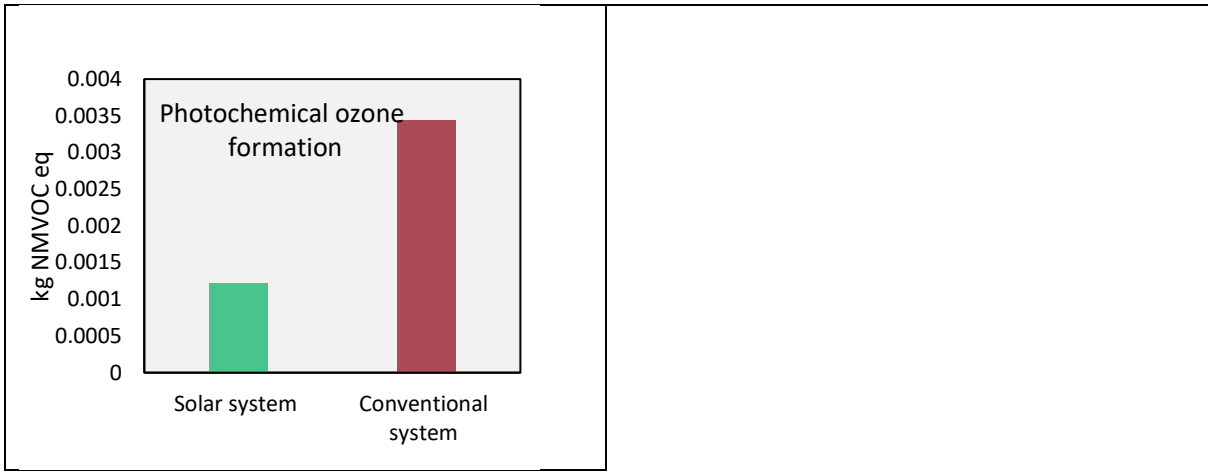
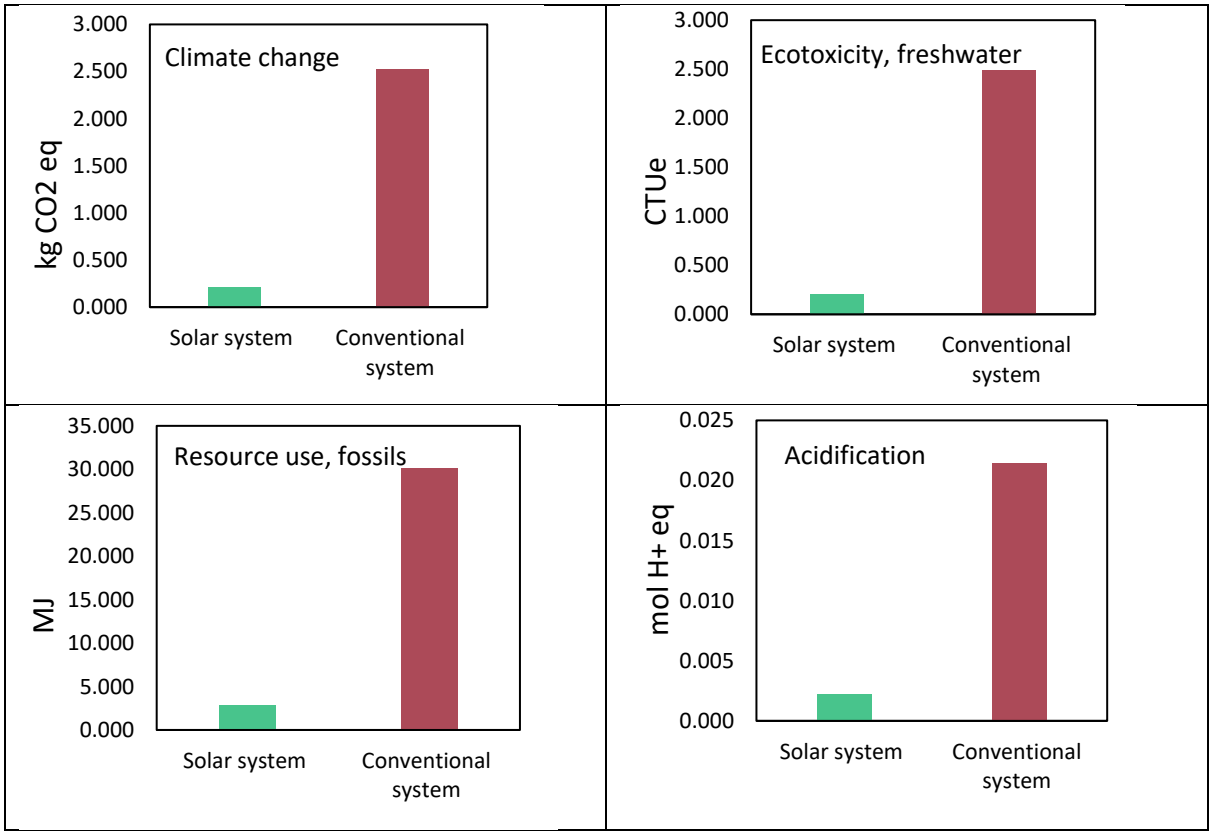


Figure 3. Environmental impact assessment of per cubic water pumping by solar-powered and conventional diesel-powered systems.

1.3.4.3. Environmental impact assessment of solar-powered and conventional cooling system

As a comparison with daily ice cubes consumption by diesel powered system, the environmental impact of daily solar-powered refrigerator reduced the climate impact by 91%, freshwater ecotoxicity by 91%, fossil resource use by 90%, acidification by 89% and photochemical ozone formation by 92% (Figure 4).



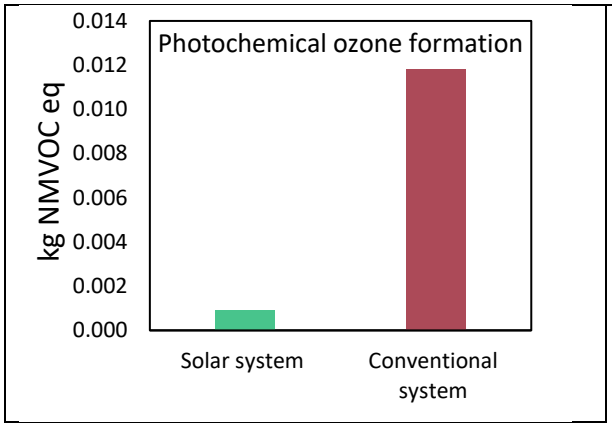


Figure 4. Environmental impact assessment of daily cold services provided by solar-powered refrigerator and conventional diesel-powered (ice-cubes) systems.

1.3.5. Scenario analysis to evaluate climate Impact Reduction in Nanogrid Solar Systems

A scenario analysis based on 10% reduction on solar panel size and battery weight was done to evaluate the climate impact reduction across three application areas of Agri-processing, Water pumping, and Cooling. The aim of this analysis is to evaluate the impact of reducing the physical size of a solar panel while maintaining the same power. The possible reduction of total climate impact is shown in Table 2.

Table 2. Scenario analysis results of reduced solar panel size and battery weight.

Application Area	**10% Reduced Battery Weight (kg CO_2 eq)**	**10% Reduced Solar Panel Size (kg CO_2 eq)**
Agri-processing	2.16 %	6.66 %
Water pumping	0.68 %	1.34 %
Cooling	4.30 %	5.66%

Solar panel size reduction consistently yields greater climate impact reduction than battery weight reduction across all applications. Agri-processing benefits most from solar panel size reduction, while cooling systems show significant gains from both battery and panel optimizations. However, reducing the physical size of a solar panel while maintaining the same power output is a complex engineering challenge, but it can be approached through several strategies. For example, panel orientation, solar tracking systems, and the optimization of electrical configurations. Also, advanced monitoring systems for maintenance and degradation protection are essential for sustaining efficiency over time (Carrera et al., 2025).

1.4. Conclusions

The LCA of solar-powered nanogrids in Madagascar demonstrates significant environmental advantages over conventional diesel-based systems. Across all three applications—rice husking, water pumping, and cold storage—the solar systems show substantial reductions in climate impact (up to 93%), fossil resource use (up to 94%), and photochemical ozone formation (up to 92%). These results validate the effectiveness of solar nanogrids in reducing emissions and resource consumption in rural energy systems.

However, the study also highlights the importance of system design and component optimization. Scenario analysis reveals that reducing solar panel size and battery weight can further decrease climate impacts, especially in agri-processing and cooling applications. This suggests that targeted design improvements can enhance sustainability outcomes without compromising service delivery.

2. Sierra Leone

2.1. LCA for biogas digester products

LCA is a powerful tool used to evaluate the environmental impacts associated with all stages of a product's life—from raw material extraction through production, use, and disposal. When applied to biogas digester products, LCA provides a comprehensive understanding of their sustainability performance, helping stakeholders make informed decisions about energy systems, waste management, and agricultural practices.

Biogas digesters convert organic waste into biogas and nutrient-rich digestate through anaerobic digestion. The LCA of these systems typically considers inputs such as feedstock collection, digester construction, operation, and end-of-life treatment. It also accounts for outputs like biogas (used for energy) and digestate (used as fertilizer), as well as avoided emissions from conventional waste treatment and fossil fuel use (Alengebawy et al., 2024).

Anaerobic digestion is increasingly recognized as a sustainable method for managing organic waste and producing renewable energy. It mitigates greenhouse gas emissions, reduces landfill use, and supports circular bioeconomy goals (Nature Research Intelligence, 2025). Technological innovations—such as improved reactor designs and microbial process control—are enhancing the efficiency and environmental performance of these systems (Nature Research Intelligence, 2025).

Digestate, the by-product of anaerobic digestion, is often applied as a fertilizer. Its use is being evaluated not only for nutrient recovery but also through ecotoxicological and LCA studies to ensure environmental safety and long-term soil health (Pivato et al., 2016).

By identifying hotspots of environmental impact—such as greenhouse gas emissions, energy use, and nutrient runoff—LCA supports the optimization of biogas systems for greater environmental benefit. It also enables comparisons with alternative waste treatment and energy generation technologies, reinforcing the role of biogas in circular economy and climate mitigation strategies.

2.2. Introduction

Biogas production through anaerobic digestion of organic waste has gained increasing relevance in the context of sustainable energy access, waste management, and climate mitigation, particularly in low- and middle-income countries. Within the ENERGICA project, a decentralized biogas digester was developed and commissioned to treat organic waste while simultaneously producing renewable energy and nutrient-rich residues. In line with the project's broader objective of evaluating environmentally and socially appropriate technologies for off-grid communities in Africa, a LCA was carried out to comprehensively assess the environmental performance of this biogas solution.

The biogas digester analysed in this study converts household and agricultural organic waste into biogas through anaerobic digestion, which is subsequently used to generate electricity and thermal energy via a combined heat and power (CHP) system. In parallel, the process yields a semi-liquid by-product—digestate—that contains nutrients and organic matter, which can be valorised through various treatment and land application strategies. The LCA aimed to quantify the environmental impacts associated with both the energy recovery pathway and the digestate management alternatives, capturing emissions and resource use across the system's life cycle (Osman et al., 2024).

Given the potential for replication and scalability of this technology in similar contexts, the assessment considers two operational configurations: one treating 300 kg/day of organic waste, representative of a small-scale community unit, and another processing 1500 kg/day, representing a medium-scale

installation. This allows for the evaluation of potential environmental trade-offs and performance gains associated with scale-up. The analysis places particular emphasis on understanding the system's contribution to climate change mitigation, nutrient recycling, and energy substitution, while also accounting for the emissions associated with treatment steps such as composting, evaporation, and land application of digestate fractions (Pivato et al., 2016).

To enhance the agricultural value of digestate and reduce its environmental footprint, the study also explored the integration of solar reactor technologies for water purification and digestate concentration. These systems aim to improve the hygienic quality and nutrient density of digestate, making it more suitable for safe and effective land application. Additionally, innovations in digestate-derived biodegradable polymers have shown promise in improving the sustainability of solar photovoltaic systems, suggesting potential synergies between waste valorisation and renewable energy technologies (Alhodaib et al., 2024).

The LCA results are intended to support strategic decision-making in the design and implementation of integrated waste-to-energy systems in off-grid and peri-urban settings. By providing quantified insights into environmental benefits and hotspots, the study contributes to ongoing discussions on the role of biogas in decentralized circular economy models, especially in sub-Saharan Africa where conventional waste treatment and energy infrastructure are often lacking or underdeveloped (Osman et al., 2024).

2.3. Materials and Method

The following subsections describe the methodological framework adopted for the life cycle assessment, beginning with the definition of the goal and scope, followed by the system boundaries, functional units, life cycle inventory modelling, and impact assessment approach used to evaluate the environmental performance of the biogas and water purification systems.

2.3.1. Goal and scope

The goal of this LCA is to evaluate the environmental performance of a decentralized biogas digester and solar-based water purification system implemented under the ENERGICA project. The study aims to quantify the environmental impacts associated with energy generation, digestate treatment, and clean water production, under varying scales of operation. The results will support decision-making regarding scalability, replicability, and optimization of sustainable solutions for energy and water access in off-grid regions of sub-Saharan Africa, with Sierra Leone serving as a demonstration site.

This LCA focuses on two system configurations for the biogas unit (300 kg/day and 1500 kg/day of organic waste) and integrates the solar photocatalytic reactor used for water purification. The systems are assessed individually and in combination, considering material and energy flows from cradle to end use. The study is intended for internal project optimization, policy recommendation, and comparative analysis of decentralized infrastructure alternatives.

2.3.2. System description

The analysed systems include (i) an anaerobic digester for biogas and digestate production, and (ii) a solar photocatalytic water purification unit designed for decentralized treatment of contaminated water sources. Both systems are implemented in a stand-alone mode but can be functionally integrated, with the biogas generator supplying electricity to the water purification unit.

2.3.2.1. System boundary

The system boundary encompasses all relevant foreground and background processes from cradle to end-use, including resource extraction, construction, operation, and final use or emissions of system outputs. As illustrated in Figure 5, the system includes two core components: an anaerobic digestion unit for energy and nutrient recovery, and a solar photocatalytic water purification reactor, which can be integrated or modelled independently depending on the scenario.

The baseline scenario (represented with solid blue lines in the figure) includes:

- Organic waste collection (e.g., food waste)
- Anaerobic digestion for biogas production
- Use of biogas in a combined heat and power (CHP) unit
- Electricity and heat recovery for on-site use
- Utilization of excess electricity to power the water purification unit
- Separation of digestate into solid and liquid fractions
- Composting of the solid fraction
- Use of the liquid fraction as a nutrient solution for land application

In the alternative scenarios (represented with dashed lines), the system considers:

- Upgrading of biogas for use as vehicle fuel or cooking gas
- Evaporation of the liquid digestate fraction to create a concentrated nutrient product
- Variations in digestate handling, including direct application, evaporation, or more advanced valorisation routes

Outputs from the system include:

- Electricity and heat (partly used internally, with potential surplus)
- Purified water
- Fertilizing products (compost, nutrient solution, or concentrate)
- Emissions (to air, soil, or water) from digestion, land application, and chemical use

The system boundary includes the construction and operation of physical infrastructure (e.g., tanks, piping, solar reactor frame), chemical and energy inputs, and machinery for digestate handling and application. Background processes such as diesel production, electricity grid mixes, and material fabrication are modelled using data from Ecoinvent 3.8.

The dashed outer line in the figure represents the full life cycle boundary of the combined system, with emissions and resource use tracked at every stage.

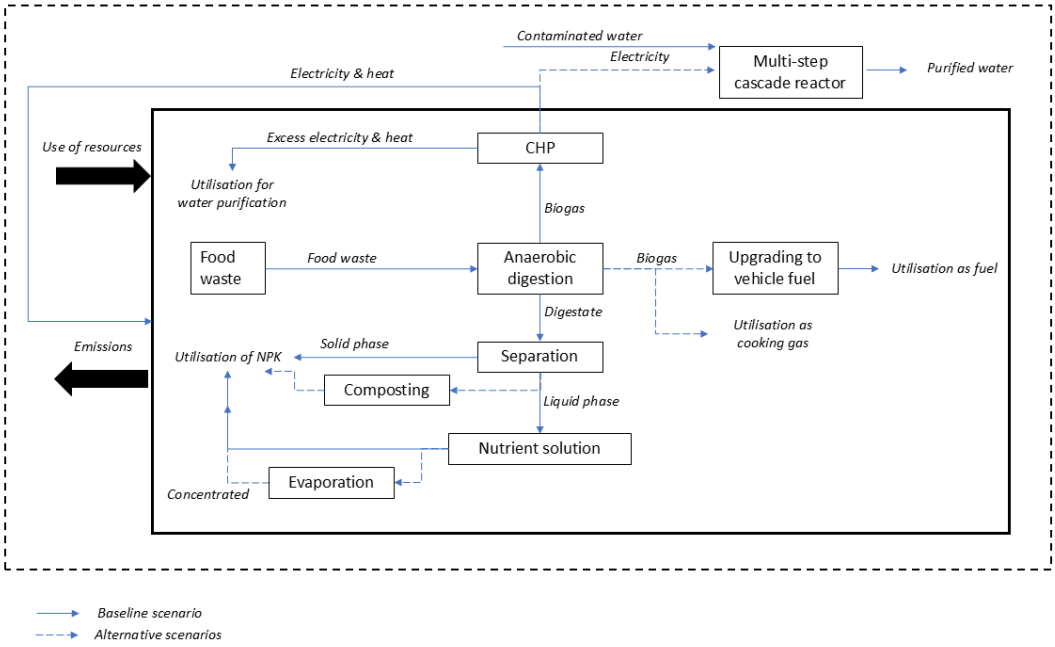


Figure 5. System boundary and process flows for the combined biogas digestion and water purification system. Solid blue lines represent the baseline scenario, including anaerobic digestion, CHP generation, digestate separation, composting, and water purification using solar photocatalysis. Dashed blue lines indicate alternative scenarios, such as biogas upgrading, use of digestate as cooking gas, evaporation of the liquid fraction, and varying routes of nutrient recovery and valorisation. The system boundary includes all relevant resource inputs, emissions, and infrastructure.

2.3.2.2. Functional unit

The functional unit for the analysis was "1 kg of organic waste treated", and system boundaries included the entire biogas production process, digestate handling (separation, composting, evaporation, and land application), and associated energy recovery. Two configurations were evaluated:

- a small-scale system processing 300 kg/day, and
- a medium-scale system processing 1500 kg/day of organic waste.

Allocation was avoided by modelling the system as multi-output and using system expansion where relevant, particularly for fertilizer substitution credits.

2.3.3. Life cycle inventory

The life cycle inventory (LCI) was developed using SimaPro 9.6.0.1 (Pre Sustainability, 2024), combining primary data from project implementation (pilot-scale trials, technical reports) and literature-based parameters.

2.3.3.1. Biodigester

The LCI for the biogas system includes:

- Feedstock input: 300 or 1500 kg/day of organic waste (1:1 mixed with water)
- Energy outputs: electricity (65–395 kWh/day) and heat (121–705 kWh/day), depending on scale
- Operation: electricity for pumps, maintenance, diesel for digestate application

- Digestate treatment: screw press separation, composting of solid fraction, evaporation of liquid fraction
- Emissions: methane leaks, ammonia and N_2O from soil application, CO_2 (biogenic), and nutrient substitution credits

Inventory values were scaled to the functional unit and adjusted for energy and nutrient content where needed.

2.3.3.2. Water Purification

The LCI for the solar photocatalytic reactor includes:

- Photocatalytic materials: titanium dioxide (TiO_2), used in immobilized form
- Chemical inputs: hydrogen peroxide (H_2O_2), bicarbonate (if applicable)
- Electricity: 0.86 kWh/m³ of water, supplied from the biogas CHP
- Operation: treatment of influent with contaminants such as sulfamethoxazole, trimethoprim, and imidacloprid (reduction from 100 to 20 µg/L)
- Emissions: mineralization of organic contaminants to CO_2, water, and minor residues (no TiO_2 release assumed)

Data were collected from commissioning reports and laboratory tests and normalized to the functional unit of 1 m³ treated water.

2.3.4. Environmental Impact Assessment

The LCA was conducted using SimaPro 9.6.0.1 (Pre Sustainability, 2024) as the modelling software. Two internationally recognized impact assessment methods were applied to ensure robust results and comparability:

- the Environmental Footprint (EF 3.0) method, developed by the European Commission, and
- the CML-IA baseline, developed by the Centre for Environmental Sciences at Leiden University.

The environmental impact assessment was conducted for the two configurations of the biogas digester system, corresponding to processing capacities of 300 kg/day and 1500 kg/day of organic waste. Mid-point impact categories considered include climate change (GWP100), eutrophication (terrestrial, marine, and freshwater), acidification, resource use (minerals and fossil fuels), and human toxicity.

2.3.5. Sensitivity analysis

A sensitivity analysis is essential to test the robustness of your LCA results and assess how changes in assumptions or uncertain parameters might influence the environmental impacts. Therefore, the sensitivity analysis was performed to evaluate the robustness of the results and identify parameters most influencing the environmental performance of the system. The use of two complementary LCIA methods, CML-IA baseline and Environmental Footprint (EF 3.0), already serves as an initial sensitivity test, allowing comparison of midpoint characterization models with different normalization approaches and indicator structures. This dual-method approach provides insight into the methodological uncertainty inherent to LCA interpretation.

Beyond methodological comparison, additional sensitivity was conducted on water use, as this category showed high influence in the normalized EF 3.0 results. Two alternative configurations were assessed:

(i) reuse of purified water from the solar photocatalytic unit as process water in the biogas digester, thereby reducing freshwater demand for feedstock dilution; and

(ii) application of the AWARE (Available WAter REmaining) method to characterize regional water scarcity more accurately in the Sierra Leone context. The AWARE indicator quantifies potential water deprivation caused by consumption, considering local availability after human and ecological needs are met. Implementing this method enabled evaluation of how regional scarcity factors and water recycling strategies could alter the overall impact profile.

These sensitivity tests support a more comprehensive interpretation of the system's environmental performance and highlight operational adjustments, such as water reuse and local scarcity weighting, that can improve resource efficiency in decentralized biogas–water treatment systems.

2.4. Results

This section presents the life cycle impact assessment results for the biogas digester and solar water treatment system. Impact analysis is performed using two methods, the CML-IA baseline and the Environmental Footprint (EF 3.0) method, to ensure both scientific rigor and policy relevance. For each method, results are shown for both operational configurations: 300 kg/day and 1500 kg/day of organic waste treated.

Mid-point impact categories evaluated include:

- Climate Change (GWP100)
- Acidification Potential
- Eutrophication Potential (terrestrial, freshwater, marine)
- Human Toxicity
- Freshwater Ecotoxicity
- Resource Depletion (Fossil & Mineral)

In addition to the absolute midpoint results, normalized scores are provided. Normalization contextualizes the impacts by comparing them to global reference values, indicating the relative significance of each category on a dimensionless scale (EC-JRC 2015). This helps identify which impact categories are most dominant and supports clearer communication of environmental hotspots.

2.4.1. CML – IA Baseline Results

The environmental profile of the 300 kg/day biogas system, assessed using the CML-IA baseline method, demonstrates clear environmental benefits across most categories due to the substitution of fossil energy and synthetic fertilizers. As shown in Figure 6, several impact categories present negative net results, reflecting the avoided burdens credited to renewable energy generation and nutrient recycling.

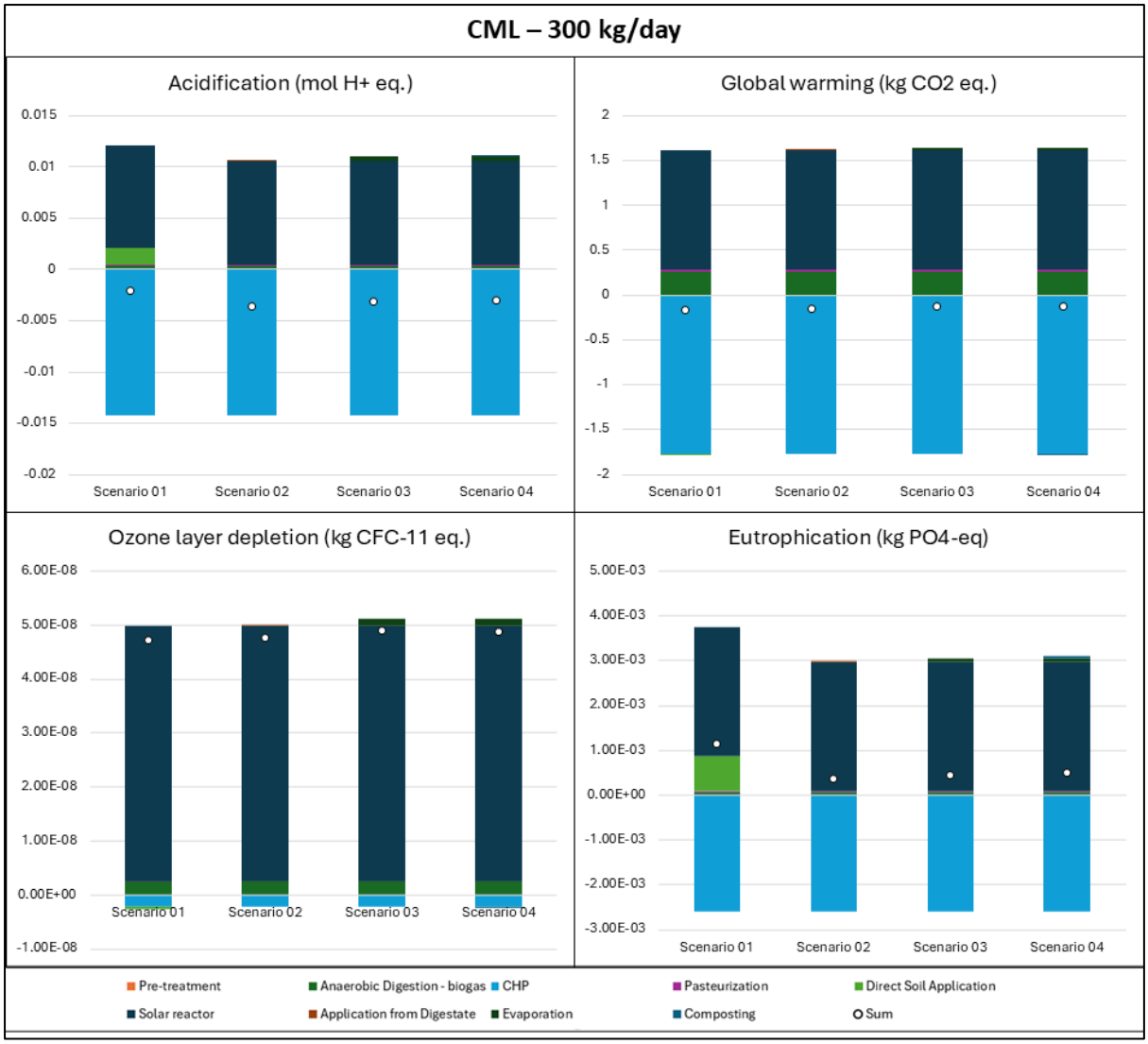


Figure 6. Characterized Results for the 300 kg/day system.

The four scenarios assessed were: Scenario 1 (baseline) that uses biogas in a CHP unit and applies the digestate after separation. Scenario 2 upgrades biogas to biomethane for vehicle fuel, Scenario 3 directs it to clean cooking, and Scenario 4 evaporates the liquid digestate to produce a nutrient concentrate. These scenarios enable a consistent comparison of environmental performance across different valorisation routes.

For global warming, the system achieves a net reduction of approximately 1.5 kg CO_2 eq. per functional unit. The largest contribution arises from anaerobic digestion and CHP operation, while the avoided impact from displaced grid electricity and mineral fertilizer production dominates the overall climate benefit.

In acidification and eutrophication, digestate handling and land application remain relevant sources of emissions due to ammonia volatilization and nitrate leaching. Nonetheless, these are largely offset by nutrient substitution benefits. The evaporation and composting stages contribute moderately to these categories, whereas solar reactor operation and pre-treatment have comparatively minor effects.

Ozone layer depletion exhibits negligible variation between scenarios, as impacts are primarily associated with background processes such as material production and electricity use rather than operational parameters.

Overall, the CML results confirm that at the smaller operational scale, Scenario 1 (baseline CHP configuration) performs comparably or slightly better than alternative valorisation routes. The results emphasize that digestate management and land application practices are the most sensitive contributors to residual impacts, while the integrated production of renewable energy and fertilizer substitutes drives most of the environmental gains.

At the larger scale of 1500 kg/day, the environmental performance of the biogas system follows similar patterns to the smaller configuration, though with amplified avoided impacts due to higher energy recovery and fertilizer substitution. As shown in Figure 7, the system continues to deliver net environmental benefits in key categories, particularly global warming, acidification, and eutrophication, where negative values indicate the predominance of avoided burdens over direct emissions.

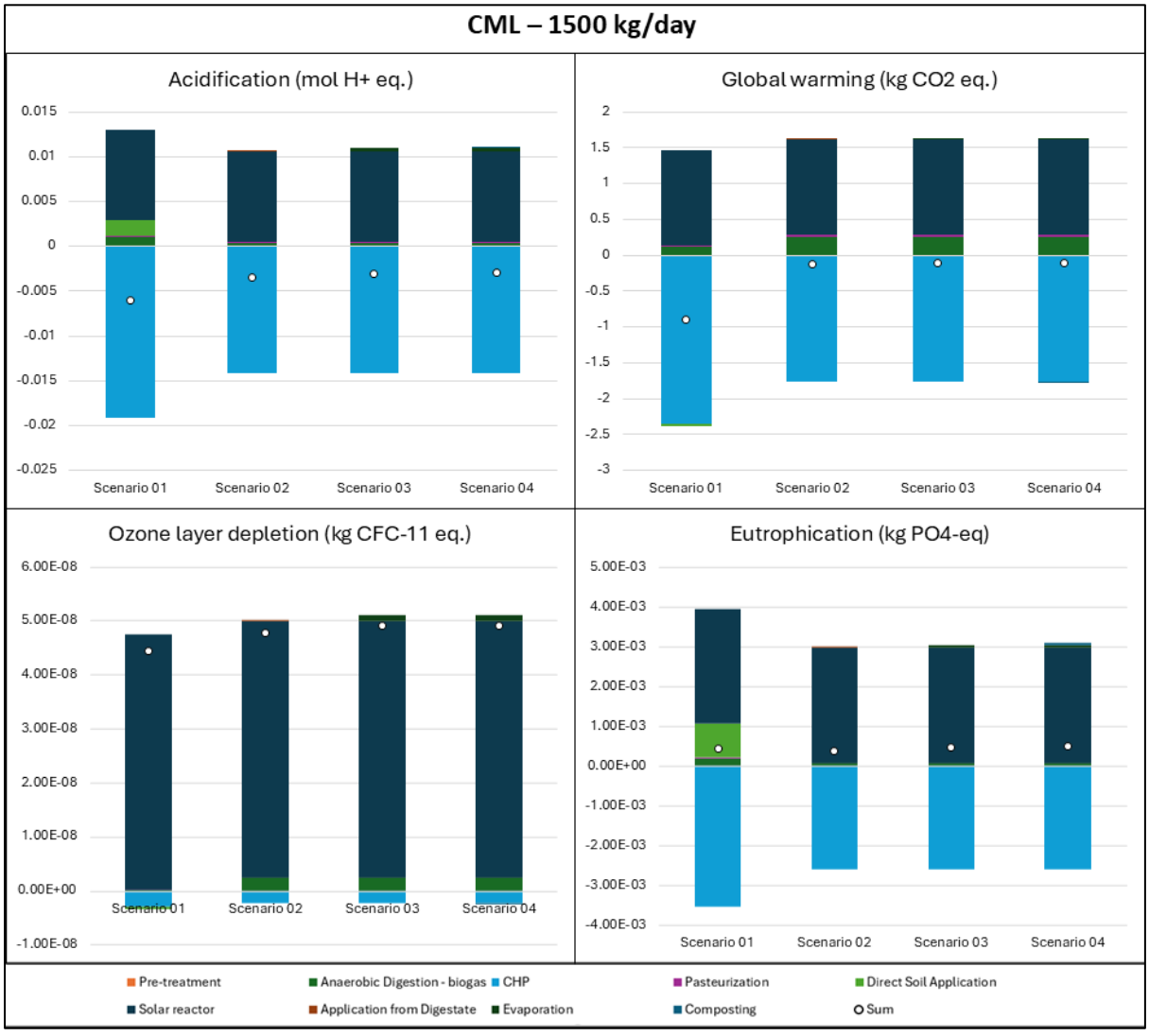


Figure 7. Normalized results for the 1500 kg/day system.

For global warming, Scenario 1 (CHP configuration) achieves the largest net reduction, over 2 kg CO_2 eq. per functional unit, driven by the substitution of grid electricity and fossil fuels through biogas-

based power and heat generation. Scenario 2 (biomethane upgrading) shows slightly lower climate benefits due to the additional energy demand of upgrading, while Scenario 3 and Scenario 4 maintain comparable performance to the baseline.

In acidification and eutrophication, digestate management remains the main source of residual impacts, linked to nitrogen losses during land application and ammonia emissions. However, these effects are counterbalanced by nutrient substitution credits, particularly in the composting and evaporation routes. The ozone layer depletion category again shows minor differences between scenarios, as it is dominated by upstream material and energy processes rather than local operations.

Overall, scaling up to 1500 kg/day enhances the system's net environmental performance, primarily through improved energy recovery efficiency and greater offset of conventional products. The results highlight the importance of maintaining controlled digestate application practices to prevent secondary emissions while maximizing the environmental gains achieved at larger operational scales.

2.4.2. Environmental Footprint (EF 3.0) Results

The Environmental Footprint (EF 3.0) assessment of the 300 kg/day configuration confirms that the system delivers overall environmental benefits, with avoided impacts from renewable energy generation and fertilizer substitution outweighing direct process emissions. As illustrated in Figure 8, climate change, acidification, and eutrophication all present net negative balances across scenarios, indicating that substitution effects dominate over operational burdens.

For climate change, the generation of electricity and heat in the CHP unit produces the highest avoided impact, offsetting emissions from digestion and land application. The acidification and eutrophication categories follow similar patterns, where minor contributions from ammonia volatilization and nitrate losses are compensated by avoided mineral fertiliser production. These results are consistent with previous LCAs of small-scale biogas systems, which report that nutrient recycling and energy substitution typically neutralize or surpass process-related emissions (Evangelisti et al., 2014; Timonen et al., 2019; Duan et al., 2020).

Ozone depletion shows very low values and limited variation between scenarios, as impacts stem mainly from background processes in material and energy supply chains rather than plant operation (Fusi et al., 2016). Water use, in contrast, exhibits comparatively higher absolute values due to pre-treatment dilution requirements, but its overall influence remains moderate when set against the avoided burdens from energy and nutrient recovery.

Taken together, the EF 3.0 results demonstrate that the baseline CHP configuration (Scenario 1) remains the most environmentally favourable option, with alternative valorisation routes yielding similar trends but slightly higher direct impacts. The findings reinforce the importance of efficient digestate handling and energy recovery as key drivers of sustainability at smaller operational scales.

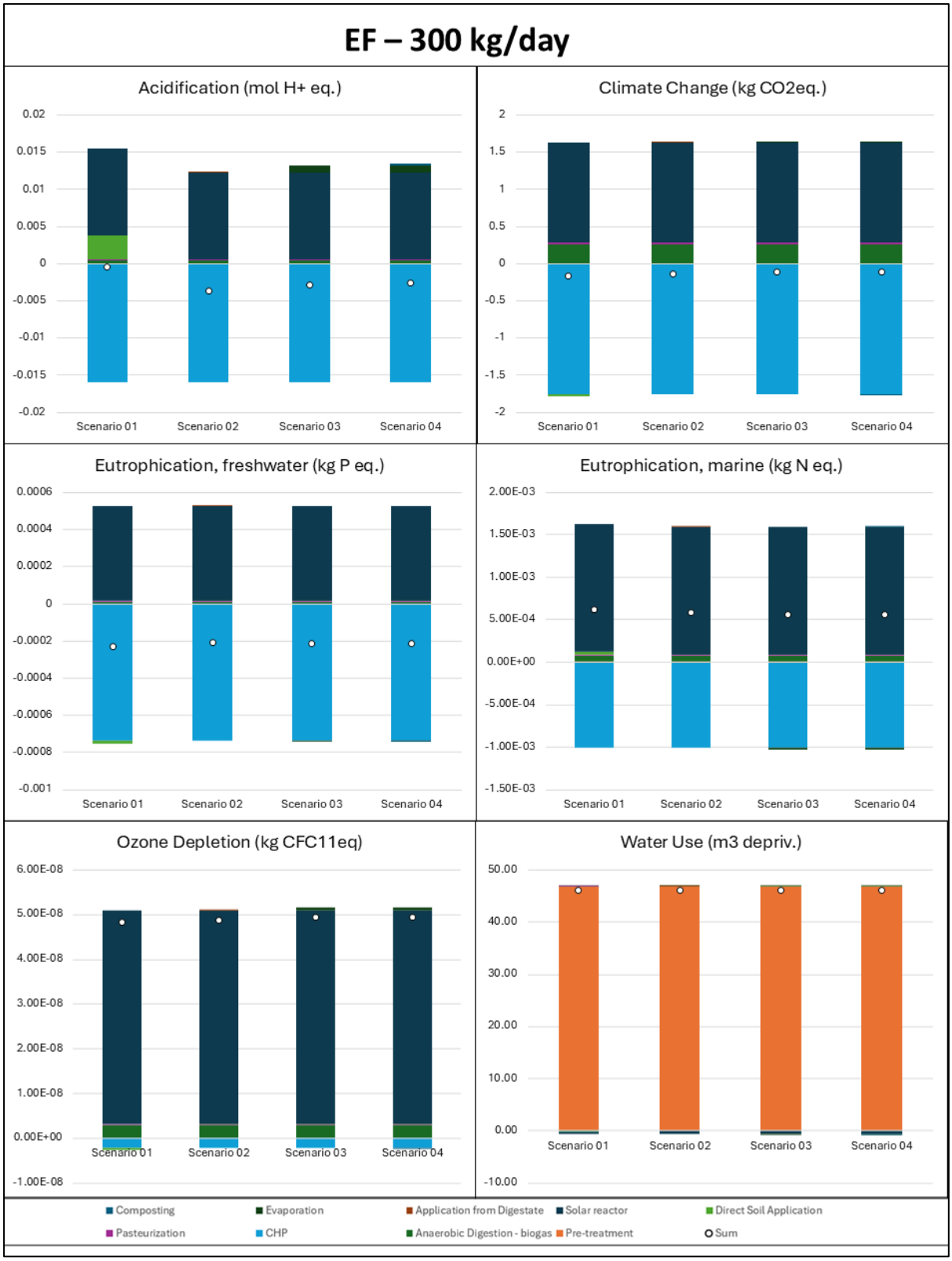


Figure 8. Environmental Footprint results for 300 kg/day configuration (acidification, climate change, eutrophication, ozone depletion and water use).

At the 1500 kg/day operational scale, the system maintains a consistent environmental profile with the smaller configuration, though avoided impacts become more pronounced due to higher energy recovery and greater substitution potential. As presented in Figure 9, climate change, acidification,

and eutrophication continue to show net negative results across all scenarios, indicating that the benefits from renewable energy generation and nutrient recycling exceed direct process emissions.

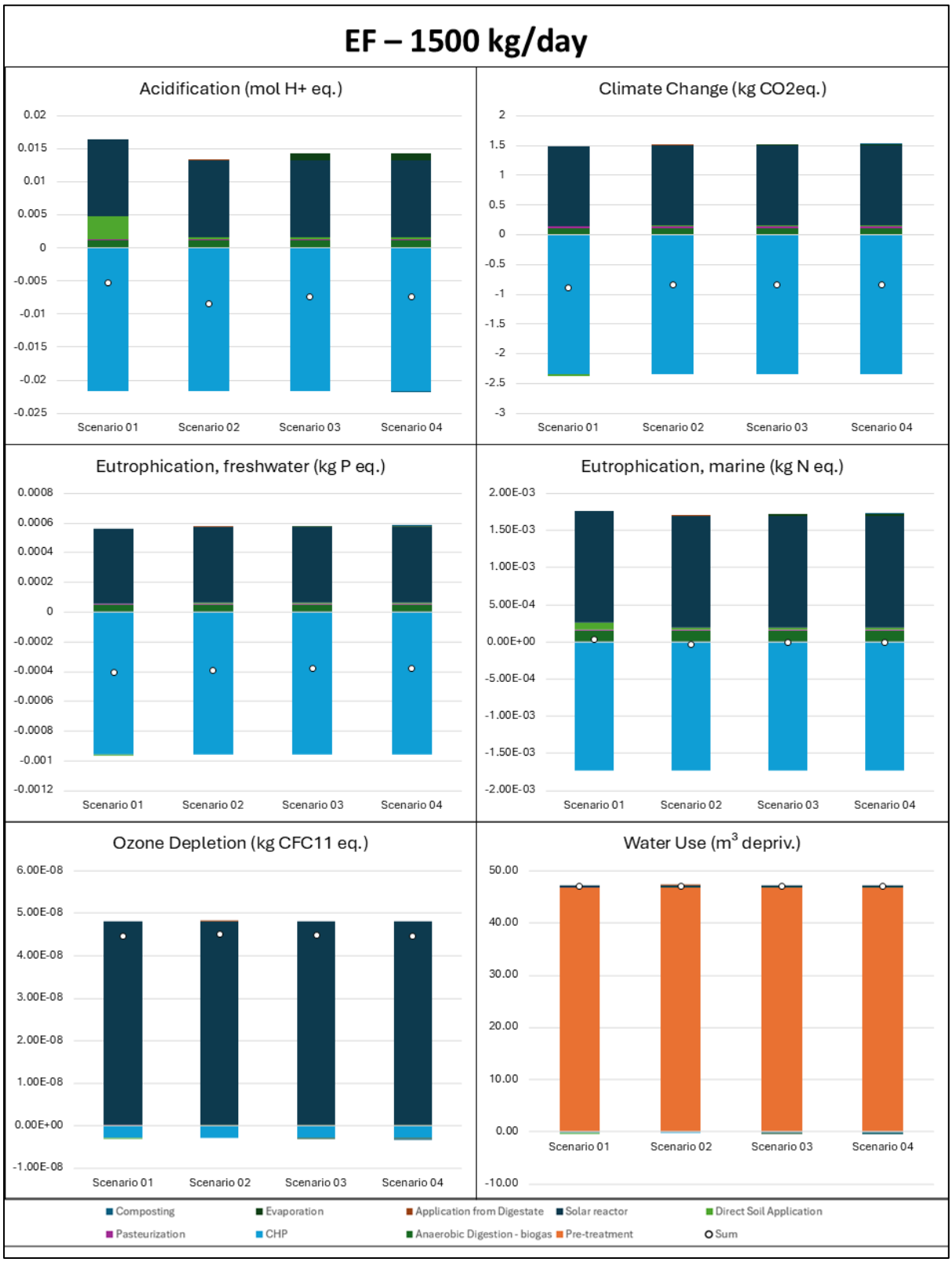


Figure 9. Environmental Footprint results for 1500 kg/day configuration (acidification, climate change, eutrophication, ozone depletion and water use).

For climate change, the combined heat and power (CHP) scenario (Scenario 1) again achieves the highest net reduction, with avoided electricity and heat from fossil sources driving the system's favourable balance. Scenario 2 (biomethane upgrading) and Scenario 3 (clean cooking) perform comparably but with slightly higher upstream energy use. This result reflects typical trade-offs identified in literature, where upgrading and gas compression increase energy demand but may enhance substitution potential when displacing transport or cooking fuels (Lorenzi et al., 2019; Lin et al., 2024).

Acidification and eutrophication (both freshwater and marine) categories remain dominated by digestate handling and land application, mainly through ammonia and nitrate emissions. Nonetheless, these are largely offset by credits from replacing mineral fertilizers, consistent with previous observations that nutrient substitution can neutralize or even surpass soil emission impacts (Evangelisti et al., 2014; Timonen et al., 2019).

Ozone depletion impacts are minimal and nearly identical among all scenarios, as background electricity and infrastructure remain the main contributors (Fusi et al., 2016). Water use presents high absolute values but shows little variation between configurations, as the pre-treatment water demand scales linearly with feedstock input.

Overall, the EF 3.0 results at higher capacity confirm that increasing system scale enhances overall efficiency and impact mitigation per functional unit. The CHP-based configuration remains the most favourable pathway, while the environmental gains of larger installations depend on maintaining controlled digestate management and minimizing energy demand in auxiliary processes.

2.5. Discussion

The combined interpretation of the CML and EF 3.0 results confirms the environmental advantages of the integrated biogas system under both small- (300 kg/day) and medium-scale (1500 kg/day) operations. Despite methodological differences, both frameworks converge in identifying renewable energy substitution and nutrient recycling as the main sources of environmental benefit. These results remain robust across impact assessment methods, reinforcing confidence in the system's sustainability performance.

Under both methods, the most relevant impact categories are climate change, acidification, and eutrophication, which are strongly influenced by digestate management and energy recovery routes. While digestate application contributes to localized emissions of ammonia and nitrates, these are largely offset by avoided mineral fertilizer production. This balance is consistent with previous studies showing that biogas systems achieve net climate benefits when accounting for energy and nutrient substitution (Evangelisti et al., 2014; Timonen et al., 2019; Duan et al., 2020).

The CML normalized results, shown in Figure 10, emphasize marine and freshwater ecotoxicity as the dominant categories at both scales, reflecting background emissions associated with material and energy supply chains. Similar patterns have been observed in LCAs of anaerobic digestion systems, where heavy-metal content in digestate and upstream electricity production contribute disproportionately to ecotoxicity (Fusi et al., 2016; Lijó et al., 2014). Nonetheless, these impacts are minor in magnitude relative to the avoided burdens in climate-related categories.

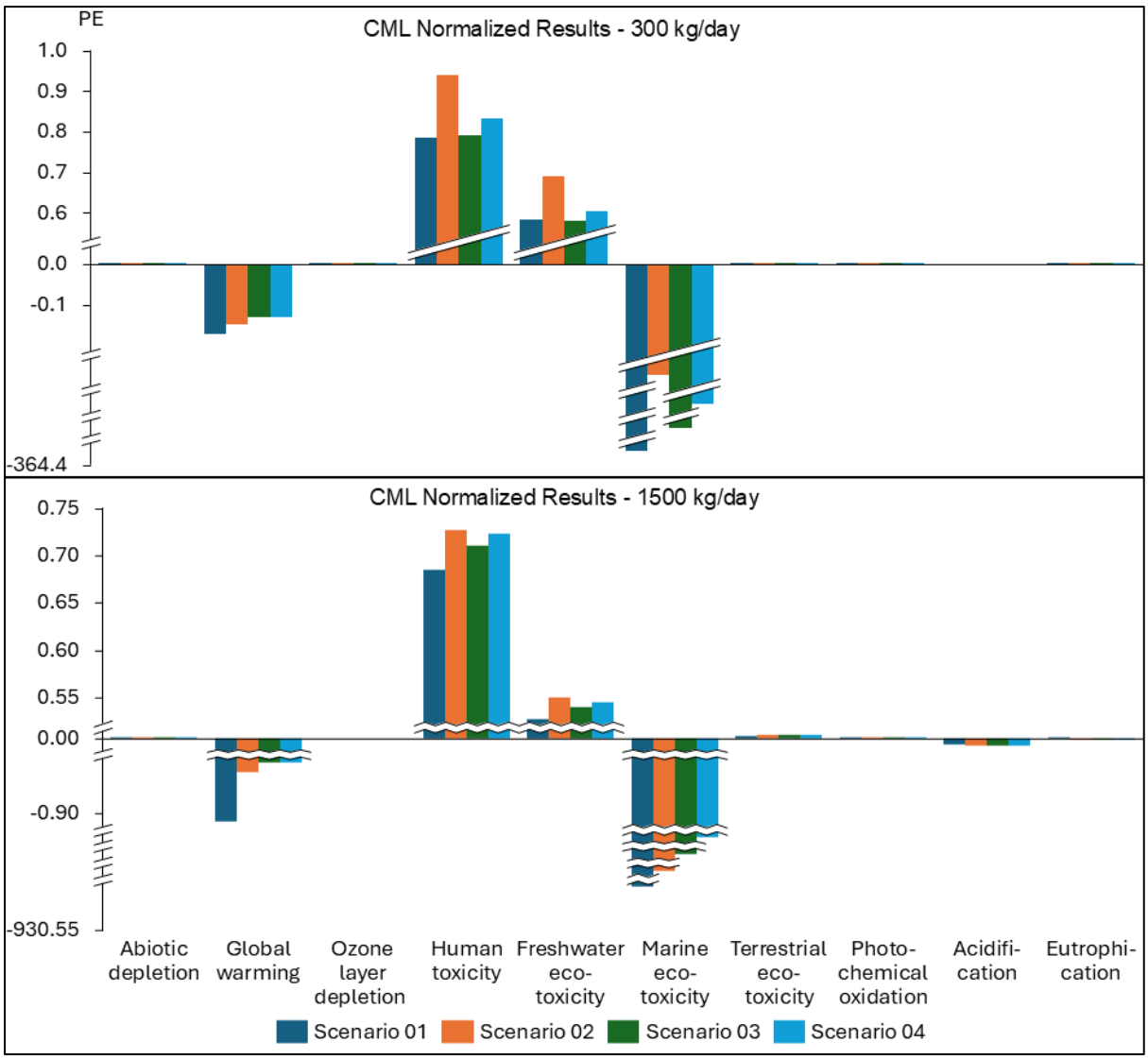


Figure 10. Normalized CML-IA results for Sierra Leone biogas system at 300 kg/day and 1500 kg/day.

In the EF normalization (Figure 11), water use and resource depletion appear as globally significant categories due to the method's weighting factors and the high-water demand during feedstock pre-treatment. However, these values should be interpreted cautiously, as site-specific water scarcity in Sierra Leone differs from global averages.

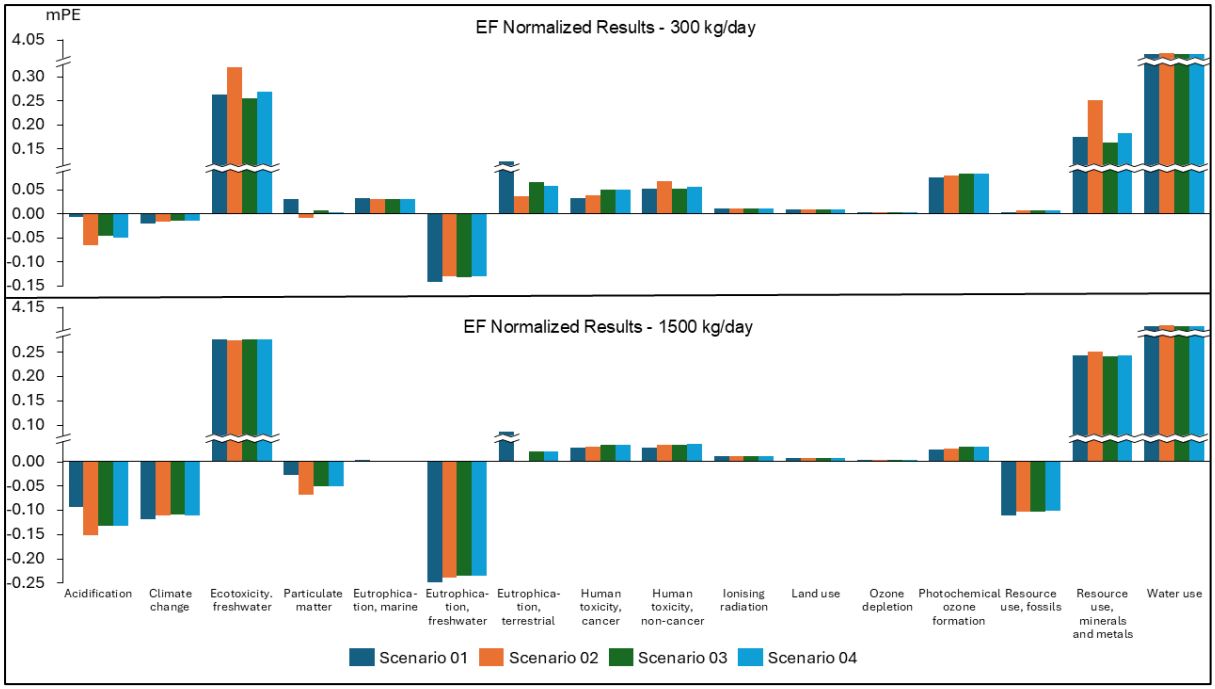


Figure 11. Normalized Environmental Footprint (EF 3.0) results for Sierra Leone biogas system at 300 kg/day and 1500 kg/day.

Scaling up from 300 kg/day to 1500 kg/day amplifies energy and nutrient recovery while improving efficiency per functional unit, confirming the environmental benefits of larger-scale systems also reported by Lorenzi et al. (2019) and Lin et al. (2024). Across both frameworks, Scenario 1 (CHP configuration) remains the most balanced and favourable option, with alternative valorisation routes offering comparable results but higher upstream energy requirements.

Overall, the alignment between CML and EF outcomes demonstrates methodological robustness and highlights the same optimization priorities, controlled digestate management and reduced water intensity, as key levers to enhance circularity and minimize environmental trade-offs in decentralized biogas systems.

2.6. Sensitivity Results

The sensitivity analysis was performed to assess the robustness of the environmental results obtained with the EF 3.0 method for the 1500 kg/day configuration, focusing specifically on the water use category. This category was selected due to its prominence in the EF normalization results and its high dependency on local conditions and process assumptions.

In the baseline assessment, water consumption primarily originates from feedstock pre-treatment, where organic waste is mixed with water at a 1:1 ratio. To test the influence of this assumption, a sensitivity scenario was modelled in which the treated water from the solar photocatalytic purification unit is reused as process water in the biodigester. The baseline results correspond to the values presented in the previous EF analysis, while the AWARE method was additionally applied to contextualize water scarcity in Sierra Leone.

As shown in Figure 12, reusing the purified water resulted in a dramatic reduction in freshwater use, nearly eliminating the impact in all scenarios. The AWARE-based results were very close to the baseline, which is why they overlap in the figure, but both indicate that the system's effective contribution to regional water scarcity is negligible once water recycling is implemented. This demonstrates that process integration between the biogas and water purification systems can

substantially enhance resource efficiency, confirming water reuse as one of the most effective strategies for improving the overall sustainability of the ENERGICA system.

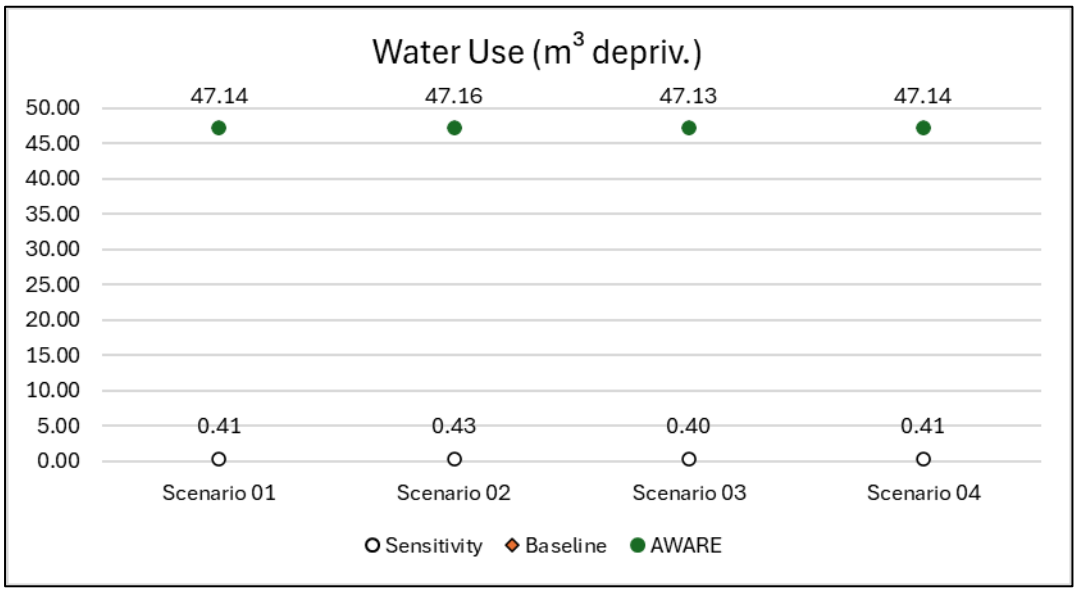


Figure 12. Sensitivity results for Environmental Footprint method.

2.7. Conclusion

This study applied life cycle assessment (LCA) to evaluate the environmental performance of a decentralized biogas system integrated with solar photocatalytic water purification in Sierra Leone, under different operational scenarios and scales. Using both the CML-IA and Environmental Footprint (EF 3.0) methods provided complementary perspectives and served as an internal sensitivity check for methodological robustness.

Across all configurations, Scenario 1 (baseline) consistently demonstrated the most balanced environmental performance, mainly due to efficient energy recovery through combined heat and power (CHP) and nutrient recycling via digestate application. While digestate handling contributed to acidification and eutrophication, these impacts were largely offset by avoided emissions from fossil electricity and synthetic fertilizer substitution. Scaling up from 300 kg/day to 1500 kg/day improved energy efficiency and reduced climate impacts per functional unit, confirming the environmental advantages of larger-scale operation.

The EF 3.0 results highlighted water use as the most significant category in absolute terms. However, the sensitivity analysis revealed that reusing treated water from the photocatalytic unit nearly eliminated water consumption impacts, demonstrating the substantial potential of system integration.

Overall, the results confirm that biogas–water integration systems can effectively support circular economy and resource efficiency goals in off-grid regions. By coupling renewable energy generation, nutrient recovery, and clean water production, the system presents a scalable and resilient model for sustainable infrastructure deployment in sub-Saharan Africa.

3. Kenya

3.1. LCA for sustainable mobility in Kenya

LCA is a comprehensive method that evaluates the environmental impacts associated with all stages of a product's life from raw material extraction through production, use, and end-of-life disposal.

Within the ENERGICA project, ROAM has developed electric motorcycles tailored to the African context. ROAM has also developed an electric bus for Africa. To support the project's goal of promoting sustainable mobility in Kenya, an LCA was conducted to compare the environmental performance of ROAM's electric bus with that of conventional diesel buses currently in use.

Electric vehicles use energy stored in batteries for propulsion. The LCA of these buses include raw material extraction (notably lithium, cobalt, nickel for batteries), vehicle and battery manufacturing, electricity production, vehicle operation, and end-of-life treatment. The environmental benefits depend heavily on the carbon intensity of the electricity grid; lower carbon grids (renewables, hydro) maximize the emission reductions while reliance on fossil-fuel based grids reduces benefits.

Given Africa's rapid urbanization and growing transport demand, electric vehicles hold strong potential to reduce life cycle greenhouse gas emissions and urban air pollution. Their zero tailpipe emissions contribute to improved air quality and reduced health risks in cities. While financial and infrastructure barriers remain, declining battery costs and technological learning curves offer promising prospects.

When applied to fossil fuel versus electric mobility in Africa, LCA provides critical insights into sustainability performance and serves as a valuable tool for shaping energy and transport policy.

3.2. Introduction and context

Buses play a crucial role in the public transportation of passengers in Kenya. Their significance lies in their ability to efficiently transport many passengers, making them indispensable for both intercity and intracity travel. Most intracity buses in Kenya are medium-capacity buses i.e. ≤15 tonnes (Notter et al., 2019). In Kenya, these buses are popularly known as *Matatus*. Most *Matatus* use power trains based on internal combustion engines that run on fossil diesel. These engines emit various pollutants, including carbon dioxide (CO_2), which contributes to climate change, and aerosol black carbon (commonly known as soot), a component of fine particulate matter produced by incomplete combustion of fossil fuels (Ayetor et al., 2021; Mbandi et al., 2023). Greenhouse gases cause climate change which is a driver of biodiversity loss (Habibullah et al., 2021; Urban, 2015). Soot particles are tiny and can penetrate deep into the respiratory system when inhaled and exposure to black carbon has negative health effects, including respiratory diseases, cardiovascular problems, and even premature death (Gatari et al., 2019). Air pollution, including emissions from buses, is already a top risk factor for health in Kenya (Gatari et al., 2019; Mbandie et al., 2023).

Transitioning to cleaner buses is essential to reduce harmful emissions and options include electric buses because these have zero tailpipe emissions. A few electric buses are now plying routes in Kenya (ESI, 2023). However, the impact of replacing diesel by electric buses could result in trade-offs with other environmental impacts commonly used in energy and transport technologies i.e., photochemical oxidant formation potential, ozone layer depletion, acidification potential and fresh water ecotoxicity potential and metal or mineral resource use (Ellingsen et al., 2022; Zackrisson, 2021). Additionally, the transfer of environment impacts outside Kenya for example to places where mining of metals used for batteries can occur. To comprehensively address these trade-offs, LCA a method

that assesses the environmental impact of a product or technology from cradle to grave, can be used to study the overall sustainability of replacing the diesel buses by electric buses in Kenya.

Few LCA studies have been performed in African countries on electric buses (e.g. Ayetor et al., 2021; El Hafdaoui et al., 2023) but several studies in countries outside Africa have been conducted (e.g. Teoh et al., 2018; Lie et al., 2021; Garcia et al., 2022; Lubecki et al., 2023). These previously published LCA studies have examined buses across different regions, shedding light on their environmental footprint providing valuable insights even for African countries. Most previous LCAs have primarily centered on the carbon footprint, emphasizing emissions reduction, but electric buses also affect other impact categories e.g. resource depletion and acidification, especially in the production of the battery (Ellingsen et al., 2022). Studies have shown that the environmental benefits of electric buses depend on the electricity generation mix in a country, i.e. if the electricity mix is largely composed of fossil fuels, the electric buses do not have an advantage over diesel buses (Cooney et al., 2013; Garcia et al., 2022). However, Kenya has a unique situation, it is one of the few countries in Africa generating 80% of its electricity from renewable sources and with plans to increase to 100% by 2030 (Clean Technica, 2023). Consequently, replacing diesel buses with electric ones in Kenya might significantly reduce carbon emissions during the use phase of the bus. The surplus of nighttime grid power will allow efficient charging without straining the system. While electric buses are recommended for Kenya, achieving net zero emissions by 2050 requires ambitious efforts. To be on track with the net zero emissions by 2050, carbon dioxide emissions from the transport sector must fall by more than 3% per year to 2030 (IEA, 2023). Detailed analysis for emission reduction related to diesel-to-electric bus replacement and changes in electricity carbon emission factors are essential.

The purpose of this study is to evaluate the implications of the replacement of diesel buses with electric ones. The objectives include comparing the environmental impact of a diesel and to an electric bus, assessing environmental trade-offs of utilizing an electric bus as opposed to a diesel bus and assessing the climate impact of the transition from diesel to electric buses at bus and fleet level in Kenya. The insights derived from this study can inform decision-making processes in transportation planning and policy development, thereby fostering more sustainable mobility solutions.

3.3. Materials and Method

The following subsections describe the methodological framework adopted for the life cycle assessment for mobility in Kenya, starting from the goal and scope, followed by the system boundaries, functional unit, life cycle inventory modelling, and impact assessment approach used to evaluate the environmental performance.

3.3.1. Goal and Scope

The study performs life cycle assessment of standard buses in Kenya. The goal was to compare the environmental impacts of a diesel bus and an electric bus and identify environmental trade-offs (impact categories) of replacing a diesel bus with an electric bus. The study focused on six mid-point impact categories i.e. climate impact, resource use, photochemical oxidant formation, ozone layer depletion, fresh water ecotoxicity and acidification because these are commonly used for energy and transport technologies (Ellingsen et al., 2022). Our life cycle assessment adhered to ISO 14044 (ISO, :2006) requirements, encompassing scope definition, inventory analysis, impact assessment, and interpretation.

For assessing the fleet climate impact of replacing the diesel buses with electric buses, the scenarios in Table 3 were used.

Table 3. Scenarios of bus fleet in Kenya

Scenario	Share in fleet %	
	Electric bus	Diesel bus
1	0	100
2	10	90
3	20	80
4	30	70
5	40	60
6	50	50
7	60	40
8	70	30
9	80	20
10	90	10
11	100	0

3.3.2. System description

The most common diesel *Matatus* model (weighing ≤15 tonnes) in Kenya is produced by Isuzu. The diesel *Matatus* is imported as a cab chassis for truck without a trailer from Japan and the bus body is built in Kenya. Kenya now has an electric *Matatus* model (51-seater), which is locally assembled by Roam, a technology-driven electric mobility company producing electric buses for emerging markets. The electric bus is specifically engineered for longevity. Detailed specifications for both types of buses are presented in Table 4. The diesel bus is powered by an internal combustion engine and does not have motor and power electronics, whereas the electric bus has no engine, but an electric motor powered by batteries. The diesel bus has tailpipe emissions such as CO_2 and NO_x, whereas the electric bus has no tailpipe emissions. The diesel bus refuels at filling stations, while the electric bus recharges at charging stations. The vehicle milage of both buses can span up to 500 000 km. The components of diesel and electric buses are shown in Table 4 and the weights in Table 6.

Table 4. Bus specifications

Parameter	Units	Diesel bus	Electric bus
Model name	-	Isuzu NQR	Roam Move
Engine	cc	4 700 (130 hp)	-
Passenger capacity	passengers	37	51
Weight	kg	6 100	10 300
Battery capacity	kWh	-	170
Length	m	7.8	9.5
Height	m	2.2	2.5
Width	m	2.6	3.2

Table 5. Bill of materials

Item	Diesel	Electric
Rolling Chassis (cradle, driveshaft, axles, differential, suspensions, braking system), Powertrain* and Transmission (clutch, gearbox and final drive)	X	X
Body	X	X
Power electronics	-	X
Motor (traction)	-	X
Battery	-	X

Item	Diesel	Electric
Engine oil	X	
Tyres	X	X
Coolant	X	X

*For diesel bus includes engine unit, fuel storage, electrical system, thermal system and exhaust system and for electric bus includes thermal system and electrical system
- Not part of the bus

Table 6. Weight of each component of the buses

Component	Diesel in kg	Electric (bus) in kg
Rolling chassis	1900	3600
Body	3900	4400
Motor	-	300
Battery	-	1600
Tyres	270	450
Engine oil	6	-
Coolant	26	-
Total	6100	10300

3.3.2.1. System boundary

The study covered several stages of the life cycle of the buses, including the manufacturing of the bus kits and batteries, transportation of these kits and batteries to Kenya and the assembly of the buses in Kenya. The study also considered the use or operation of the buses, for diesel bus, this involved the combustion of diesel fuel and for the electric bus this involved the generation of electricity used for charging. The process flow chart of the system boundary used in this study is shown in Figure 13.

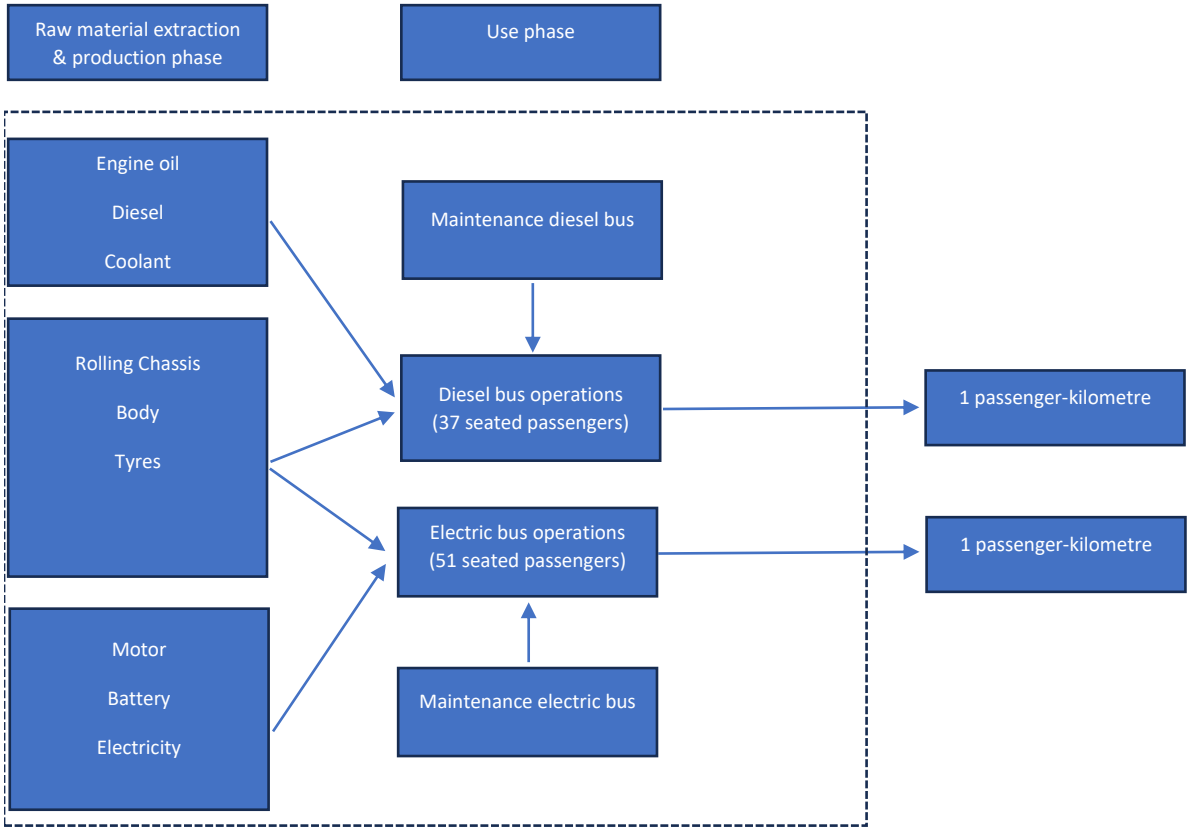


Figure 13. The flow of the chart of system boundary.

3.3.2.2. Functional unit

To allow for a comparison of the two buses despite their different capacities, the functional unit was defined as 1 passenger-kilometre (pkm), which is equivalent to the transportation of 1 passenger over a distance of 1 kilometre.

3.3.3. Life cycle inventory

3.3.3.1. Manufacture of a diesel and an electric bus

The production of the diesel bus began with the cab chassis with a powertrain. The vehicle inventory for medium and heavy-duty vehicles from Iyer et al. (2021) was used to model the manufacturing of the diesel cab chassis and powertrain i.e., the medium duty truck. This assumption was made due to the difficulties in obtaining component composition and manufacturing data, as well as the lack of product declaration information for an Isuzu NQR cab chassis. The weight breakdown of the cab chassis and the composition of each of the components in Table 4, were also derived from Iyer et al. (2021). These are presented in Appendix Table A1. This component composition was used to create a bill of quantities, which was later used as input into Simapro 9.6.0.1 (Pre-Sustainability, 2024) for raw material extraction and processing and manufacturing emissions from Ecoinvent 3.8 (Ecoinvent, 2021). The production of the electric bus also began with a rolling chassis, but the chassis was built directly for the bus in China. The components for making the chassis and powertrain for the electric bus were produced in China. The weight breakdown of the electric bus chassis and the composition of each of the components are also displayed in Table 3.

The bus bodies for both the diesel and electric buses were produced in Kenya. Due to the challenges in obtaining bill of quantities from Kenyan coach builders for the diesel bus, a Zimbabwean coach builder was consulted for a bill of materials. The bill of materials was estimated based on the dimensions of the bus and the cab chassis by the Zimbabwean coach builder. The materials are shown in the Appendix in Table A2. Roam produces the body for the electric bus and provided the bill of materials for coach building for the electric bus. However, this is not presented due to confidentiality reasons.

3.3.3.2. Manufacture of the battery and charging station

High voltage batteries are required to power the traction motors for the electric bus, and these were produced in China. The assembly of a lithium-ion battery involves several components: a cathode, an anode (typically made of carbon/graphite), an electrolyte (for example, Lithium hexafluorophosphate or LiPF6), and a separator (a porous plastic polymer used to prevent the cell from short-circuiting) (Arshad et al., 2022). The electric buses in Kenya used a depot charging station with plug-in chargers. A bill of materials for battery production was estimated and used for calculation of the emissions from raw material extraction and processing and the manufacturing of the battery using Ecoinvent 3.8 (Ecoinvent, 2021) in Simapro 9.6.0.1 (Pre Sustainability, 2024). Due to lack of data for LiFePO4 batteries in in Ecoinvent, the LiMn2O4 battery dataset in Ecoinvent was used. The charging station was excluded from the assessment, as the diesel storage depot was also not considered.

3.3.3.3. Transportation of bus kits and batteries from Asia to Kenya

For the diesel bus, the cab chassis was transported from Japan to Kenya. For the electric bus, the batteries and components of the chassis were transported from China to Kenya. Containerized ships were used for the transportation of the cargo, and the emissions were calculated in Simapro 9.6.0.1 (Pre Sustainability, 2024) using tonne-kilometres as input. For the transportation for cab chassis for the diesel bus the weight for each cab (2.79 t) was multiplied by the distance in km from Yokohama

port in Japan to Mombasa port in Kenya (14900 km; Port.com, 2024). For the electric bus, batteries and components of the chassis were transported from Shanghai to Mombasa (12900 km; Port.com, 2024).

3.3.3.4. Assembly of the buses

The energy required for the assembly of the buses was assumed to be 2.74 kWh electricity and 2.74 kWh heat per kg bus weight (Velandia Vargas et al., 2019).

3.3.3.5. Use phase of the buses

Diesel was produced from the refinery of crude oil via distillation and Ecoinvent 3.8 (Ecoinvent, 2021) in Simapro 9.6.0.1 (Pre Sustainability, 2024) was used for the calculation of emissions. For upstream production and distribution of electricity, Ecoinvent 3.8 was used for the grid intensity.

The life span of the buses was 500,000 km over 9 years, with an annual mileage of 54 750 km, an estimated capacity utilization of 90%, and a fuel consumption of 0.35 litres/km for the diesel bus (Mbandi et al., 2019). Steer tyres were be replaced 2.5 times and drive tyres 1.6 times over the life span of the bus. Additionally, the engine oil was changed 10.4 times and coolant 2.1 times during the bus's lifespan (Iyer et al., 2021). The total transport work over a total diesel bus life was 16.2 million passenger-kilometres.

For the electric bus, similar assumptions were made regarding the lifespan, annual mileage, capacity utilization and tyres. The amount of electricity i.e. the average amount of charging electricity was 610 00 kWh calculated from an energy consumption of 0.85 kWh/km (Velandia Vargas et al., 2019). A discharging efficiency of 90% and charging efficiency of 90% were assumed. Energy losses in the grid were assumed to be 11% (Zackrisson et al., 2010) and the battery was replaced 2.5 times during the life span of the electric bus Velandia Vargas et al., 2019).

3.3.3.6. Disposal of the buses

Diesel buses are disposed of in Uganda and Rwanda, but it's unclear what these buses are used for. As for the electric buses, they are still new in Kenya, and none have been disposed of yet. Therefore, disposal emissions were not included in this study due to a lack of data.

3.3.4. Impact assessment

3.3.4.1. Diesel and electric bus environmental impact assessment

Simapro 9.6.0.1 (Pre Sustainability, 2024) was used to assess the environmental impacts. Both Environmental Footprint (EC, 2022) and CML 2016 baseline (University of Leiden, 2016) were used in the impact assessment. Ecoinvent 3.8 allocation cut-off by classification unit database (Ecoinvent, 2021) was used for the impact assessment.

A 37-seater diesel bus was compared to a 51-seater electric bus for resource use (mineral), climate impact, photochemical oxidant formation potential, ozone layer depletion, acidification potential, and fresh water ecotoxicity potential. This impact assessment was based on the total annual mileage per bus, which amounts to 54 750 kilometres of travel in Kenya (Mbandi et al., 2019).

3.3.4.2. Fleet climate impact assessment

The climate impact of the fleet was calculated based on the proportion of electric buses. For example, if 20% of the fleet is electric, the total greenhouse gas (GHG) emissions reflect the combined impact of both electric and diesel buses according to their respective shares. The climate impact of the fleet

was based on the passenger km per year in 2016 estimated from a fleet size of 13 206 buses (Ogot et al., 2018).

3.3.5. Sensitivity analysis

3.3.5.1. Environmental impact of diesel and electric buses

The electricity production mix in Kenya currently comprises of 80% renewable energy but this will change to 100% renewable energy by 2030 (Clean Technica, 2023). Considering this shift, we conducted a sensitivity analysis to determine which factor had a greater impact on the climate: a ± 10% change in grid intensity for electricity production with equal diesel to electric bus mix.

3.3.5.2. Fleet climate impact

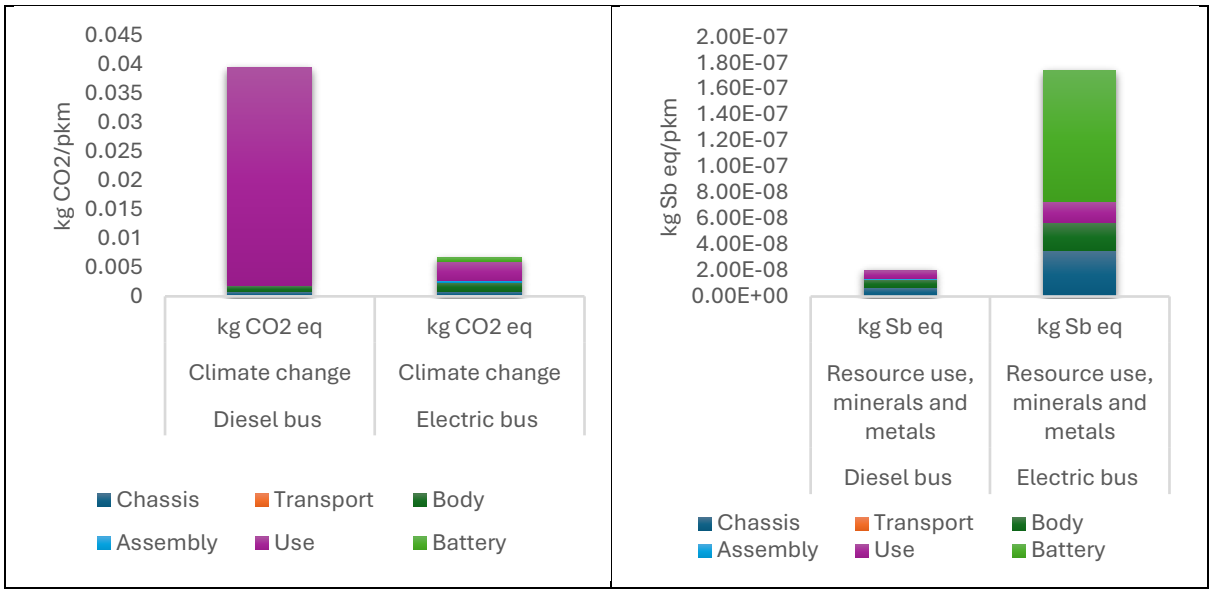
The fleet size of electric buses is expected to grow due to a partnership between the EU and the Kenyan government. Assuming a future 50:50 split between diesel and electric buses, a sensitivity analysis was conducted using a ±10% variation in the share of electric buses. The analysis was based on the current fleet size and grid intensity, with 80% of electricity sourced from renewables.

3.4. Results

The following section presents the comparative results of the environmental impact assessment for diesel and electric buses, highlighting key findings from both individual vehicle and fleet perspectives.

3.4.1 Environmental impact of diesel and electric buses

Replacement of diesel buses by electric buses presents a 68-94% decrease in environmental impact for climate impact, photochemical oxidation, ozone depletion, and acidification but increased fresh water ecotoxicity 5% and resource use, minerals and metals by 780% (see Figure 13 and Figure 14). For the diesel bus, the use phase contributed the highest impact for impact categories. For the electric bus, the use phase contributed the most to climate change, photochemical oxidation, ozone depletion and freshwater ecotoxicity. The battery production contributed the most to resource use.



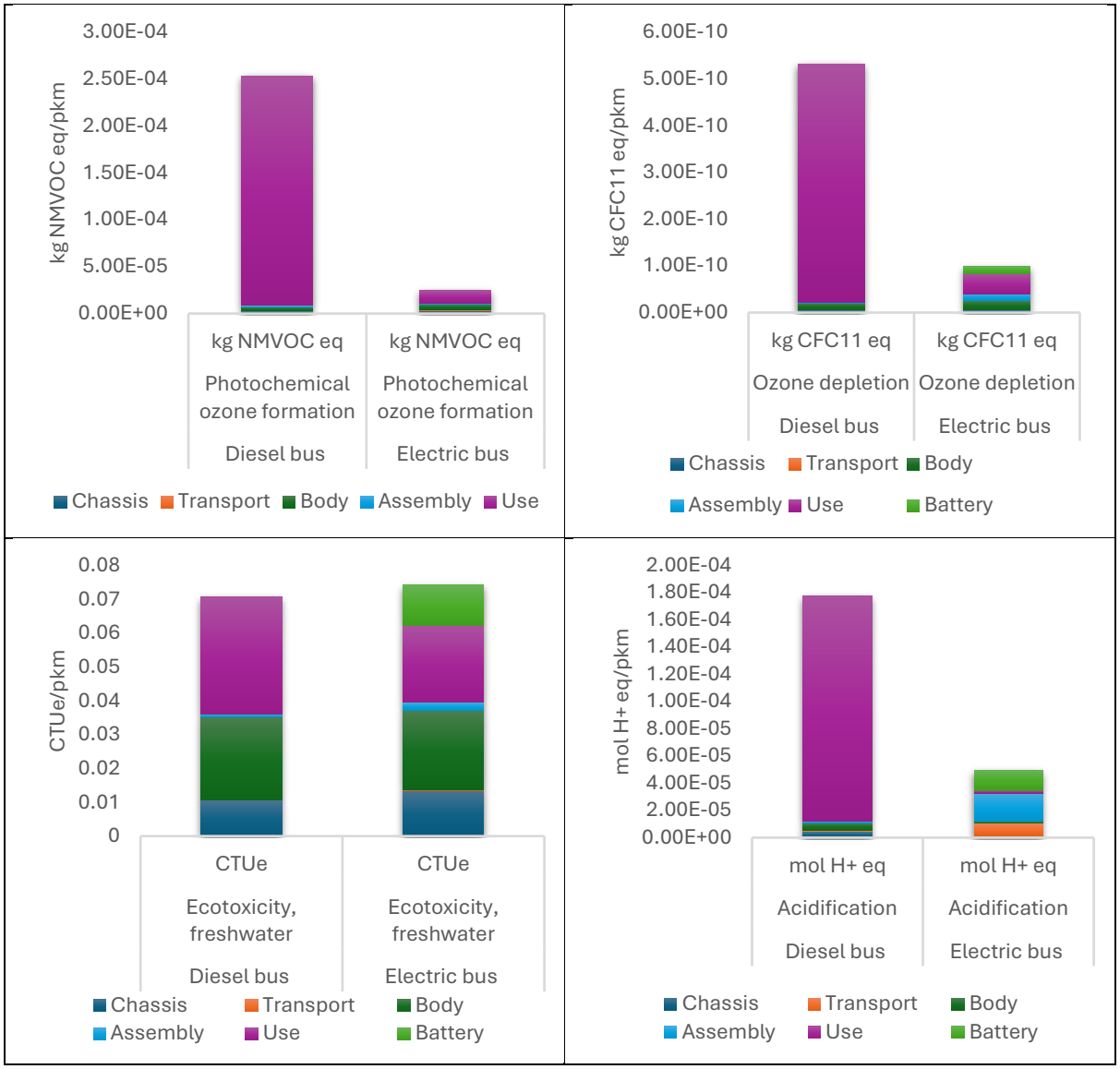
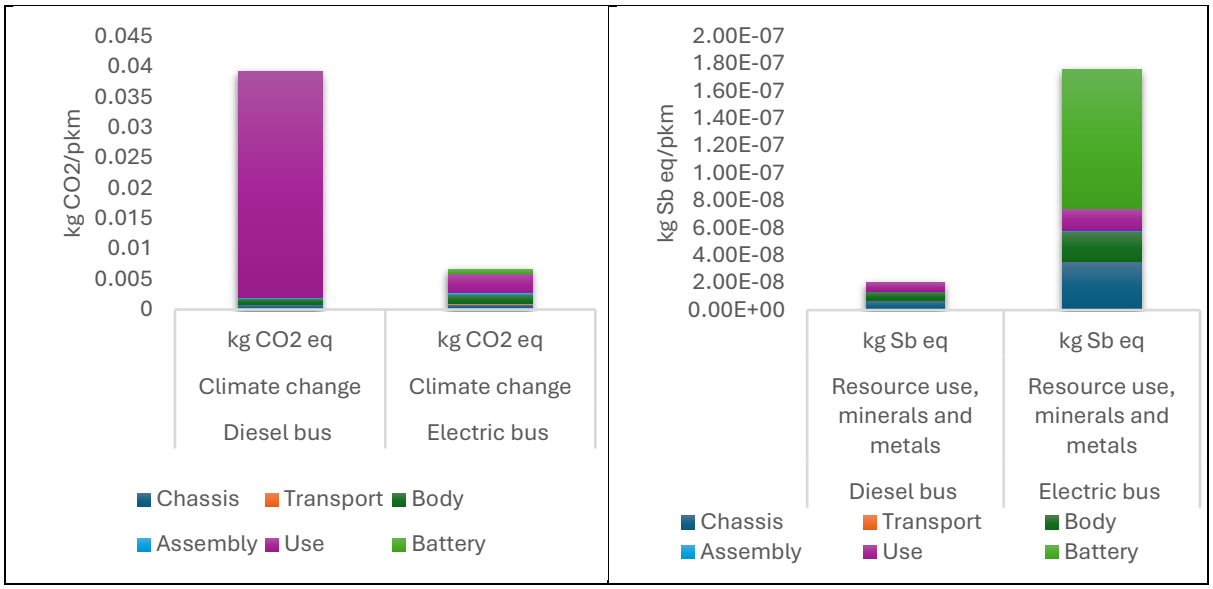


Figure 14. Environmental impacts for the diesel and electric buses per passenger-kilometre pkm using Environmental Footprint 3.1 method (EC, 2022).



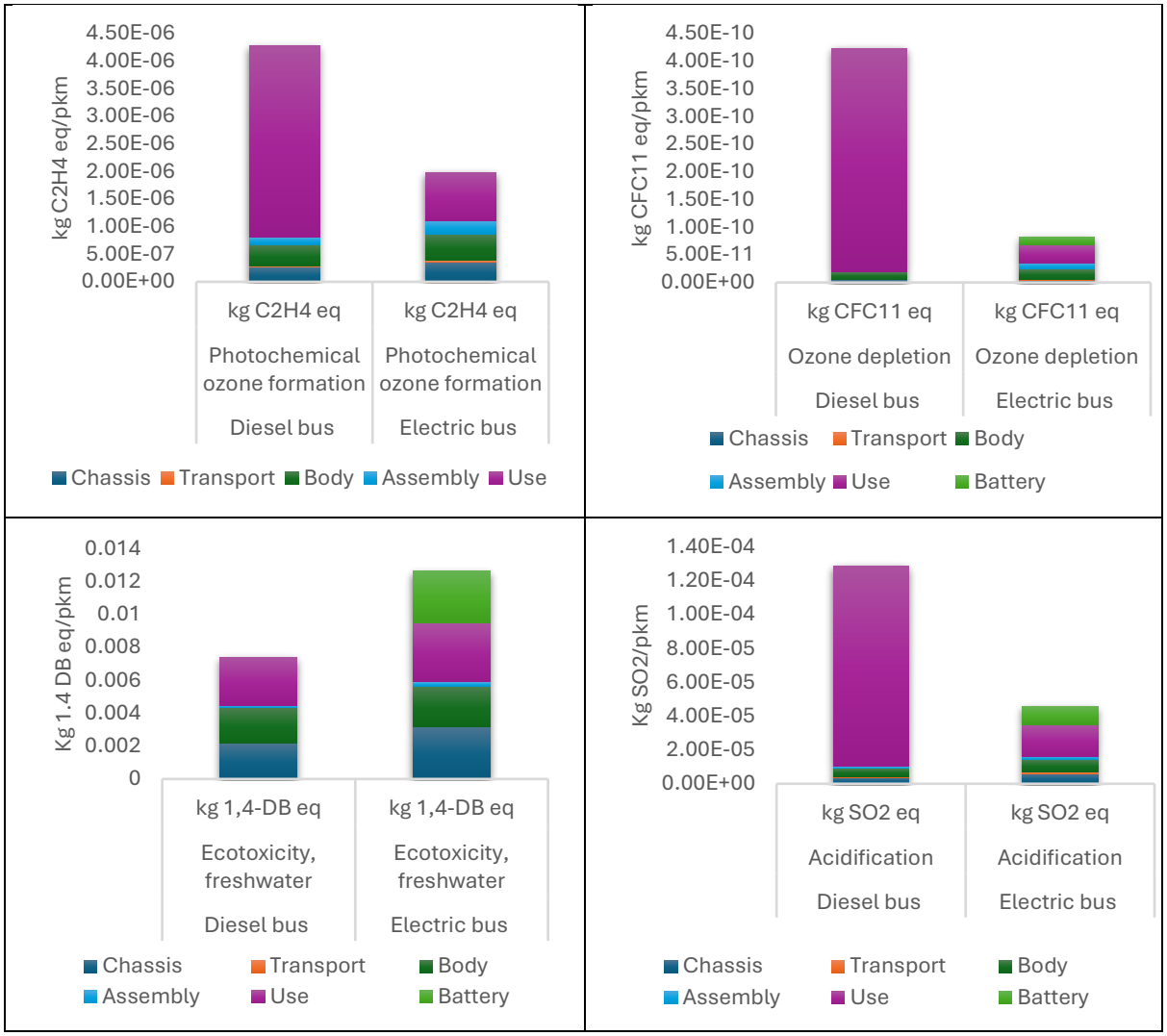


Figure 15. Environmental impacts for the diesel and electric buses per passenger-kilometre pkm using CML 2016 baseline method (University of Leiden, 2016).

3.4.2 Fleet climate impact

Replacement of the entire fleet of 13 206 diesel buses by electric buses, reduced climate impact by 83%. Table 7 shows the results of the total climate impact for the entire fleet with different bus mixes.

Table 7. Fleet climate impact based on the emission factors from the composite bus using the current electricity mix in Kenya using Environmental Footprint 3.1 method (EC, 2022)

Scenario	Share in fleet %		Mt CO_2 eq
	Electric bus	Diesel bus	
1	0	100	0.92
2	10	90	0.85
3	20	80	0.77
4	30	70	0.69
5	40	60	0.62
6	50	50	0.54
7	60	40	0.46
8	70	30	0.39
9	80	20	0.31
10	90	10	0.23
11	100	0	0.16

3.4.3 Sensitivity analysis

Increasing the proportion of electric buses in a fleet from 50% to 60% (while reducing diesel buses from 50% to 40%) decreases the climate impact per pkm (see Table 8). Conversely, decreasing the proportion of electric buses increases the climate impact per pkm. Increasing the grid intensity (i.e., the carbon intensity of the electricity used) by 10% results in a small increase in the climate impact per pkm for a 50:50 diesel to electric bus mix. Decreasing the grid intensity by 10% has the opposite effect, small reduction in the climate impact per pkm.

Table 8. Change in climate impact due to changes in grid intensity and fleet composition

Scenario	Change in greenhouse gas emission in Mt CO_2 eq
Change in electric buses in the fleet	
+10%	-14.0%
-10%	+14.0%
Change in grid intensity	
+10%	+0.6%
-10%	-0.6%

3.5. Discussion

The purpose of this study was to evaluate the implications of replacing diesel with electric buses per passenger-kilometre in Kenya and the objectives included assessing the climate impact and environmental trade-offs of producing and utilizing an electric bus compared to a diesel bus. Previous studies assessing the environmental impact of buses have mainly focused on countries outside Africa (e.g. Teoh et al., 2018; Lie et al., 2021; Garcia et al., 2022; Lubecki et al., 2023). These studies have primarily focused on buses that are directly manufactured, rather than those converted from a truck cab-chassis to a bus, as is the case with the diesel bus in Kenya. Replacing diesel buses by electric buses in Kenya can result in changes in the climate impact, photochemical oxidant formation potential, ozone layer depletion, acidification potential and freshwater ecotoxicity potential per passenger kilometre.

Increasing electric buses in the fleet in Kenya, decreases the overall climate impact, photochemical oxidant formation potential, ozone layer depletion and acidification. This means that there are benefits of substituting diesel buses with renewable energy sources with electricity as an energy carrier for vehicle propulsion in emerging economies. The decision by policy makers to consider electrification of vehicles as a policy goal (Adjej-Ampomah, 2020) is an important move towards reducing the climate impact of Kenya. However, increases in electric buses result in increases in fresh water ecotoxicity and resource use, minerals and metals. This is because of the higher production impacts of the lithium-ion battery production for electric buses. Lithium-ion batteries have garnered substantial global attention due to their exceptional characteristics such as high specific energy, compact size, impressive capacity, and a low self-discharge rate. The types of cathodes commonly used include lithium nickel-cobalt-manganese oxide (NMC = LiNixCoyMnzO2), lithium iron phosphate (LFP = LiFePO4), lithium nickel-cobalt-aluminum oxide (NCA = LiNiCoAlO2), and lithium manganese oxide (LMO = LiMn2O4) (Zubi et al., 2018) but metals are finite resources. Even though we used lithium nickel-cobalt-manganese oxide (NMC = LiNixCoyMnzO2) due to lack of data in Ecoinvent for lithium iron phosphate (LFP = LiFePO4), the impact of the battery is high for resource use, minerals and metals. The material extraction and processing of the metals i.e. the handling and treatment of waste from mining of metals can lead to leakage of toxic substances into ground water and rivers, and eventually to fresh water used by humans. Therefore, there is a need to for research on possibilities of developing and using carbon fiber-based electrode batteries for electric vehicles and the mitigation of the toxicity impact of metals

for the production of batteries. However, it is important to note toxicity indicators come with a high degree of uncertainty and the precision of characterization factors can vary (Finnveden et al., 2009).

The climate impact of the electric bus 6.7 g CO2 eq per passenger-kilometre and diesel bus i.e. 39 g CO2 eq per passenger-kilometre are comparable to other studies using the same functional unit (e.g. Garcia et al., 2022; Spreafico and Russo 2020; Nordelöf et al., 2019; Chang et al., 2019). It is not possible to compare the other impact categories used in this study with results from the studies by Garcia et al. (2022); Spreafico and Russo (2020); Nordelöf et al. (2019); Chang et al. (2019) because they only focus on climate impact. It is not possible to compare this study with others that use different impact categories, such as endpoint impacts (e.g., Jakub et al., 2022; Lubecki et al., 2022). Additionally, the use of different functional units, such as per bus (e.g., Gabriel et al., 2021), further complicates the comparison due to variations in bus sizes.

The electric bus with 6.7 g CO2 per passenger-kilometre (this study) outperforms the electric motorcycle with 8.4 g CO2 per passenger-kilometre (Trångteg and Winter, 2023) for climate impact. Therefore, it may be more beneficial to use electric buses for transporting people compared to electric motorbikes. The Bus Rapid Transit Line funded by EU is a positive development (EU, 2023) and is expected to cut commuting time, reduce traffic accidents, increase travellers' safety and improved mobility for differently abled people. However, in developing countries in Africa and Asia the two and three wheelers motorbikes employ a lot more people as riders of motorbikes than drivers of buses.

Given the limited resources, it's crucial to determine which is more environmentally beneficial: investing in reducing grid intensity or increasing the number of electric buses in Kenya's fleet. The results of the sensitivity analysis indicates that the increasing environmental performance of electric buses is highly dependent on the electric bus fleet composition than the electricity grid intensity. Currently, Kenya's grid intensity is below 600 g CO2 eq./kWh, i.e. the threshold identified by Nordelöf et al. (2019) as the point at which electric buses begin to lose climate impact advantages over diesel buses. According to the future energy generation performed by NTNU in this project, offshore winds will increase, and renewable energy proportion will increase for Kenya. The decrease by 10% in the grid intensity will not have the same climate benefit as increasing electric buses in the fleet. The increase of electric buses in the fleet will result in more climate benefits.

The study was limited to analysing electric buses as a replacement option for diesel buses but different fuel options that can replace diesel buses exist for example fuel cell, compressed natural gas, and hybrid buses. Future studies could focus on these options in Kenya. The study is theoretical for the diesel bus and not based on inventory data from the producer of Isuzu because of challenges of lack of data for bus design, operation and manufacturing. Future studies could collect data from producers and compare with data from Iyer et al. (2021). The study focuses on the environmental impacts but economic, and social impacts are also important when comes to the question of sustainability. Transitioning from diesel to electric buses involves social and economic issues for example the cost of electric buses is generally higher than diesel buses and this can curtail the transitioning. In Africa fuel stations employ service personnel and replacement of the diesel buses by electric buses may result in loss of employment for these people. The study did not account for the disposal of the buses. However, in the disposal phase observed in other countries, lithium-ion battery cells are disassembled and subjected to a pyrometallurgical recovery process (Dunn et al., 2014). Implementing this process in Kenya could further enhance the performance of electric buses.

3.6. Conclusion

The replacement of diesel buses with electric ones results in environmental trade-offs i.e. decreases of climate impact, photochemical oxidant formation potential, ozone layer depletion and acidification

but increase of increases in fresh water ecotoxicity and resource use, minerals and metals. Increasing the electric buses in the national fleet will have more benefits than maintaining the current fleet of buses dominated by diesel buses and investing in reduction of the grid intensity. The insights derived from this study can inform decision-making processes in transportation planning and policy development, thereby fostering more sustainable mobility solutions.

Acknowledgements

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EXECUTIVE CONCLUSION

This deliverable synthesizes life cycle assessment (LCA) results from three distinct case studies: solar-powered nanogrids in Madagascar, integrated biogas–water systems in Sierra Leone, and electric bus deployment in Kenya. Across all cases, renewable and integrated technologies consistently outperform conventional fossil-based solutions in terms of climate impact and resource efficiency. These findings highlight the potential of such systems to reduce environmental burdens and accelerate progress toward sustainability goals.

In Madagascar, solar nanogrids designed for rice husking, water pumping, and cold storage achieve up to 93% lower climate impact and 94% less fossil resource use compared to diesel-based systems. Further improvements are possible through design optimization, such as downsizing panels and batteries, which can enhance performance without compromising service delivery.

In Sierra Leone, decentralized biogas systems combined with solar photocatalytic water purification demonstrate strong circular economy benefits. Scaling these systems improve energy efficiency and climate performance, while water reuse strategies nearly eliminate water consumption impacts. This integrated approach offers a scalable and resilient model for off-grid infrastructure.

In Kenya, replacing diesel buses with electric alternatives significantly reduces greenhouse gas emissions and air pollution, although it introduces trade-offs in mineral and metal resource use. These trade-offs can be mitigated through complementary measures such as grid decarbonization and battery recycling, which amplify the overall benefits and support a sustainable transition in national transport fleets.

Key insight: Renewable energy solutions, whether decentralized power systems, integrated biogas technologies, or electrified transport, deliver substantial environmental gains. However, system-level design choices and complementary strategies, including resource optimization, water reuse, and grid decarbonization, are critical to maximizing sustainability outcomes and minimizing trade-offs. This calls for a holistic policy approach that combines technical standards, financing mechanisms, and governance frameworks.

To enable implementation, financing and market development measures are essential. Community energy cooperatives, pay-as-you-go models, and blended finance combining EU grants with private investment can improve affordability and scalability. Carbon credit monetization and green bonds should be promoted to attract investment, while leasing schemes can accelerate electric mobility adoption.

Finally, robust monitoring and governance are needed to ensure continuous improvement. LCA-based performance indicators should be integrated into national strategies, aligned with the EU Green Deal and Fit for 55 targets, to track progress and maintain accountability.

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Table A1 Vehicle parts and material compositions for the cab chassis imported from Japan

Vehicle part	Item	Material compositions	Quantity in kg
Chassis			
	Steer axle	Steel	120
		Iron	78
	Drive axle	Steel	190
		Iron	58
		Rubber	2.5
	Suspensions	Steel	260
		Iron	8.7
		Rubber	17
	Shafts	Steel	28
		Iron	1.5
	Cradle	Steel	580
Powertrain			
	Engine unit	Iron	140
		Steel	97
		Aluminium	22
		Plastic	2.6
		Rubber	2.6
	Engine fuel storage + exhaust system	Aluminium	37
		Ceramic	27
		Plastic	22
		Stainless steel	16
		Steel	11
Transmission			
		Steel	89
		Iron	31
		Aluminium	7.7
		Rubber	1.3
Body			
	Body and glass	Glass fiber	110
		Steel	65
		Glass	59
		Aluminium	47
		Plastic	12
	Interior	Steel	160
		Plastic	55
		Aluminium	24
		Rubber	13
		Leather/resin	8
		Brass	2.6

Vehicle part	Item	Material compositions	Quantity in kg
	Exterior	Plastic	29
		Steel	23
		Rubber	7.6
		Aluminium	6.8
		Glass fiber	6.1
		Brass	3.8
Tyres			
	Tyres	Rubber	97
		Steel	48
	Wheels	Aluminium	120
Engine oil			
		Oil	5.9
Coolant			
		Water	13
		Ethylene glycol	14

Table A2 The bill of materials for whole diesel bus body including seats

Input	Units	Quantity
Cab chassis	**kg**	**2792**
Steel/iron	kg	1500
Aluminium	kg	300
Rubber	kg	820
Leather	kg	110
Glass	kg	240
Paint	kg	10
Wood	m^3	0.45