Heliyon 10 (2024) e38954

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Environmental impacts of a stand-alone photovoltaic system in sub-saharan Africa: A case study in Burkina Faso

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ARTICLE INFO

Keywords:
PV systems
Sub-saharan africa
Life cycle assessment
Batteries
Landfill
Recycling

ABSTRACT

This study aims to evaluate and compare the environmental impacts of stand-alone photovoltaic (PV) systems with storage installed in Burkina Faso using the life cycle assessment (LCA). SimaPro 9.4 software, Ecoinvent 3.7 database, and the ReCiPe 2018 (H) median method were used to assess the environmental impacts. The functional unit considered is "1 kWh of electricity produced in Burkina Faso by a stand-alone PV system". Four scenarios combining two variables, battery technology (lead-acid and lithium-ion) and end-of-life management (landfill and recycling), were studied to assess 08 environmental indicators. The results show that production and end-of-life management of batteries and PV modules are the main contributors to the environmental impact, with batteries' impact ranging from 73 to 98 % for lead-acid and 50–68 % for lithium-ion batteries. Compared to landfilling, recycling significantly reduces environmental impacts, achieving reductions of 17–77 % for lead-acid batteries (LABs) and 3–99 % for lithium-ion batteries (LIBs). The comparison between scenarios indicates that the LABs PV system with landfilling generates significantly higher scores across all impact categories than LIBs PV scenarios. Specifically, it shows scores over 10 times higher for human carcinogenic toxicity, 5 times higher for human non-carcinogenic toxicity, and 2 times higher for freshwater ecotoxicity. Despite extending battery lifespan, the sensitivity analysis revealed that landfill PV systems remain the most polluting, while in recycled scenarios, this extension brings them closer to the environmental performance of LIBs PV systems. The use of LIBs in photovoltaic systems is more environmentally friendly than that of LABs, regardless of the end-of-life scenario.

1. Introduction

Sub-Saharan Africa is one of the least electrified regions in the world, with approximately 590 million people without access to electricity, and 80 % of these people are in rural areas [1]. The quality and reliability of energy services are poor in grid-connected areas and hinder development (education, health, agriculture, and industry) [2,3]. The current energy context can be broken down into two issues. The first is the scarcity of fossil resources (oil, coal, gas) that are limited in time. The second issue is the reduction of greenhouse gases produced by fossil fuels. In this context, we are witnessing the search for new alternatives to the traditional polluting electricity production systems [4]. The development of renewable energies can respond in a relevant way to this new energy objective and thus constitute an anchor for development. Indeed, Sub-Saharan Africa has unevenly distributed renewable energy potentials in

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https://doi.org/10.1016/j.heliyon.2024.e38954
Received 21 November 2023; Received in revised form 11 July 2024; Accepted 3 October 2024
Available online 4 October 2024
2405-8440/

wind, solar, hydroelectric, and even geothermal energy [5,6]. Exploiting solar photovoltaic (PV) resources represents a vast potential among these renewable energies. The African solar potential represents 60 % of the world's solar resources [7].

Recently, investment in research and development to improve PV module production efficiencies and the mass production of PV components by Asian countries have led to a drastic drop in costs, 70–80 % for modules [8] and around 60 % for batteries [9]. This price drop has led to an explosion in the use of solar products in Africa as a substitute for traditional sources of electricity production, such as diesel generators. Among the different types of PV systems, small-scale solar PV systems are the most attractive [10,11]. They are suitable for rural and non-electrified populations close to the grid, such as suburbs [12]. These systems represent a solution for quick and independent access to electricity. They consist mainly of PV modules, inverters, and cables. Batteries and charge controllers are added in the systems with storage to cope with the problems of intermittency of solar, which depends on the climate, alternation of days and nights, or used as a backup system in case of power outages [13–15]. While the lifespan of the PV system is estimated to be 20–30 years, premature aging of batteries due to deep discharges, non-use of charge controllers, or use in hot climates can occur [16,17]. These battery age reductions result in large quantities of batteries reaching end-of-life. The most prevalent batteries are lead-acid batteries (LABs). This preference for LABs is due to the population's lower purchase cost and easy access [18].

Although considered a clean, environmentally friendly form of energy during the use stage, the PV system's potential risks to human health and the environment should not be overlooked. The technology has the potential to present a threat to both human well-being and the ecosystem. Indeed, numerous studies have shown that the component production and end-of-life management stages have significant environmental impacts [19–24]. In addition, studies led by Akinyele et al. [14], Hiremath et al. [25], and Wang et al. [26] have shown that the addition of a storage system could lead to increased environmental impacts. Evaluating the environmental performance of electricity production systems over their entire life cycle is becoming a vital issue for decision-makers.

The literature contains numerous studies assessing the life cycle assessment (LCA) of PV systems [19,22,27–32]. Muteri et al. [22] conducted a literature review on life cycle assessments of different PV systems; they showed that environmental impacts were functions of cell efficiency and type, PV module technology and manufacturing location, installation location, and end-of-life management of components. Kamal et al. [23] examined in detail in a review paper the environmental impacts of small and large commercial and emerging PV systems; waste minimization and recycling were recommended for the sustainability of its systems. These studies also found that PV module manufacturing has the most environmental impact on PV systems without energy storage.

The environmental impact of solar battery systems has been examined in other studies [33–39]. Studies conducted by Yudhistira et al. [39] and Thomas et al. [33] found that lithium-ion batteries (LIBs) have less environmental impact than LABs. In addition, Haefliger et al. [40] studies have shown that the mismanagement of LABs at the end of their life can have drastic environmental and human health consequences.

Among all these studies mentioned above, only a few studies [14,20,41–46] have focused on the environmental assessment of PV with storage systems in Africa. Furthermore, none of these studies have addressed battery technology type and end-of-life management

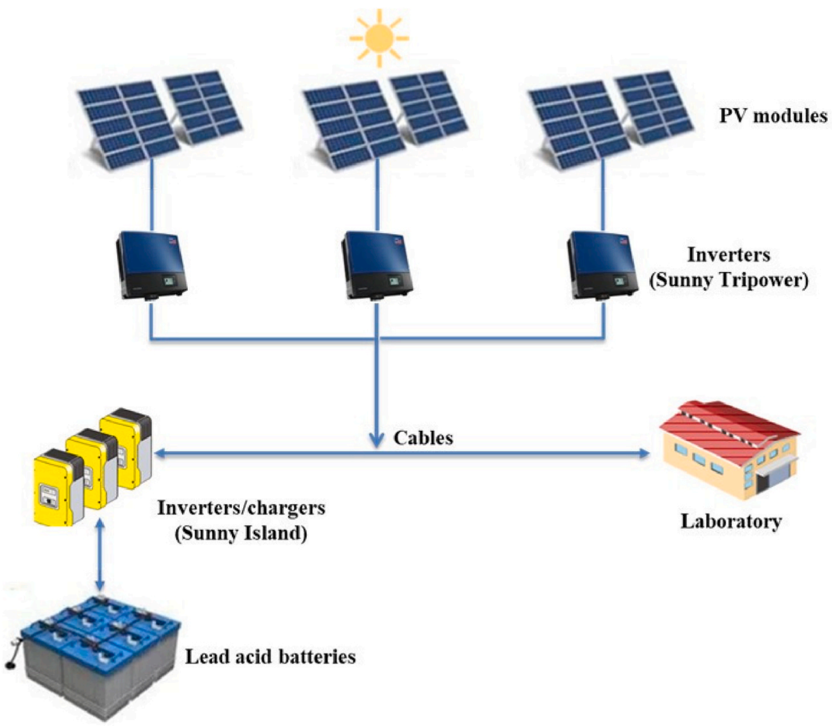

Fig. 1. The architecture of the PV system installed at 2iE Institute on the laboratory's roof.

in PV with storage. The main contribution of this study is to provide African policymakers with data on the environmental impacts of PV systems with storage in the current context characterized by the informal management of PV wastes. The present study aims to assess, through the life cycle assessment tool, the environmental impacts of a PV system with energy storage installed in Burkina Faso. This study also aims to evaluate the influence of the type of battery and the type of end-of-life management on the overall impact of the PV system.

2. Materials and methods

In this section, the LCA methodology is presented in detail after describing the PV system studied.

2.1. Photovoltaic system description

The PV system studied in this paper is located at the International Institute of Water and Environmental Engineering (2iE), Burkina Faso, 15 km from the capital Ouagadougou, with geographical coordinates 12°27′ N and 1°33′ W. It was built in 2013 in the "Solar Capacity Upgrading Project" framework financed by the World Bank. With a power of 17 kWp, it has a double function: to boost the electrical energy needs of the Institute's electrotechnical laboratory and serve as an experimental field for training students and professionals in solar PV.

The PV system consists of 72 modules: 24 monocrystalline silicon modules (240 Wp), 24 polycrystalline silicon modules (230 Wp), and 24 HIT modules (235 Wp). The technology group installed the PV modules on the laboratory roof, oriented at azimuth −20°, at an inclination of 15° to the south on steel structures. Modules of the same technology are strung together on a network inverter via a DC protection box. The system, therefore, has 03 SMA grid inverters (Sunny Tripower 8000 TL). Although the PV system is connected to the grid, a stationary battery bank has been added to ensure continuity of service when grid power is no longer available. In this case, the laboratory building is islanded and powered autonomously. Three SMA Sunny Island 5048 inverters manage the island operation, which drives a 9000 Ah stationary battery bank of 72 FAAM (24STG125) OPZV - Gel VLRA lead-acid batteries. Fig. 1 shows the architecture of the 2iE PV system.

The production results of the PV system from the commissioning to the present day have been obtained from the 03 Sunny Tripower 8000 TL inverters, and a projection of the future production data has been made by the PV system sizing software PVSYST. The production and simulation results give a global production of 632.668 MWh over the 25 years of the installation's lifespan.

2.2. Life cycle assessment (LCA)

The standard Life Cycle Assessment (LCA) methodology defined by ISO 14040 [47], ISO 14044 [48], and the one defined by the International Photovoltaic Energy Agency Task 12 [49] are used to assess the potential environmental impacts of the electricity

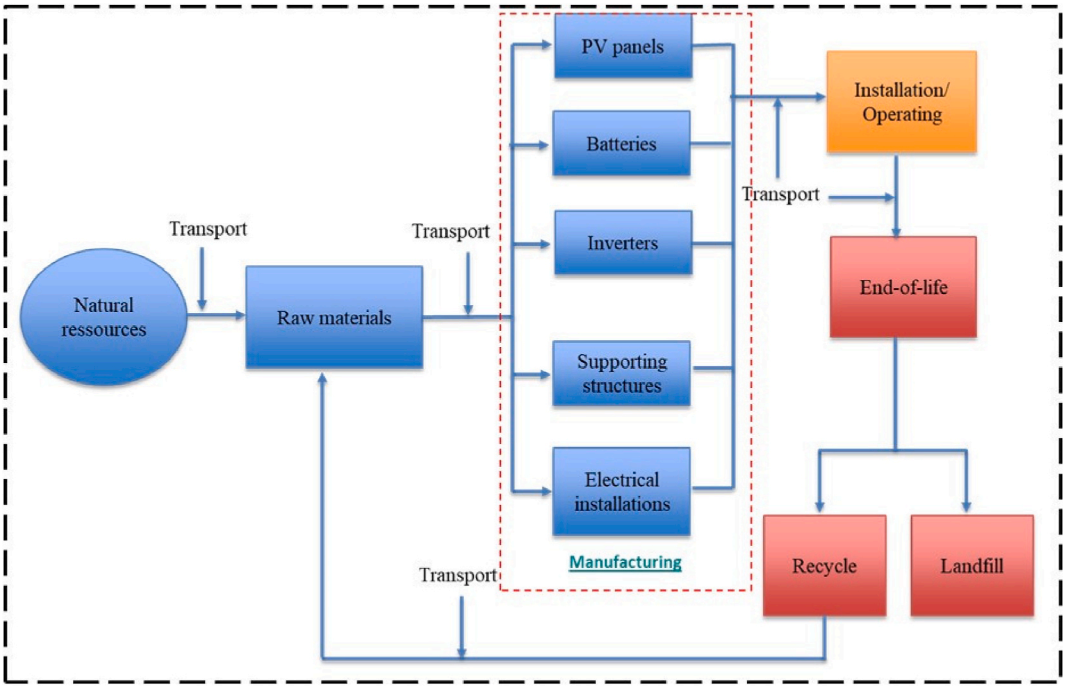

Fig. 2. Life cycle stages include in the system boundaries.

generation system by a PV system. According to standards ISO 14040, the LCA methodology is defined in 04 interdependent and iterative steps.

i. Definition of study objectives and scope;
ii. Data inventory;
iii. Impact assessment;
iv. Interpretation of results.

2.2.1. Goal and scope definition

This study aims to investigate and compare the environmental impacts of stand-alone PV systems (17 kWp) in a developing country context. This study will guide decision-makers on the environmental risks associated with electricity production by the PV system with energy storage.

The functional unit of this study is "1 kWh of electricity produced in Burkina Faso by a stand-alone PV system with energy storage". The modeling considers the manufacturing of PV modules, inverters, mounting structures, electrical installations, and batteries, their transportation from their manufacturing site to their installation site, the construction on the roof, and their end-of-life management. This study did not consider the maintenance stage, including cleaning the modules and battery energy losses. Fig. 2 shows the boundary of the studied system. It was also assumed that no significant repairs were made during the system's lifespan.

This study considered 04 scenarios depending on battery technology (lead-acid and lithium-ion) and end-of-life management (landfill and recycling). The other components of the PV system (modules, inverters, mounting structures) are assumed to be identical in all scenarios. The technical characteristics of the scenarios are presented in **Table 1**.

Scenario 1, the baseline scenario, uses LABs for its storage system. In this scenario, end-of-life PV waste landfills are assumed due to the non-existence of recycling structures in the West African sub-region. End-of-life management differs between Scenarios 1 and 2. In Scenario 2, the existence of a PV waste recycling facility is assumed. Recycling considers all materials that can be recycled, such as steel, copper, aluminum, and plastics. The non-recyclable fraction is landfilled. The recycled materials are considered raw materials, and therefore, their environmental impacts are reduced from the total impact. Scenarios 3 and 4 differ from Scenarios 1 and 2 in battery technology. The use of LIBs is considered for these two scenarios. Indeed, LIBs are increasingly used to overcome the problems posed by LABs batteries, as they have a longer lifespan and can withstand deep discharges [50].

2.2.2. Life cycle inventory

The inventory of inputs (consumptions) and outputs (emissions) for each process was done mainly with secondary data from literature, technical reports, and the Ecoinvent 3.7 database. Component production data comes from Antonanzas-Torres et al. [50], Xie et al. [51] for PV modules, Premrudee et al. [52] for LABs, LIBs, and Ecoinvent for cables and inverters. The 2.5 kW inverter data from the Ecoinvent database was used to extrapolate the PV system's 5 kW and 8 kW inverters. The transportation process is modeled based on the components' weight and the distance from their production location to the operating site. The transport of the PV components to Ouagadougou was assumed to be by sea in commercial freighters to the port of Lomé in Togo and by road from Lomé to Ouagadougou using 32-ton trucks. Transportation of end-of-life components to the recycling site was also considered. The innovative

Table 1
The composition and the technical characteristics of the PV systems considered for the four scenarios studied.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV Modules	• 24 Mono-Si (240 Wc): Voc: 37.6 V, Isc: 8.22 A, η:17 %, Mass: 509 kg • 24 HIT (235 Wc): Voc: 51.8 V, Isc: 5.84 A; η:15 %, Mass: 360 kg • 24 Poly-Si (230 Wc): Voc: 37.1 V, Isc: 8.3 A, η:13.9 %, Mass: 432 kg			
Batteries 9000 Ah/48 V	72 Lead-acid batteries OPzV Nominal Capacity: 3000 Ah Nominal voltage: 2 V Batteries mass: 17 280 kg Lifespan: 08 years		180 Lithium-ion batteries Nominal Capacity: 50 Ah Nominal voltage: 48 V Batteries mass: 3960 kg Lifespan: 20 years	
Inverters	03 Sunny Tripower STP 8000 TL-10 03 SMA Sunny Island 5048			
Fixed mounting structures	Galvanized steel 15° South face			
Electric cables	AC cable 4Gx4 mm^2 : 25 m; DC cable 1 × 4 mm^2: 250 m AC cable 4Gx10 mm^2 : 100 m; DC cable 1 × 6 mm^2 : 40 m AC cables 4Gx6 mm^2 : 200 m			
End-of-life management	Landfill	Recycle	Landfill	Recycle

PV module recycling method described by Latunussa et al. [53] was used for end-of-life. This method combines mechanical, thermal, acid-leaching, and electrolysis treatments. This method allows the recovery of products such as glass, aluminum, silver, and silicon that can be reused in the module manufacturing process. Due to the lack of data on informal battery recycling in Africa, the pyrometallurgical battery recycling technique proposed by Rajaeifar et al. [34,54] was considered. Although the landfilling of end-of-life PV components is done without prior separation of the constituents, these wastes are separated based on their composition for modeling purposes.

All data of the manufacturing, transport, use, and end-of-life stages of the PV system components are then adapted to the geographical location or the production technology and related to the production of 1 kWh of electricity.

2.2.3. Environmental impact assessment

The median ReCiPe 2018 (H) method, a combination of the Eco-Indicator and CML methods [55], was used to assess the environmental impact of the PV system. Indeed, the ReCiPe method is one of the most widely used environmental assessment methods [56, 57]. The following impact categories were evaluated: global warming (GW), freshwater ecotoxicity (FE), marine ecotoxicity (ME), terrestrial ecotoxicity (TE), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), mineral resource scarcity (MRS) and fossil resource scarcity (FRS). The land use indicator was not studied because the PV system is on the laboratory's roof. SimaPro 9.4 LCA software was used to assess the life cycle impact of the PV systems. A sensitivity analysis was conducted to evaluate the impact of battery lifespan on the environmental impact of the studied PV systems.

3. Results and discussion

3.1. Environmental impacts of the scenarios studied

The electricity production by the PV system considered in this study has been characterized for each of the 04 scenarios. All the characterization results are presented in Fig. 3. These results highlight the contributions of the different life cycle stages (production, transportation, construction/use, and end-of-life management) to the environmental indicators' overall results.

The components production and end-of-life stages contribute the most to environmental impacts. The contributions of the construction/use and transportation stages are less than 5 %. Different authors have reported the same trends for PV systems with storage. Hiremath et al. [25] and Tannous et al. [44] showed that the component production stage dominates the environmental impacts. By comparing various end-of-life scenarios, Lunardi et al. [58] demonstrated that the environmental impacts depend on the type of end-of-life dedicated to wastes.

3.1.1. Production of the PV system components

The production stage includes the production of PV modules, batteries, and the balance of system (inverters, electrical cables,

Fig. 3. Results of the characterization of the electricity production by the 04 scenarios studied.

mounting structures, and protection equipment). This production stage is dominated mainly by the production of batteries, 73–98 % for PV systems with LABs (scenarios 1 and 2) and 50–68 % for PV systems with LIBs (scenarios 3 and 4). Therefore, the production of LABs generates more environmental impact than LIBs. Comparing the environmental impacts of different battery technologies [25,39,59] come to the same conclusion. Similarly, Antonanzas-Torres et al. [50], in assessing the environmental impacts of solar home systems in Sub-Saharan Africa, concluded that in a PV system with storage, the contribution of LABs was 36–76 % of the environmental indicators assessed.

LABs contribute to fossil resource scarcity (FRS) and global warming (GW) more than LIBs during manufacturing, mainly due to the energy required for lead extraction, processing, and assembling battery components. This energy is often produced from fossil resources, leading to higher carbon dioxide emissions. Additionally, the lead production process may generate additional carbon dioxide emissions. In contrast, LIBs use materials such as lithium, cobalt, and nickel, which also require energy for extraction and processing, but their manufacturing process is generally less carbon-intensive than LABs. These same processes were previously identified by Wang et al. [26]. Fig. 4 Sankey diagram of global warming indicator of PV lead-acid battery production shows the contribution of electricity consumption to the overall global warming impact in LABs production.

LABs contribute to fossil resource scarcity and global warming mainly due to the electricity used during the electrodes' production and the assembling stage of the different battery components. Indeed, assembling 1 kg of LABs requires an average of 0.3 kWh of electricity, usually produced from fossil resources.

The ecotoxicities (marine, freshwater, and terrestrial) are due to 82.5 % of toxic compounds such as lead, zinc, and copper emission into water and air while producing LABs electrodes. The main sources of emissions of these metals into water and air are lead processing and residue treatment during rolling, forming, and protective coating processes or electrode galvanizing processes. Lead, zinc, and copper are toxic heavy metals that, when released into air, freshwater, and marine waters, can cause significant damage to aquatic and terrestrial ecosystems [60]. They can reduce biodiversity by affecting species' reproduction, development, and survival, thus upsetting ecological balances. The ecotoxicity generated by the production of LIBs is mainly due to the metals copper (73.7 %) and zinc (21.5 %) released into water while manufacturing the cathode and graphic anode. Fan et al. [61] studied the life cycle assessment of LIBs and showed that the production phase impacted the environment.

The main contributors to the human toxicity indicator (carcinogenic and non-carcinogenic) are 75.7 % hexavalent chromium (chromium VI) and 19.9 % arsenic emitted to water during electrode production. Lead metal production generates smelting waste, which is generally disposed of in landfills and thus contributes to more than 80 % of the chromium emission to water by leaching. The human toxicity of LIBs is due to the emission of zinc (65.2 %) and arsenic (10.1 %) into the water while producing the graphite anode and the cathode.

The mineral resource use indicator characterizes the criticality of the materials, i.e., its supply risk, and is expressed by its scarcity coefficient. In the ReCiPe (2018) method, this coefficient is calculated from the estimated reserves of each mineral and compared to that of copper, hence the unit kg copper equivalents. The mineral resource scarcity is due to the extraction of lead and lithium to produce LABs and LIBs.

3.1.2. End-of-life of PV systems

As illustrated in Fig. 3, for each PV system with storage, two scenarios are studied: a pessimistic one assumes total disposal of the

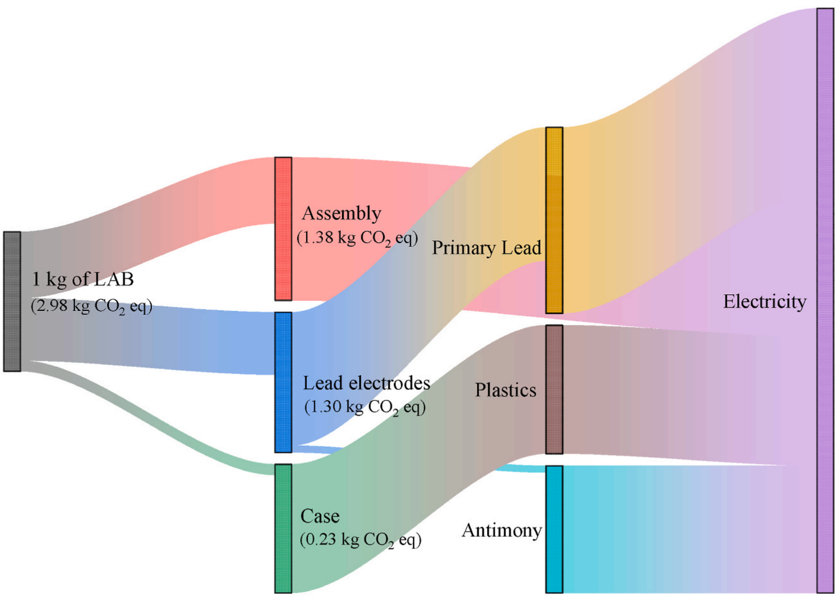

Fig. 4. Sankey diagram of global warming indicator of PV lead-acid battery production.

components at the end of their life due to the lack of recycling systems in the region, and a more optimistic one assumes complete recycling.

The landfilling PV components (scenarios 1 and 3) result in environmental impacts. In PV systems with LABs (scenario 1), landfilling mainly affects human carcinogenic (32.23 %), non-carcinogenic (28.10 %), freshwater (12.55 %), and marine (13.32 %) toxicities. This is mainly due to lead leaching from the battery electrodes and chromium, copper, and zinc from the PV modules. The LIBs system landfill affects only the freshwater (18 %) and marine (17 %) ecotoxicities. This contribution is mainly due to the landfilling of the PV module.

The negative values of the recycling scenarios (scenarios 2 and 4) in Fig. 3 represent positive contributions, i.e., avoided emissions. Recycling of PV components (Scenarios 2 and 4) results in significant reductions depending on the studied scenario, 17–77 % for LABs PV systems and 3–100 % for LIBs PV systems. End-of-life recycling in scenario 2 leads to impact reductions in all studied indicators. Indeed, since LABs are the main contributors, their recycling reduces overall impacts. Recycling end-of-life components is highly significant for the indicators of mineral resource depletion, carcinogens, and non-carcinogens. Davidson et al. [38] showed that recycling LABs could minimize and, in some cases, completely avoid the environmental impact of their production stage.

Recycling LIBs systems benefits global warming and resource scarcity (fossil and mineral) indicators. The categories of ecotoxicity impacts (terrestrial, freshwater, and marine) are not affected by LIBs recycling. Rajaeifar et al. [34] showed that recycled materials could reduce global warming and energy demand by comparing the environmental impacts of different pyrometallurgical LIBs recycling technologies. This is also verified in the studies of Gaines et al. [62] and Hong et al. [63].

The high contribution of recycling to the mineral resource depletion indicator in both recycling scenarios (scenarios 2 and 4) is because the recycled components will be considered raw materials in manufacturing new components, reducing impacts due to their extraction and manufacture. However, recycling LABs has a more significant environmental benefit than lithium-ion ones.

3.2. Comparison of the scenarios

Fig. 5 compares environmental impacts between the scenarios considered in this study. The baseline scenario (scenario 1) dominates all environmental indicators studied. This is mainly due to LABs' production and disposal at the end of their life. The recycling of LABs allows the reduction of the overall environmental impact by 105 % for mineral resource scarcity, 85 % for non-carcinogenic ecotoxicity, 78 % for carcinogenic ecotoxicity, 74 % for terrestrial ecotoxicity, and about 32 % for global warming. For the same end-of-life, i.e., landfill, substituting LABs with Li-ion batteries leads to considerable decreases in impacts of 98 % for mineral resource scarcity reduction and 90 % for non-carcinogenic human toxicity.

For the GW, FRS, and HNCT indicators, the LIBs PV system with landfill or recycling has lower impacts than the LABs PV system with recycling as an end-of-life. On the other hand, for the other environmental indicators, i.e., ecotoxicities, the impact of the LABs PV system on recycling is less than that of the LIBs PV system. Similarly, there is almost no difference between landfilling and recycling regarding the LIBs PV system. LIBs recycling has almost no influence on FE, ME, TE, and HCT. For the GW and FRS indicators, battery recycling reduces by about 15 % compared to landfills (scenario 3).

To better illustrate and compare the importance of the environmental indicators, the indicator results presented in Fig. 5 have been normalized. Normalization in LCA consists of adjusting the results of environmental indicators according to specific reference data, in order to consider local, regional, or temporal characteristics that may influence the potential environmental impacts of a product. Normalized results for the indicators studied are presented in Fig. 6. The environmental indicators like FE, ME, and HNCT are the most

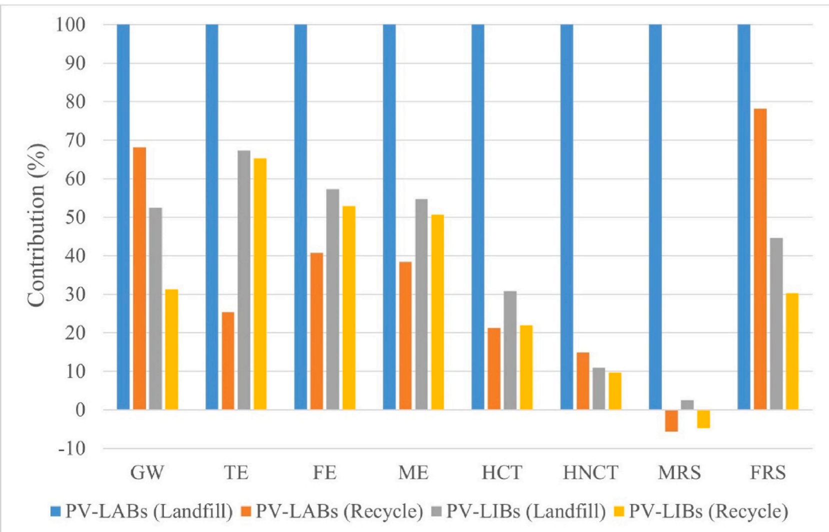

Fig. 5. Contribution of the PV systems to the environmental impacts: comparison between the different scenarios studied.

significant impacts. The predominance of these indicators compared to GW, MRS, FRS, and TE means that PV systems' activities significantly impact water (fresh and marine) and non-carcinogenic human health. A normalized comparison of the scenarios concludes that the LABs PV system with end-of-life disposal exceeds the other three scenarios on all normalized indicators except TE, where the normalized values of the four scenarios are in the same range. There is a slight difference between scenarios 3 and 4 on all indicators. This is because the recycling of LIBs does not significantly influence the overall impact of the PV system. These results agree with the results of Wang et al. [26].

3.3. Sensitivity analysis: battery lifespan

A sensitivity analysis based on the battery lifespan was performed for all the scenarios to assess its influence on the impacts. The results of the most relevant indicators identified during the standardization phase are presented in Fig. 7. The figure shows that, in general, extending the life of LABs from 10 to 20 years significantly reduces the impacts of LABs PV system. The baseline scenario, LABs PV system landfill, is the most affected by this extension. When the lead-acid battery lifespan is extended from 10 to 20 years, there is a reduction of about 36 % in the ecotoxicity impact category, 42 % in human carcinogenic toxicity, and 48 % in human non-carcinogenic toxicity. The PV LABs system with recycling has a lower environmental improvement than in the basic scenario. Indeed, for the same lifespan variations, all indicators decrease by about 21 % except for non-carcinogenic human toxicity, which is about 41 %. This decrease is because the extension of the battery lifespan has, as a direct consequence, reduced the number of batteries used during the life cycle of the PV system.

Despite the increase in the number of LABs cycles, the environmental impacts of scenario 1 remain higher than those of the other scenarios in all impact categories studied. This difference is mainly due to the landfilling of the batteries. The environmental impacts of scenario 2 are lower than scenario 1 but higher than scenarios 2 and 4. Thus, the environmental impacts of PV systems with landfilling are higher than those with recycling as the end-of-life management.

In the freshwater and marine ecotoxicity categories, the recycling of lead in scenario 2 leads to better environmental performance, 1.5 times less than the LIBs system in scenarios 3 and 4 for a battery life of 10 years. By doubling the lifespan (20 years), scenario 2 becomes 1.8 times less than scenarios 3 and 4. On the other hand, in the human carcinogenic toxicity category, the environmental impact of scenario 2 becomes significant from 10 years onwards. However, this difference remains marginal, and a less than 10 % reduction is observed in the 20th year. In the non-carcinogenic human toxicity category, lead recycling in scenario 2 does not significantly improve despite the longer battery lifespan. These results are consistent with the results for the impact of component production. In summary, a longer battery lifespan would increase the environmental performance of PV systems, so it would make sense to access research on long-lifespan LABs.

4. Conclusion

This study aimed to assess and compare the environmental impacts of stand-alone PV systems with storage installed in Burkina Faso. Two scenarios differing in battery technology (lead acid and lithium-ion) and two others in end-of-life management (landfill and recycling) were studied. The study examined impacts on all life cycle stages, from the raw materials extraction stage through to end-of-life, in line with the LCA methodology described in ISO14040 and 14044 standards. The study found that the component's production and end-of-life stages significantly contribute to environmental impacts. The main contributors to these main stages are batteries and

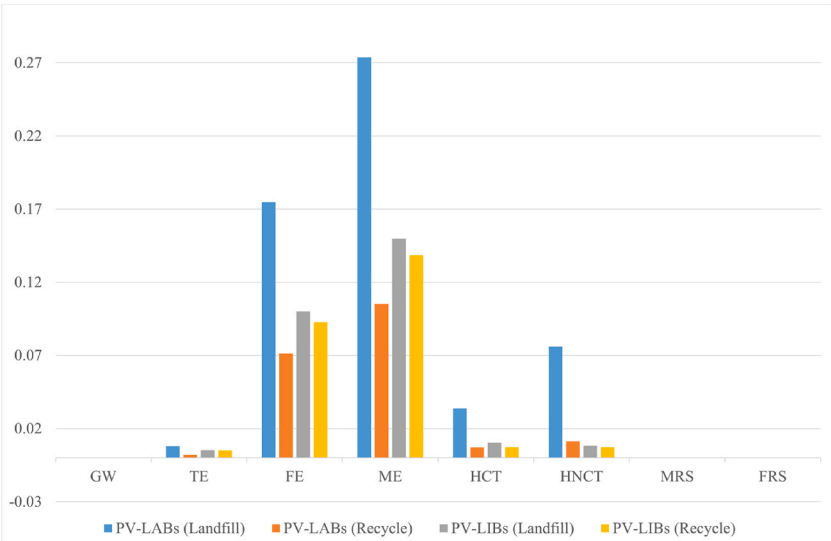

Fig. 6. Normalized results for the environmental indicators of the PV systems studied.

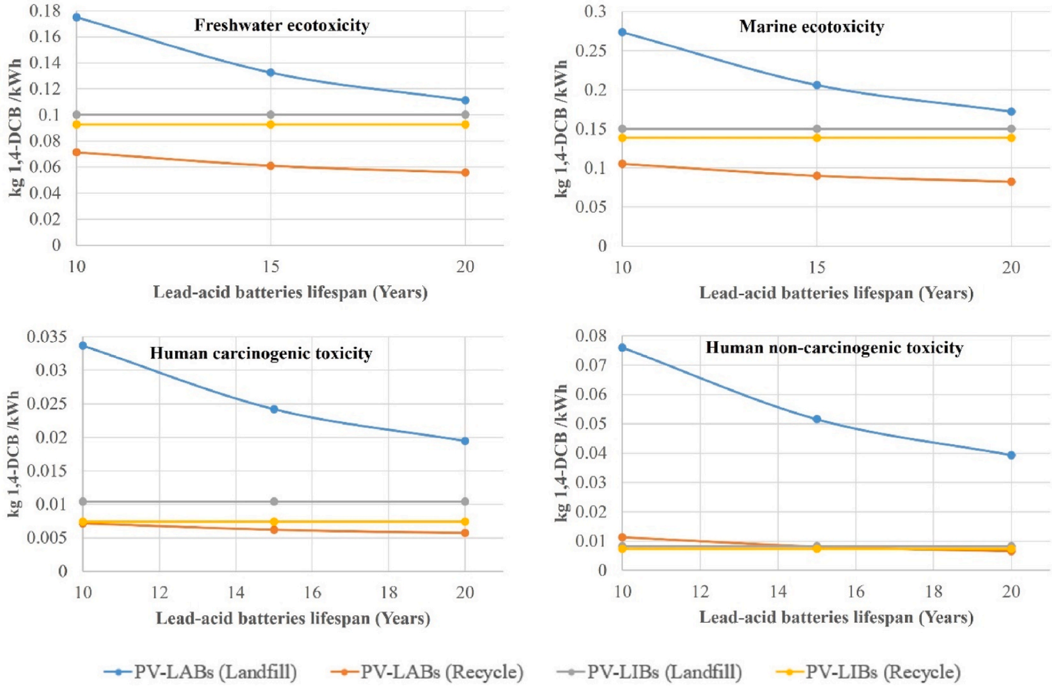

Fig. 7. Results of sensitivity analysis based on the lifespan of the battery for 4 mains environmental indicators.

PV modules. The batteries contribute to most environmental indicators, 73–98 % for LABs and 50–68 % for LIBs.

End-of-life management of PV system components is the second largest contributor. These contributions vary depending on the battery technology and the end-of-life management, landfill, or recycling. The recycling of LABs contributes to the reduction (17–77 %) of the environmental impacts on all the environmental indicators studied, as it reduces the impacts due to the landfill of lead. Recycling LIBs allows the reduction of global warming and resource scarcity (mineral and fossil).

PV systems with LIBs as storage have lower environmental impacts on the whole life cycle than the traditional storage system, LABs. This is mainly due to the short lifespan of the latter and the toxicity of the lead used as electrodes. It also appears that the end-of-life management of the PV system influences the overall impact. Indeed, the recycling of LABs PV systems allows an average reduction of about 40 % in all environmental indicators studied. Free of toxic substances, the landfill of LIBs has low environmental impacts. However, their recycling allows environmental gains, including resource scarcity (fossil and mineral) and reduced greenhouse gas emissions. The study shows that the PV systems' environmental performance depends on the battery technologies and end-of-life wastes management. Among the four scenarios examined, the LABs PV system with end-of-life component disposal is the scenario with the most significant impact on all environmental indicators studied.

This study highlights the importance of battery technology selection and environmentally friendly end-of-life management methods to minimize the environmental impact of PV systems. It also underlines the need for effective policy planning and regulation to ensure the sustainable management of PV wastes while highlighting future research opportunities to improve the sustainability of these systems. In addition, economic studies need to be carried out to assess the impact of this choice, mainly by evaluating the financial viability of recycling PV wastes.

Funding

No financial support was received for this study.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Kodami Badza: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Marie Sawadogo:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Y.M. Soro:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the "Agence Nationale des Energies Renouvelables et de l'Efficacité" (ANEREE) for providing data on PV system in Burkina Faso.

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