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Sustainable Environment Research (2023) 33:38
https://doi.org/10.1186/s42834-023-00201-x

Sustainable Environment Research

RESEARCH **Open Access**

Life cycle assessment of a 33.7 MW solar photovoltaic power plant in the context of a developing country

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Abstract

This work aims to determine the Energy Payback Time (EPBT) of a 33.7 MWp grid-connected photovoltaic (PV) power plant in Zagtouli (Burkina Faso) and assess its environmental impacts using the life cycle assessment tool according to ISO 14040 and 14044 standards. A "cradle to grave" approach was used, considering 1 kWh of electricity produced and injected into the national grid over 25 years as a functional unit. In addition to the baseline scenario, the other simulated scenarios combining three variables, module technology (mono c-Si, poly c-Si, and CdTe), type of mounting structure (aluminum and steel), and end-of-life treatments (landfill and recycling) were considered. SimaPro 9.4 software and the ReCiPe 2016 Midpoint (H) evaluation method were used for the calculations considering four environmental indicators. A sensitivity analysis of the change in the electricity mix was also performed. Results showed that the EPBT of the scenarios varies between 1.47 and 1.95 years, with the shortest and longest corresponding to scenarios 4 (CdTe modules, steel mounting structure, and recycling as end-of-life treatment) and scenario 3 (mono c-Si modules, aluminum mounting structure, and recycling as end-of-life treatment), respectively. All the EPBT scenarios studied can be considered acceptable given the long lifetime of PV systems (25 years). The following environmental impact results were obtained: climate change 37–48 CO_2-eq kWh^{-1}, freshwater ecotoxicity 4–11 g 1,4-DCB kWh^{-1}, mineral resource scarcity 0.4–0.7 g Cu-eq kWh^{-1} and 11–13 g oil-eq kWh^{-1} for fossil resource scarcity. Scenario 3 (mono c-Si modules, aluminum mounting structure, and recycling as end-of-life treatment) dominates all environmental indicators studied except freshwater ecotoxicity, which is dominated by scenario 4 (CdTe modules, steel mounting structure, and recycling as end-of-life treatment). The sensitivity analysis showed that the change in the electricity mix could reduce around 30% the EPBT, climate change, and fossil resource scarcity. Considering the environmental indicators studied, using CdTe modules manufactured in a country with a less carbon-intensive electricity mix, using galvanized steel as the mounting structure, and completely recycling components at the end of their lifetime is the most environmentally friendly scenario. However, particular attention needs to be paid to the land occupation that this plant could generate.

Keywords Photovoltaic power plant, Life cycle assessment, Energy payback time, Climate change, Resource scarcity, Sub-saharan Africa

1 Introduction

Sub-Saharan Africa has one of the lowest electricity access rates in the world, with 20% in rural areas and 60% in urban areas [1]. Burkina Faso faces a major energy challenge, with an electricity access rate of about 21% in 2020 and a known growing demand of 10% annually

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[2]. The electricity mix on the existing interconnected national grid is mainly composed of diesel thermal power plants (55.01%), and importations from neighboring countries: Côte d'Ivoire and Ghana (37.06%), mini hydro dams (7.35%) and solar photovoltaic (PV) power plants (0.58%) [2, 3]. However, the country has no oil resources and depends heavily on oil imports. Private and public sector investments in the advancement of renewable energy, specifically solar PV, have been instrumental in diminishing the reliance on fossil fuels and mitigating greenhouse gas (GHG) emissions from diesel power plants in recent times [4, 5].

Solar energy is the most abundant and under-exploited renewable energy source in Burkina Faso, with daily solar radiation of 5.5 kWh m^{-2} [6]. To increase electrical power generation capacity and cope with daily load shedding, the state has implemented policies to promote the development of solar PV energy in all regions by exempting solar energy equipment from customs and Value-Added Taxes. In 2017, major progress was made with the installation of two PV plants: the Ziga plant (1.1 MWp) and the Zagtouli plant (33.7 MWp). The latter will be the subject of this study.

Large-scale PV power plants consist mainly in a field of PV panels, inverters, cables, mounting structures, and transformers. The chemical composition of these components can impact the environment during the raw material acquisition and manufacturing process, operation (use) phase, and dismantling, including the environmental impacts generated during the transportation stage. In addition, the waste generated at the end of the installation's lifetime may be harmful if no management plan is implemented.

With the increase in the number of plants and the strong political interest in PV systems, coupled with the lack of legislation and consideration for the end-of-life management of components, there is a risk that these environmental impacts will also increase exponentially in the coming years. Therefore, it is necessary to assess the environmental impacts of large-scale PV plants in the context of developing countries.

Numerous studies on the life cycle assessment (LCA) of PV systems have been carried out in the literature [7–10]. These studies have mainly focused on small (1–100 kWp) and medium-sized (100 kWp–1 MWp) stand-alone PV installations. The environmental impacts of large-scale grid-connected PV installations (˃ 1 MWp) are less addressed and discussed in the literature: only a few studies have addressed them [11–16].

From 2003 to 2016, three studies focusing on LCA of large-scale facilities were conducted by Ito et al. [14, 15, 17]. The first studies compared mono-Si, a-Si, and CdTe systems of large-scale PV systems in the desert. These studies show that in desert areas, from an environmental point of view, the energy payback time (EPBT) is 2–3 years, and the carbon emission rate is 17–23 g CO_2-eq kWh^{-1}. These studies also show that thin-film technologies require less energy to produce than crystalline PV modules, but their efficiency is, unfortunately, lower than crystalline PV modules. In their 2016 studies, Ito et al. [15] evaluated the environmental impacts and cost analysis on simulated large PV systems at two sites in Carpentras (France) and Ouarzazate (Morocco). This study found that the lowest GHG emissions are obtained assuming a CdTe module at the Morocco site.

Deriche et al. [12] evaluated the performance of four grid-connected PV systems based on four PV module technologies installed in the Sahara region of Algeria. Due to its low life-cycle energy requirements, the CdTe PV system outperformed the other module technologies regarding EPBT and GHG emissions under Algerian climatic conditions.

Beylot et al. [11] studied the environmental performance of large-scale ground-mounted PV installations by considering four scenarios: (1) fixed aluminum structures, (2) wooden structures, (3) mobile structures, single-axis trackers, and (4) dual-axis trackers. According to this study, the fixed aluminum structure has the greatest impact on human health, energy consumption, and climate change indicators. It also shows that the type of support, the composition, and the location of the PV system installation appear as the main parameters affecting the environmental impacts of large-scale installations.

Recently, the primary energy consumption and environmental performance of a large-scale PV system (37.57 MW) installed in Malaysia were evaluated by Mohd Nordin et al. [18] through the LCA tool. A cradle-to-grave approach was considered, assuming a 30 years lifetime and an irradiation rate of 1950 kWh m^{-2} yr^{-1}. The system boundary includes all parts of the PV installation and other infrastructures, such as buildings, roads, fences, and electrical substations. The EPBT and climate change impact were 3.43 years and 31 g CO_2-eq kWh^{-1}, respectively. The sensitivity study also showed that increasing the systems' lifetime from 15 to 40 years can reduce climate change by 55%.

These impact studies on large-scale installations are sometimes carried out on simulated PV plants [15, 17], while others focus only on the impacts of the balance of system [16, 19]. Moreover, in the majority of these studies, the end of life of the PV plant is not considered. Only Desideri et al. [13] investigated the LCA of a 1778 kWp PV plant installed in Italy, considering all end-of-life stages.

Data on the environmental impacts of African Sub-Saharan PV plants are almost nonexistent. This study aims to determine the EPBT and environmental impacts of a grid-connected PV power plant (33.7 MWp) installed in Burkina Faso, considering scenarios based on module technologies (poly c-Si, mono c-Si, and CdTe), the type of mounting structures (aluminum, steel) and the end-of-life management of the PV system.

2 Methodology

2.1 Description of the Zagtouli PV plant

Located 14 km from the city of Ouagadougou (Burkina Faso), the Zagtouli solar PV power plant (33.7 MWp) is based in the locality of Zagtouli with a geographical coordinate of 12°18'33.3" North, 1°38'27.7" West. It spans an approximate area of 60 ha. The Zagtouli solar power plant is the first milestone in a vast program to develop solar energy production in Burkina Faso to supply more than 150 MW of solar energy to the Burkina Faso grid (around 30% of the country's total production).

The solar field consists of 129,600 PV modules of 260 Wp in poly c-Si, 1800 structures of 72 modules, 5400 strings of 24 modules in series, 466 grouping boxes, 32 inverters, and 16 transformers. The 1800 structures are held in the ground by piles (steel profiles) driven 1.20 m into the ground. A spacing of approximately 5.26 m between the mounting structures allows the solar panels to be freely accessible by cleaning equipment.

The solar power plant includes a connection link to the Zagtouli substation in the form of a double 33 kV buried line, approximately 400 m long; a delivery station or solar substation; three 33 kV distribution loops operated in an open loop to supply 16 Integrated PV Centers. In addition, the plant is also equipped with 17 infrared surveillance cameras around the PV field. A partial aerial view of the plant is shown in Fig. 1.

The technical characteristics of the PV modules, inverters, transformers, and mounting structures are presented in scenario 1 of Table 1.

The plant has four small meteorological stations, each consisting of pyrometers and thermometers. The monthly sunshine data for the site for the year 2021 is presented in Fig. 2.

The Zagtouli site has an average global irradiation of about 2140 kWh m^{-2} yr^{-1} and, therefore, benefits from the sunshine favorable to the operation of the PV plant.

2.2 LCA

The LCA methodology used to determine the environmental impacts of the PV plant based on the International Standards Organisation ISO 14040 and ISO 14044 and the more PV-specific guidelines of the International PV Power System Task 12 [20]. It consists of four main parts: goal and scope definition, inventory analysis, impact assessment, and results interpretation.

2.2.1 Goal and scope definition

The main objective of this LCA is to evaluate the EPBT and environmental impacts of the Zagtouli PV plant by comparing different scenarios: module technology, type of mounting structure, and end-of-life management of the components.

This study is meant for policymakers, researchers, and environmental impact practitioners, as it provides data on the potential environmental impacts of PV power plants in Sub-Saharan Africa.

The functional unit, i.e., the reference to which the inventory and impact assessment calculations are related, is defined as follows: "1 kWh of electricity produced by the solar PV plant and injected into the Burkinabe national grid". As the functional unit is 1 kWh of energy

Fig. 1 Partial aerial view of the Zagtouli solar power plant

Table 1 Technical characteristics of the different study scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenarios 5	Scenario 6
PV Panels	Poly-Si (P: 260 Wp, 1,675 m^2, h: 15.51%, W: 18 kg) 129 600 modules		Mono c-Si (P: 280 Wp, 1,63 m^2, h: 17.21%, W: 18 kg) 120 358 modules	CdTe (P: 128 Wp, 1,42 m^2, h: 9.5%, W: 12 kg) 263 283 modules	Poly-Si (P: 260 Wp, 1,675 m^2, h: 15.51%, W: 18 kg) 129 600 modules	
Mounting structure: fixed Slope: 15° facing South	Galvanized steel Tables: 1800	Aluminum Tables: 1800	Aluminum Tables: 1800	Galvanized steel Tables: 3100	Aluminum Tables: 1800	Galvanized steel Tables: 1800
Foundations	Galvanized steel Total mass: 193.23 t	Concrete Total mass: 16 590 t	Galvanized steel Total mass: 193.23 t	Concrete Total mass: 28 571 t	Galvanized steel Total mass: 193.23 t	
Inverters	Type: 1165TL B420 Indoor (AC Power: 1 071 kVA AC voltage: 420 V) Weight: 1860 kg 32 inverters					
Transformers	CG POWER SYSTEMS BELGIUM NV (Power: 2330 kVA, voltage: 420 V, oil: 1095 kg) Total mass: 5170 kg 16 transformers					
Batteries (ESS Storage Container)	No energy storage					Li-Ion 10 MW/ 10 MWh

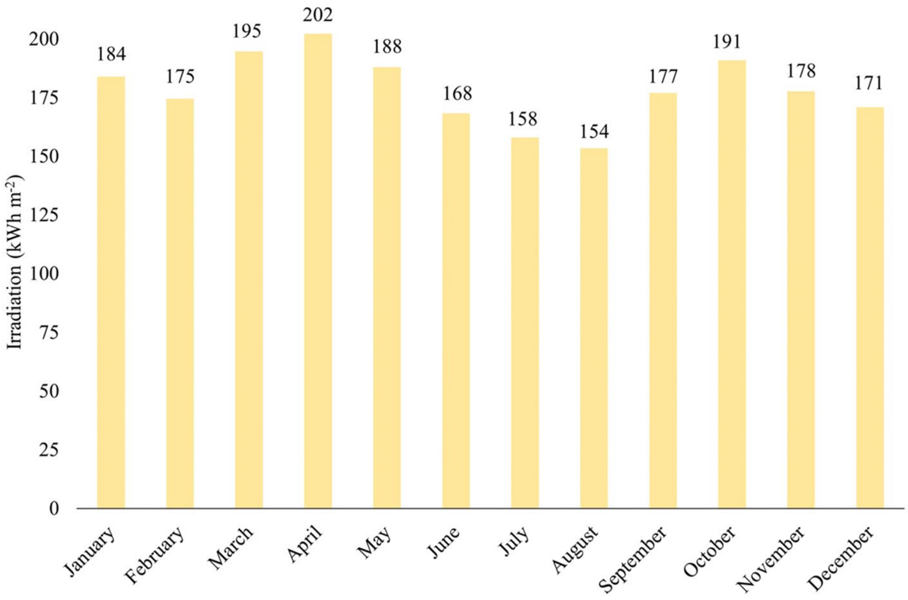

Fig. 2 Monthly distribution of annual global horizontal irradiation at the Zagtouli site in 2021

produced over 25 years, the energy generated by the PV plant during the 25 years operation stage has been calculated and is shown in Fig. 3. Based on the energy estimated by the developer of the plant (*Vinci Energies*) and the annual energy production of the PV plant since its commissioning, it is estimated that the total energy produced would be 1,334 GWh over the 25 years of operation.

The cradle-to-cradle assessment was carried out. The study considered all the elements that make up the PV plant: PV modules and the balance of the system (mounting structures, inverters, transformers, and cables). All life cycle stages and potential impacts of raw material extraction, material processing, component manufacturing, transport, installation, operation phase, and end-of-life were considered (Fig. 4). Conventional production technologies are considered within the system boundaries for each component manufacturing stage. The use stage of the PV systems is also considered to assess the electricity production over the entire lifetime of the PV

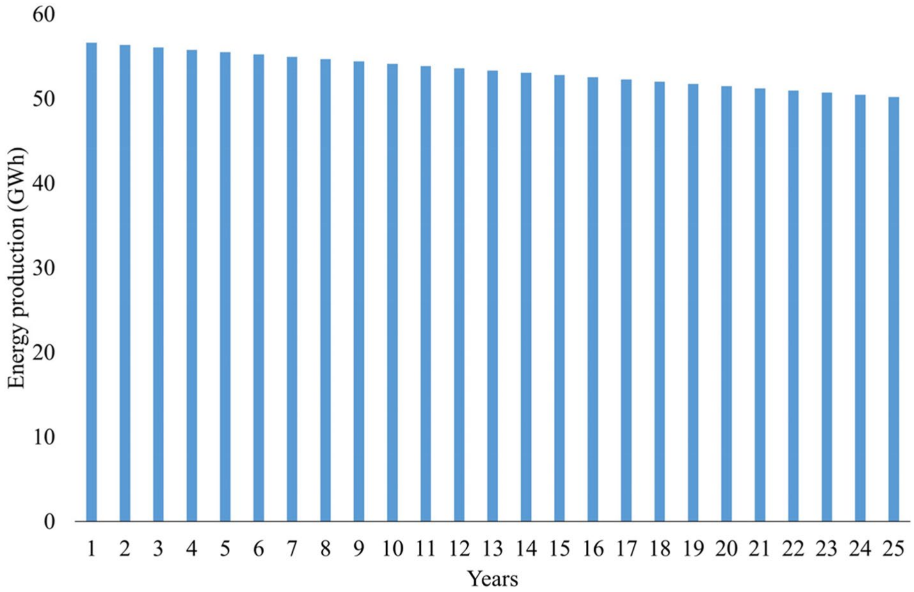

Fig. 3 Estimated energy production during the life cycle of the Zagtouli PV plant

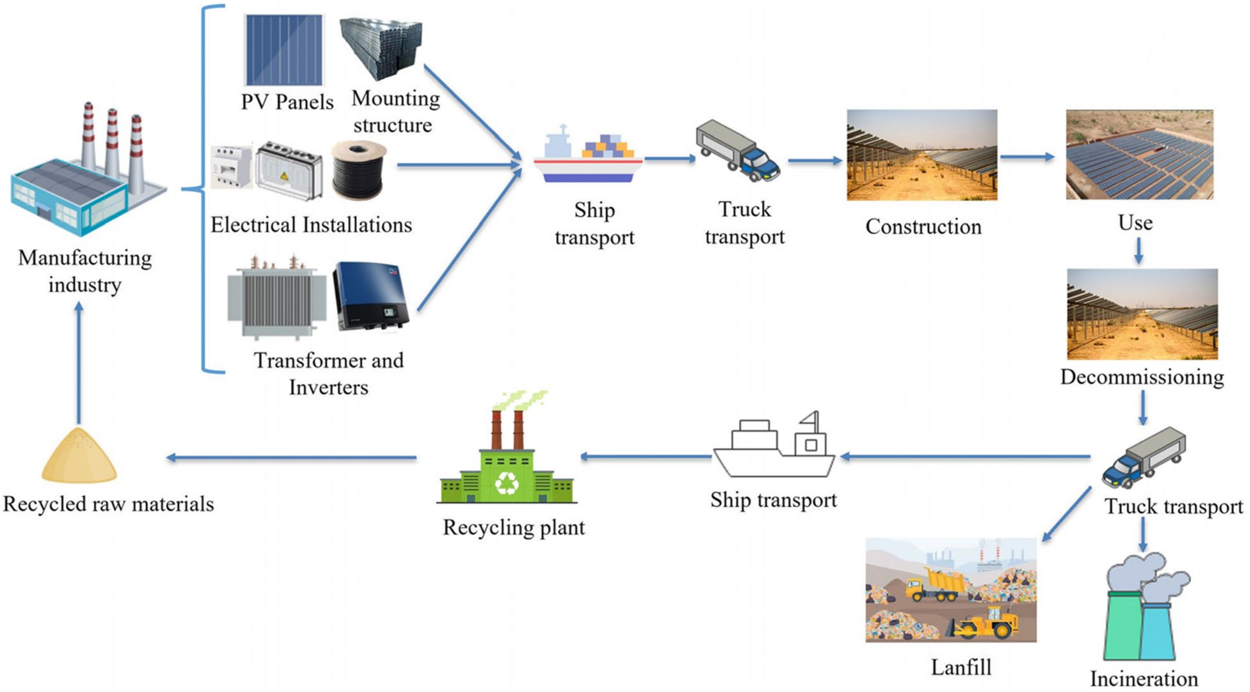

Fig. 4 System boundary of the Zagtouli plant LCA

systems. System maintenance is included in the current study because motorized cleaning of the PV modules is frequent due to dust and the short rainy season. End-of-life considerations were included to better assess the role of end-of-life component management in the context of developing countries.

2.2.2 Scenarios

Six different scenarios are studied. Inverters, electrical installations, and transformers are assumed to be the same in all scenarios. They differ from each other either in the type of module technology, the type of mounting structure, or the end-of-life management of the components. Table 1 shows the main differentiating features of the studied scenarios.

Scenario 1 is the baseline scenario in this study and represents the actual composition of the Zagtouli PV plant. The poly c-Si PV modules and the galvanized steel mounting structures are manufactured in Germany and purchased in Burkina Faso. At the end of the PV plant operation, it is assumed that all the power plant materials will be buried except for the aluminum frame of the module and the galvanized steel structure, which is assumed to be recycled. Landfill of PV components is the only option for end-of-life management in the West African sub-region.

The landfill results from the sub-regions lack of PV waste recycling facilities. The recycled or reused materials in these scenarios will be considered substitutes for the materials in the component manufacturing stage.

The substitution of the galvanized steel mounting structure with an aluminum mounting structure and the concrete foundation is shown in scenario 2. Monocrystalline silicon and thin-film module technologies are studied in scenarios 3 and 4, respectively, while varying the type of mounting structures and foundations.

A more promising alternative for end-of-life components is studied in scenario 5. PV modules, inverters, and electrical installations at the end of their lifetime will be recycled into an approved PV-CYCLE Belgium PV waste management structure by the thermochemical process. In scenario 6, the addition of a Lithium-ion battery storage park with a capacity of 10 MW 10 MWh^{-1} is considered.

The environmental impacts of PV components manufacturing, transport, construction, operation, maintenance, plant dismantling, and end-of-life management are included in the LCA calculation of each scenario.

The mono c-Si and CdTe thin-film PV modules are assumed to be produced in the same country as the module in the baseline scenario (scenario 1). In this study, sea and land transport are considered for the transportation of the components from the manufacturing sites to the Zagtouli site via the seaport of Lomé (Togo). The manufacturing locations of the components and transport distances (in t.km) are described in Table 2.

The following assumptions have been made: a 25 years lifetime for all module technologies with 3% replacement over this period, 25 years for the mounting structures and foundations, and 25 years for the inverters and transformers with 10% replacement of total mass every 10 years.

Table 2 Components transport from the manufacturing location to Ouagadougou

	Manufacturing location	Transports	
		Sea (t.km)	Land (t.km)
mc-Si module	Germany	$2.17\ 10^{7}$	$2.34\ 10^{6}$
CdTe	Germany	$7.35\ 10^{7}$	$7.93\ 10^{6}$
Inverters	Spain	$7.99\ 10^{5}$	$1.06\ 10^{5}$
Transformers	Belgium	$6.91\ 10^{5}$	$8.06\ 10^{4}$
Steel structure	Germany	$1.52\ 10^{7}$	$1.63\ 10^{6}$
Aluminum structure	Germany	$1.20\ 10^{7}$	$1.30\ 10^{6}$
Steel foundation	Germany	$1.74\ 10^{6}$	$1.88\ 10^{5}$
Concrete foundations	Burkina Faso	0	$1.65\ 10^{6}$
Electrical installation	Germany	$7.48\ 10^{5}$	$8.06\ 10^{4}$
Batteries	China	$2.16\ 10^{6}$	$8.79\ 10^{4}$

2.2.3 Energy performance: EPBT

The EPBT of a solar PV system is the time it takes for an energy system to generate the amount of energy equivalent to the amount needed to produce the PV system [21, 22]. The EPBT is calculated for each scenario using the following formula, Eq. (1):

$$EPBT = \frac{(E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})}{((E_{agen}/\eta_G) - E_{aoper})} \tag{1}$$

E_{mat}: Primary energy demand required for the production of materials comprising PV system.

E_{manuf}: Primary energy demand involved to manufacture PV system process.

E_{trans}: Primary energy demand associated with the transportation of materials throughout the PV system's life cycle.

E_{ins}: Primary energy demand needed for the installation of the PV system.

E_{EOL}: Primary energy demand for managing the system at its end-of-life stage.

E_{agen}: The amount of electricity generated by the PV system on an annual basis.

E_{aoper}: Annual energy demand, in terms of primary energy, for operating and maintaining the PV system.

η_G: Grid efficiency refers to the average efficiency of converting primary energy into electricity on the demand side

The EPBT is a variable that gives an idea of the benefits of exploiting renewable energy. This indicator can also be used as a base for the energy sector to assess each energy according to its EPBT to have a long-term vision and better orient its strategies.

2.2.4 Life cycle inventory

The data required for a complete analysis of the PV power plant concerns the raw materials used, the energy consumed, and the emissions generated at each stage of the life cycle studied. This study was based on secondary data, i.e., generic or theoretical data from commercial databases, various study reports, or other published sources.

Manufacturing inventory data for the different components were obtained from recently published studies: modules [10, 23–25]. Where possible, average data has been calculated. The Ecoinvent 3.7 database was used to obtain inventories of inverter manufacturing, transformers, electrical installations, and transport (sea and land). Inventory data on construction, use, and maintenance were provided by *Vinci Energies*, responsible for the construction of the Zagtouli power plant, and the national electrification company of Burkina Faso (SONABEL). Data on the end-of-life management of the components are taken from previous studies [24, 26, 27]. All inventory data used in this study are detailed in the Supplemental Materials (Tables A1-A11; B1-B6; C1 and D1-D7).

2.2.5 Environmental impact assessment

The life cycle impact assessment of the PV plant was determined using the ReCiPe Midpoint (H) method, as described by Goedkoop et al. in 2013 [28]. The ReCiPe is one of the most recent and updated impact assessment methods available for LCA practitioners. Four indicators were chosen: climate change, freshwater ecotoxicity, and mineral and fossil resource scarcity. These indicators are widely used in the literature to assess the environmental impacts of PV systems [9, 13, 29].

SimaPro 9.4.0.2 LCA software, one of the leading software tools used for LCA, is used to build the LCA model and perform the environmental impact calculations. The software is provided with a combination of an extensive international life cycle inventory database and a variety of different impact assessment methods. The European environmental inventory database, Ecoinvent 3.7, was used.

3 Results and discussion

3.1 Energy performance: EPBT

The EPBT of the six scenarios of a PV power plant installed in Burkina Faso are presented in Fig. 5.

The results show that the EPBT of the scenarios varies between 1.47 and 1.95 years, with the shortest and the longest times corresponding to scenarios 4 and 3, respectively. Scenarios 1, 2, 5, and 6 have approximately the same EPBT of around 1.6 years. The PV module technology used largely explains this disparity in EPBT between the scenarios. The PV installation in scenario 3 (mono c-Si) has an EPBT 1.2 times higher than scenarios 1, 2, 5, and 6 (poly c-Si) and an EPBT 1.3 times higher than scenario 4 (CdTe). Thus, for PV installations with the same power but different technologies, the EPBT in ascending order is CdTe thin-film technology, poly c-Si, and mono c-Si. This is due to the energy required to manufacture them [9]. Ito et al. [15] made the same observation when they compared the EPBT of the different module technologies installed in Morocco.

Studies conducted on the energy performance of PV installations in Africa have reported an EPBT of 0.83–2.3 years for a 1.5 kWp mono c-Si installation in Nigeria in different locations with irradiation 1493–2223 kWh m^{-2}

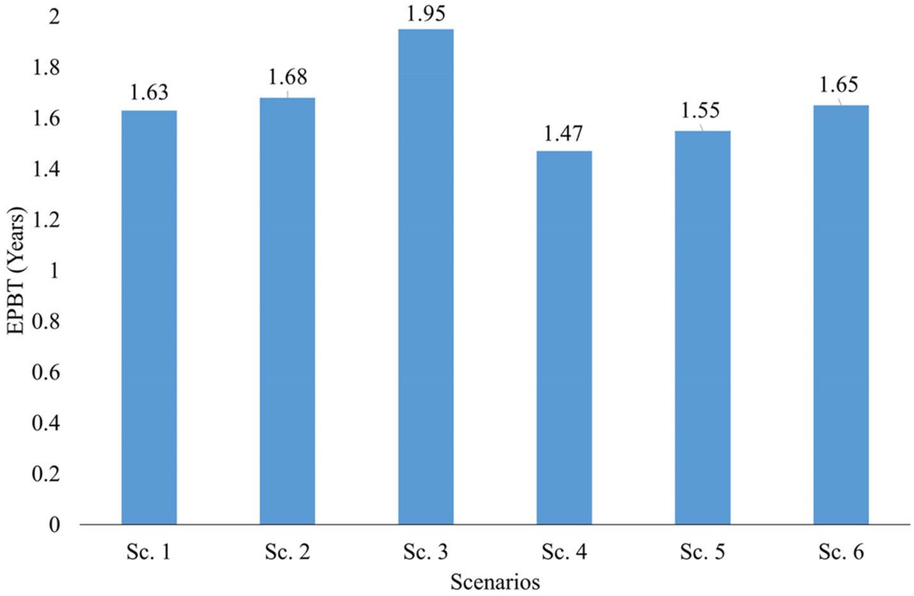

Fig. 5 EPBT of ground-mounted PV systems scenarios in Burkina Faso (2140 kWh m^{-2} yr^{-1})

yr^{-1} [30] and 2 years for a 48 kWp ground-mounted PV system in Tanzania with solar irradiation 1900 kWh m^{-2} yr^{-1} [31]. Similarly, EPBTs of 0.9–1.7 years were found for a PV plant with different module technologies in Morocco [15].

The EPBT values of all the scenarios in this study are close to those in the literature, i.e., less than 3 years. From an energy payback point of view, all the scenarios studied can be considered acceptable given the long lifetime of PV systems (25 years). Indeed, the energy consumed by the PV systems during their whole life cycle will be compensated in less than 2 years.

3.2 Environmental performance

3.2.1 Climate change

Figure 6 presents the results for the climate change indicator of the production of 1 kWh of electricity injected into the national grid by a PV plant.

The GHG emissions for the six scenarios range from 0.37 to 0.48 kg CO_2-eq kWh^{-1} for scenario 5 and scenario 3, respectively. It is characterized by three major groups dominated mainly by the PV module manufacturing stage, the mounting support, and the end-of-life management of the PV components.

Manufacturing PV modules account for the largest share of the emissions (61–86%) of the total impact) except for scenario 4, which accounts for only 31% of the global impact. This is due to the high-energy consumption during the solar-grade silicon and aluminum manufacturing stage, which is used as a frame for PV panels. Panels have been manufactured in Germany, while the German electricity mix is dominated by fossil fuels and is characterized by a gross electricity production of 44% (lignite, coal, natural gas, oil) from fossil fuel power plants until 2021. The production of 1 kWh of electricity from the German electricity mix is accompanied by 1.22 kg of CO_2-eq emission.

In scenario 3, mono c-Si, PV modules emit about 1.2 times more CO_2-eq than those in scenarios 1,2,5, and 6 (poly c-Si) and 2.5 times more than CdTe modules in scenario 4. This is because mono c-Si, which is more elaborate than poly c-Si, requires additional energy-intensive purification steps, thus increasing the CO_2-eq emission rate. The lowest CO_2-eq emitting CdTe cell is obtained by a rapid deposition process of cadmium telluride at low temperatures. Earlier studies by Ito et al. [17] and Gerbinet et al. [9] conducted on the LCA of different PV module technologies also showed that mono c-Si technologies are more CO_2-eq emitting than poly c-Si, which in turn is more emitting than thin film technologies, notably the CdTe module.

Manufacturing the mounting structures appears to be the second component that impacts the climate change indicator, with its most significant contribution of about 56% in scenario 4. This contribution differs from one scenario to another and depends on the type of material used by the mounting structures. Scenarios 2, 3, and 4 with aluminum structure emit about 6.9 times more CO_2-eq than the steel structure in scenarios 1, 5, and 6. The type of structure is responsible for the difference observed between scenarios of the same module technology in several cases (e.g., between scenarios 1 and 2).

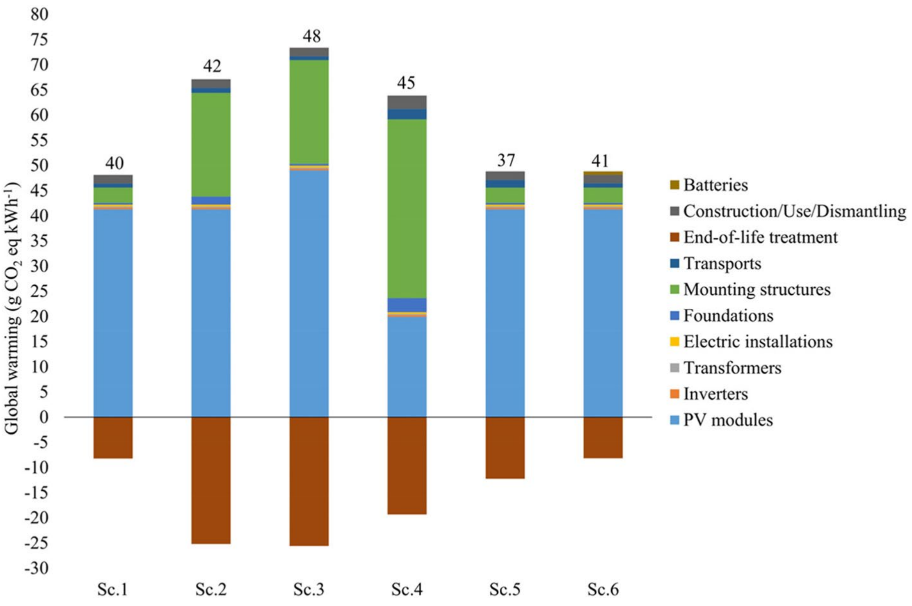

Fig. 6 Global warming potentials of PV plant systems

Primary aluminum production by electrolysis produces GHG emissions ranging from 4.3 to 30 kg CO_2-eq kg^{-1} of primary aluminum ingot [32, 33]. Emissions associated with steel manufacturing are 1.1 kg CO_2-eq kg^{-1} of steel, about 4 times less than aluminum [34]. Others [11, 13, 15] studying the environmental impacts of PV power plants have also highlighted the significant contribution of structural supports to the emission of CO_2-eq, sometimes reaching more than 45% of the total impact of the PV plant.

The contributions of inverters, transformers, electrical installations, the addition of an energy storage system, transport, and the construction/operation/dismantling stage represent a small part (less than 10% of the total impact). This conclusion is similar to that of Sinha et al. [35], who worked on the environmental impacts of the connection system of a PV plant.

The end-of-life management of components has an environmental benefit due to recycling. It contributes to a 17–38% reduction in carbon emissions. It is partly due to substituting raw materials for recycled materials in manufacturing the components, leading to a decrease in the cumulative environmental impacts. Previous studies on the life management of PV components [25, 36, 37] have shown that the recycling of aluminum and steel supports could reduce impacts by 25%, considering that the structures were 100% recycled. As for module recycling, the study by Latunussa et al. [25] on the innovative recycling process of crystalline modules showed that recycling could considerably reduce energy consumption during manufacturing as it allows the recovery of aluminum from the frame, copper, glass, silver, and solar grade silicon.

Potential climate change is the most studied environmental indicator in LCA of PV systems in the literature. The total emissions for PV systems installed in Europe have been estimated at 38–88 g CO_2-eq kWh^{-1}, according to previous studies [38–40]. According to Fu et al. [41] and Huang et al. [27], Asian PV installations have been found to exhibit values ranging from 50 to 87.3 g CO_2-eq kWh^{-1}. Studies carried out in sub-Saharan Africa, specifically in Nigeria and Tanzania, resulted in 37.3–180 g CO_2-eq kWh^{-1} emissions, depending on the localities where the PV systems were installed [30, 42]. The climate change values of the six scenarios studied (37–48 g CO_2-eq kWh^{-1}) fall within the range of values obtained for installations in sub-Saharan Africa.

Regarding the climate change indicator, this study shows that CdTe technology is the least CO_2-eq emitting considering a lifetime of 25 years among the studied technologies. However, for installations of the same power technologies, the CdTe module will require more surface area and, therefore, an environmental cost for transport, the construction stage, and an increase in mounting structures. As for the type of structure, it will be preferable for African countries to use steel structures rather than aluminum because, in addition to requiring less energy to manufacture, steel has a higher strength than aluminum and will allow the mounting structures to withstand the high winds in the region. Implementing a recycling structure for the components in life will allow a gain in the carbon rate emitted into the atmosphere.

3.2.2 Fossil resources scarcity

The impacts on fossil resource scarcity in Fig. 7 show a similar pattern to the impacts on climate change in terms of the most contributing stages of the life cycle (module and mounting structure manufacturing and end-of-life) and in terms of comparison between the scenarios.

This graph shows that the main component responsible for fossil resource scarcity is the PV module (50–76%), except for scenario 4, where the module contributes 28% to the total impact. The large impact of the module on fossil resource scarcity is mainly due to the energy consumption and the coal and coke used as a reducer for silica reduction during silica transformation into silicone. Almost all of the fossil resource scarcity impact of the scenarios is attributed to coal consumption (46–52%), followed by natural gas (23–28%), crude oil (20–31%), and peat (less than 1%). This fossil fuel consumption is similar to the amount of fossil fuels used by German thermal power stations [43].

CdTe PV modules in scenario 4 consume 2.1 times fewer fossil resources than poly c-Si modules in scenarios 1, 2, 5 and 6, and 2.5 times less than mono-Si modules in scenario 3. The crystalline silicon technologies (mono and poly) lead to high fossil resource scarcity values due to the energy consumption during the purification of the metallurgical grade silicon into solar grade silicon and during the ingot crystallization phase. The latter stage is the main reason for the difference in energy consumption between mono c-Si and poly c-Si technologies. In a research conducted by Kim et al. [44], comparing the environmental performance of mono-crystal silicon and polycrystalline silicon modules in Korea, the crystallization of mono-crystal silicon at high temperatures (1500 °C) consumes more energy than the crystallization of polycrystalline silicon at room temperature. This consumption of fossil energy confirms the high carbon emission of PV modules. Furthermore, Zahedi et al. [45] have also demonstrated that polycrystalline module technologies consume 2.5 times more fossil fuels than thin-film technologies during the production process.

Manufacturing the mounting structure is the second largest contributor to the fossil resource indicator (10–40%). The use of coal and natural gas for the

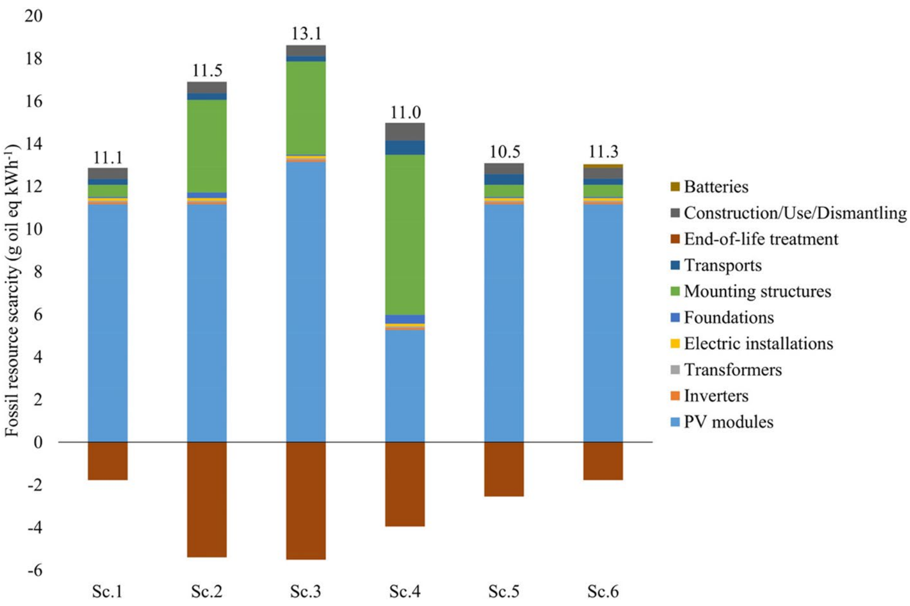

Fig. 7 Fossil resources scarcity of the Zagtouli plant PV systems

manufacturing of steel and aluminum is the leading cause. Thus, the aluminum structure in scenarios 2, 3, and 4 consumes 7.9 times more fossil resources than the steel structures in the other scenarios (1, 5, and 6), which also explains the high CO_2-eq emission rate. Bauxite refining, alumina reduction, and smelting are the three most intensive energy in primary aluminum manufacturing. The main energy resources consumed during these steps are coal, oil, and natural gas. Manufacturing one kg of aluminum ingot consumes about 178 MJ and 18.2 MJ for one kg of steel, which is 6–10 times less energy. These results are similar to studies by Farjana et al. [46] and Burchart-korol [34], who found consumption of 108–179 MJ kg^{-1} of aluminum and 24.5 MJ kg^{-1} of steel, respectively.

Transporting the various products to the place of use and the recycling sites contributes to about 3% of fossil resource scarcity. Recycling the end-of-life components, especially the aluminum and steel mounting structures and aluminum frame of the PV module, will reduce fossil resources by an absolute value of 12–24%. The complete recycling of the PV module in scenario 5 reduces the total energy consumption by about 18%.

3.2.3 Mineral resource scarcity

Mineral resource scarcity reflects the consumption of mineral resources in all electricity generation processes. A resource availability factor is calculated for each mineral resource extraction based on the available reserves and exploitation rate. Figure 8 illustrates the contribution of the different stages of the PV plant life cycle to reducing mineral resources.

Similar trends to climate change and fossil resource scarcity indicators, the decrease in mineral resources is dominated by module manufacturing, structural support, and end-of-life management. However, the significant contributions of electrical installations and the addition of battery energy storage units are worth noting.

The contributions of poly c-Si and mono c-Si modules are of the same order of magnitude 0.64 g Cu-eq kWh^{-1}, which is 1.8 times that of CdTe thin film technology 0.36 g Cu-eq kWh^{-1}). Silver, copper, lead, and aluminum are the mineral resources responsible for this contribution. These metals are used as metallization agents in the PV cell. Metallization consists of depositing metallic contacts on at least one side of the cell to collect the current and interconnect the cells. Silver and lead are used to metalize the front of the cells, while copper and aluminum are used for the back. Indeed, according to the International Energy Agency, the solar panel industry is a growing source of demand for silver metal. Feltrin and Freundlich [47] and Zuser and Rechberger [48], in assessing the limits of energy production for different modules technologies concerning the world's supply of available mineral resources, have shown that despite the abundance of silicon, crystalline silicon technology will be hampered by the world's supply of silver as an electrode. The scarcity of tellurium could affect the large-scale deployment of CdTe thin-film technology.

Mounting structure, the second largest component of mineral resource scarcity, is dominated by iron ore

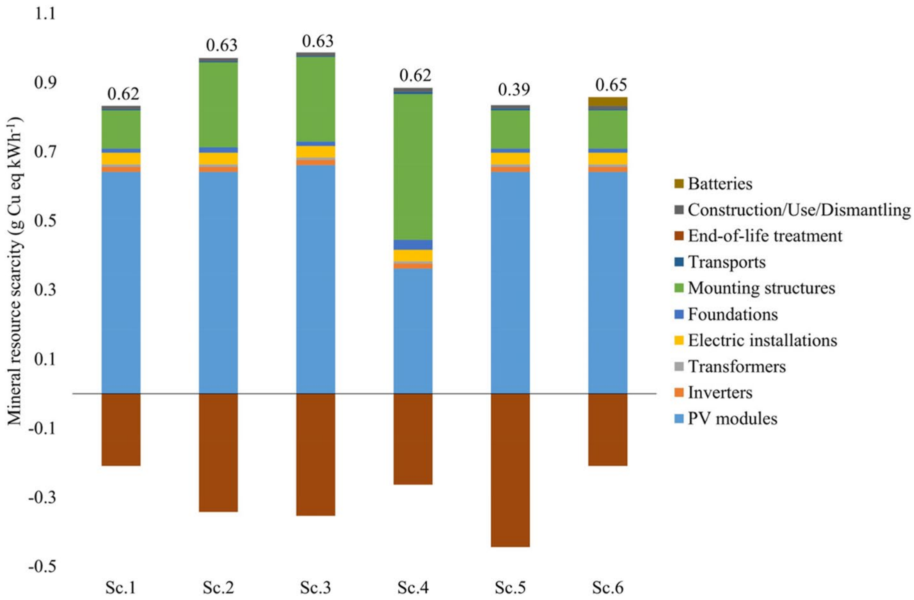

Fig. 8 Mineral resource scarcity of plant PV systems

and bauxite consumption for steel and aluminum structures, respectively. The aluminum structure accounts for 19–37% of the total impact of scenarios 2, 3, and 4, i.e., 2 to 3 times more than the steel structure of scenarios 1, 5, and 6 if the benefits of their end-of-life recycling are included. Indeed, 4 t of bauxite mineral resources are needed to obtain 2 t of alumina, from which 1 t of aluminum is extracted by electrolysis.

In contrast to the environmental indicators, where the contributions of the electrical installation and the inverters are low (less than 3%), in the mineral resource use indicator, they reach about 15%. Indeed, for each of the components, copper metal is used in the process of their manufacture. Harmsen et al. [49], in studying the impact of copper scarcity on renewable energy efficiency by 2050, showed that over the next few decades, copper scarcity is likely to lead to a deterioration in ore quality and a higher gross energy requirement for its production.

The environmental benefits derived from recycling the various metals contained in end-of-life PV waste allow a reduction in the use of mineral resources by 20% for steel structures and 23–35% for aluminum structures. Recycling aluminum is important because it limits mineral resource consumption, especially bauxite. In addition, it reduces energy consumption, as the amount of electricity needed to produce one ton of recycled aluminum is only 5% of that used to produce one ton of primary aluminum.

3.2.4 Freshwater ecotoxicity

Water pollution is a major environmental issue. The main water pollutants for the aquatic environment are heavy metals, which are toxic to living aquatic organisms. This pollution leads to the disappearance of species and the degradation of the ecosystem over the long term. Figure 9 shows the contribution of the different life cycle stages of the PV plant to the environmental indicator of freshwater ecotoxicity.

The main contributors to freshwater ecotoxicity are PV panels, electrical installations (13–22%), and end-of-life management. In contrast to the other environmental indicators, the mounting structure has a low contribution to freshwater ecotoxicity.

The poly c-Si (scenarios 1, 2, 5, and 6) and mono c-Si (scenario 3) PV module technologies contribute 65%. Thin film technology (scenario 4) contributes 73% if end-of-life management is excluded. CdTe technology has more impacts on freshwater ecotoxicity than mono c-Si and poly c-Si.

The substances in the modules that contribute most to freshwater ecotoxicity are mainly copper (57–69%), zinc (24–35%), and nickel (1–4%). The concentration of copper ore during the manufacturing stage generates tailings rich in toxic metals (copper, zinc, silver, nickel). These tailings are usually stored behind dammed impoundments, known as tailings ponds. These ponds present a significant long-term pollution risk because the metals may leach into the surrounding environment, potentially over very long periods. This leaching is, therefore, the cause of the toxicity of the surrounding freshwater. This also explains the contribution of electrical installations (as they are mainly made of copper).

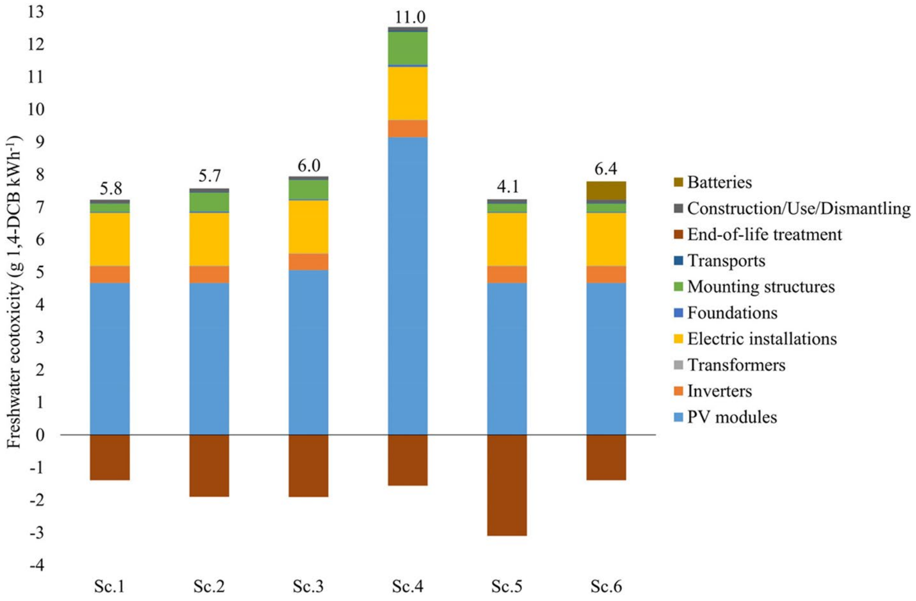

Fig. 9 Freshwater ecotoxicity of PV plant systems

During the manufacture of the PV module, the interconnection of the PV cells results in the release of copper and zinc into the water. Copper and zinc are used in the PV cell as electron collectors. For a 33.7 MWp PV plant with the same power output, the installed area of CdTe thin-film technology is 1.7 times the area of polyc-Si and mono c-Si modules. Indeed, the larger the module surface, the more electron collector it consumes, which explains the high impact of CdTe technology.

Regarding the impact of end-of-life management on freshwater ecotoxicity, all the scenario scores are negative, i.e., generate environmental benefits. Environmental benefits come from PV modules and mounting structures recycling. Recycling the copper and zinc contained in the PV module at the end of its life reduced the total impact by around 20–32%. Research conducted in the literature has demonstrated that the recycling of PV modules can significantly mitigate the environmental impact of freshwater. According to studies by (Sharma et al., 2023), panel recycling reduces human and freshwater toxicity by about 32%.

The freshwater toxicity values for the six scenarios analyzed in this study range from 4.1 10^{-3} to 10.9 10^{-2} kg 1,4-DCB kWh^{-1} for scenarios 1 and 4. All these values are on average 1.83 times higher than those found in the literature [45, 50]. Freshwater ecotoxicity values of 5.96 10^{-2} kg 1,4-DCB kWh^{-1} were found by Shah et al. [50] when studying environmental impacts in Pakistan. Zahedi et al. [45] compared the environmental impacts of different technologies and estimated the freshwater ecotoxicity of polycrystalline and thin-film panels at 4.47 10^{-2} and 5.98 10^{-2} kg 1,4-DCB kWh^{-1} respectively. These differences in values between the literature and the data from this study are mainly due to the system boundaries considered. The majority of studies in the literature do not include the manufacturing stages of the connection system (electrical installation, inverters, and transformers) in the system boundaries. Furthermore, these studies do not consider the end-of-life management of PV components.

3.3 Sensitivity analysis

The electricity source was the most significant contributor to the EPBT and environmental indicators (climate change and fossil resource scarcity). As this source of electricity varies considerably from country to country, a sensitivity analysis of the EPBT and environmental impacts was performed by choosing a country with a less carbon-intensive energy mix than Germany and Norway. The sensitivity analysis was carried out only on the PV modules' manufacturing location, as the other components' production location remains unchanged.

The resulting EPBT values of the change in the electric mix are presented in Fig. 10. The results show a decrease of about 30% in the EPBT in all scenarios except scenario 4, where it is 15%. The thin film technology, which is less energy-intensive during the manufacturing stage, is less affected by the change in the electricity mix. The choice of the manufacturing location of a PV module plays a crucial role in a faster payback of energy investments.

Table 3 presents the effect of the change in electricity mix on the environmental indicators studied. It can

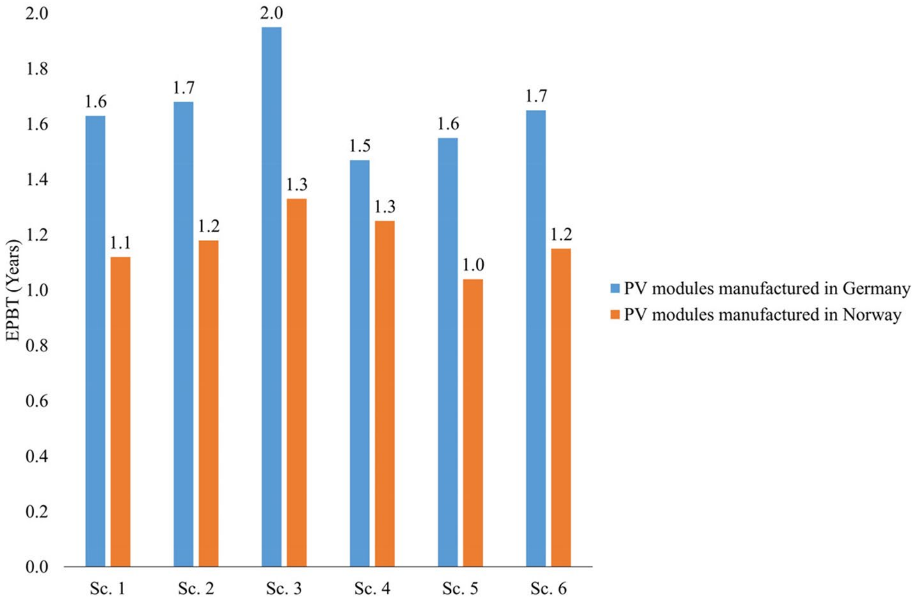

Fig. 10 EPBT Sensitivity analysis

Table 3 Environmental impact of the 06 scenarios according to the manufacturing location of the PV module

	Germany						**Norway**					
	Sc.1	**Sc.2**	**Sc.3**	**Sc.4**	**Sc.5**	**Sc.6**	**Sc.1**	**Sc.2**	**Sc.3**	**Sc.4**	**Sc.5**	**Sc.6**
Global warming (%)	83.5	87.7	100	93.2	76.5	84.9	51.4	57.3	59.8	100	41.9	53.4
Freshwater Ecotoxicity (%)	53.2	51.7	55.1	100	37.5	58.3	46.1	44.5	45.8	100	29.9	51.4
Mineral resource scarcity (%)	96	96.8	97.6	95.7	60.1	100	95.9	96.8	96.6	96.9	59	100
Fossil resource scarcity (%)	84.6	87.7	100	84	80.4	85.9	65.8	70.5	75	100	59.4	67.8

🟥 A similar trend. but the difference is more than 15%
🟧 Close results
⬜ Trend reversal

be seen that the change in the electricity mix generates significant decreases in environmental impacts in all six scenarios: 30–40% in climate change and 18–20% in fossil resource scarcity. A trend reversal is observed between scenarios 3 and 4. The electricity mix change in these scenarios decreases the module's contribution to the impacts. However, the share of the mounting structure remains unchanged. Indeed, the CdTe thin film module in scenario 4 consumes more mounting structures than the other technologies. For PV installations produced in countries with a less carbon-intensive electricity mix, such as Norway, the contribution of the mounting structures becomes dominant in the environmental impacts.

Contrary to the climate change and fossil resource scarcity indicators, the impact of the electricity mix on the mineral resource scarcity and ecotoxicity indicators is very low (less than 5%), and they are, thus, independent of energy consumption.

Electricity consumption during the components' manufacturing phase, mainly the PV modules, has an important impact on climate change and fossil fuel consumption. Therefore, a change in the electricity mix will reduce these impacts. As Norway has a lower carbon mix than Germany, this will result in low consumption of fossil resources and, thus, low GHG emissions; so, the place of manufacture is a parameter that significantly influences carbon emission. The production of PV modules should, therefore, ideally take place in countries with a lower carbon electricity mix, but special attention should be paid to the availability of materials. Nevertheless, the distance from the production site to the plant must be reduced to avoid the pollution shift due to transport.

It should be noted, however, in Europe, where environmental concern is the most determining factor of PV panel adoption factors [51]. In Africa, economic and social factors may influence the choice of where to purchase PV modules. Further studies are needed to determine the factors influencing the choice of module technology and production location.

4 Conclusions

This study highlights PV installations' energy and environmental performance in Africa, considering different module technologies, mounting structure types, and components' end-of-life management. The study shows that: The EPBTs obtained in this study ranged from 1.47 to 1.95 years. These EPBTs are satisfactory and comparable to results obtained in other African locations. The analysis of the environmental performance of the six scenarios showed that climate change varies between 37 and 48 g CO_2-eq kWh^{-1}, freshwater ecotoxicity of 4.1–10.9 g 1,4-DCB kWh^{-1}, mineral resource scarcity 0.39–0.64 g Cu-eq kWh^{-1} and fossil resource scarcity 10.5–13.1 g oil-eq kWh^{-1}. The evaluation of PV systems revealed that CdTe technology has the lowest impacts on climate change and mineral and fossil resource scarcity. However, it has the highest contribution to freshwater ecotoxicity. The mono c-Si technology has the highest impact on most indicators. These results depend to a large extent, on the electricity mix of the country in which the modules were manufactured. Aluminum mounting structures showed higher emissions than steel structures due to the energy-intensive manufacturing process and the high credit avoided during recycling. Inverters, transformers, and foundations have a low manufacturing, use, and end-of-life contribution for all cases studied. The sensitivity analysis highlighted the need to purchase PV panels in a country with a lower carbon electricity mix to reduce EPBT and significantly reduce CO_2-eq emission rate and fossil resource scarcity. For a large PV installation in Africa, purchasing the panels in a country with an electricity mix dominated by renewable sources is recommended. The galvanized steel structure is more recommended. Concerning end-of-life management, panel recycling units should be set up to facilitate management.

Studies on the variation of the lifetime of the components (modules, inverters, transformers) and the percentage of recycled material in the composition of the mounting structure should be conducted to optimize the energy and environmental performance of PV power plants in West Africa.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-023-00201-x.

Additional file 1. Life cycle inventories.

Acknowledgements
The authors wish to thank the German state for financial support through the DAAD Scholarship and the National Electricity Company of Burkina Faso (SONABEL) for providing data from the Zagtouli photovoltaic power plant.

Authors' contributions
All authors contributed to the study conception and design. Kodami BADZA collected the data, conducted the LCA, analyzed and interpreted the data and wrote the manuscript. Y.M. Soro and Marie SAWADOGO guided the study and revised the manuscript. All authors read and approved the final manuscript.

Funding
No financial support was received for this study.

Availability of data and materials
All data used and/or analyzed during the current study are available from the corresponding author upon request.

Declarations

Competing interests
The authors declare they have no competing interests.

Received: 27 June 2023 Accepted: 30 October 2023
Published online: 10 November 2023

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