Energy Conversion and Management: X 28 (2025) 101274

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Techno-economic analysis of local manufacturing of perovskite photovoltaic modules for electricity generation in Ethiopia

Getnet M. Meheretu [a,b,*], Ababay Ketema Worku [a], Moges T. Yihunie [b], Richard K. Koech [c], Getasew A. Wubetu [a,b,d]

[a] Bahir Dar Energy Center, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar P.O. Box 26, Ethiopia
[b] Department of Physics, College of Science, Bahir Dar University, Ethiopia
[c] Department of Mathematics, Physics and Computing, School of Science and Aerospace Studies, Moi University, Kenya
[d] School of Applied and Engineering Physics, Mohammed VI Polytechnic University, Benguerir 43150, Morocco

ARTICLE INFO

Keywords:
Levelized cost of energy
Local manufacturing
Perovskite solar cells
Techno-economics
Viability

ABSTRACT

Perovskite solar cells can be potential contenders for future photovoltaic technologies due to their high efficiency, affordability, and simple manufacturing process. This study focuses on the techno-economic analysis of local manufacturing of perovskite solar panels in Ethiopia. The total manufacturing costs were found to be \$0.29 /wp or \$/69.6/m^2. The Minimum Sustainable Price was calculated to be \$0.38 /wp or \$91.2/m^2. Using a Monte Carlo simulation, the techno-economic metrics such as Net Present Value, Pay Back Period, Rate of Return, Profitability Index, and Levelized Cost of Energy were evaluated to determine project viability. The analysis showed a positive Net Present Value, a Payback Period of 7 to 8 years, an Internal Rate of Return of about 12 % with its average rate of return greater than the weighted average cost of capital, and a profitability index of 1.22, indicating project viability. The levelized cost of energy was estimated to be \$0.019/kWh, which is lower than the selling price of electricity by the Ethiopian electric power authority, suggesting economic viability.

Introduction

The high concentration of CO_2 resulting from the burning of fossil fuels significantly impacts climate change, leading to prolonged droughts. Solar energy, as a highly abundant renewable resource, has the potential to completely replace fossil fuels, mitigating environmental damage and climate change. Recent developments indicate that photovoltaics (PVs) will play a crucial role in the future of global electricity generation, supported by public interest and growing environmental concerns.

Silicon based PV technologies currently dominate the global PV market, however they are heavy, rigid, expensive to produce, and limited in power conversion efficiency, can reach only up to 27 % [1]. In contrast, perovskite PV technology offers lightweight, flexible, and low cost alternatives, making it suitable for integration into buildings. Within just a decade of research, perovskite solar cells have shown rapid improvements in PCE and attracted considerable attention for their excellent optoelectronic properties and ease of fabrication [2–8].

On-going research focuses on scaling up perovskite PVs to produce stable and efficient large-area modules, essential for real-world applications such as rural off-grid electrification [9–11]. As the technology approaches commercialization, industry interest mainly focuses on performance, stability, and manufacturing cost [12].

The transition from laboratory-scale development to commercial production involves significant uncertainty in terms of processes, inputs, and costs. A comprehensive techno-economic analysis (TEA) is therefore essential to assess local manufacturing feasibility. Perovskite PVs offer economic advantages due to their high absorption coefficient, requiring minimal material and low-temperature, solution-based fabrication. Despite this promise, the technology is still in the early stages, requiring a detailed cost analysis to identify both technical and economic barriers to commercialization [13–15].

Although previous studies have emphasized the potential of perovskite PVs, limited research has incorporated complete cost metrics such as depreciation and indirect costs into the minimum sustainable price (MSP) framework [16]. This study addresses this gap by offering a comprehensive TEA that includes the overlooked factors, providing a more realistic estimate of production costs and commercial viability.

* Corresponding author at: Bahir Dar Energy Center, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar P.O. Box 26, Ethiopia.
E-mail address: getnet.melese@bdu.edu.et (G.M. Meheretu).

https://doi.org/10.1016/j.ecmx.2025.101274
Received 30 January 2025; Received in revised form 16 September 2025; Accepted 16 September 2025
Available online 20 September 2025

A distinctive aspect of this research is its focus on the Ethiopian and broader African markets, regions characterized by low labor costs, locally available raw materials, and urgent energy access needs. By incorporating local economic parameters such as inflation, infrastructure constraints, and resource availability, the analysis is tailored to the realities of emerging markets. While global research on perovskite PVs often centers on high-efficiency demonstrations in developed markets, this study shifts the focus to manufacturing feasibility in low-resource settings. Specifically, it explores the potential for local production in Ethiopia, a country with rising energy demand and high solar potential but limited capacity for advanced technology manufacturing.

The research introduces an integrated evaluation framework linking manufacturing costs to economic metrics such as the Levelized Cost of Electricity (LCOE), Net Present Value (NPV), and Profitability Index (PI). This dual-layered analysis offers a holistic perspective by connecting production economics with the broader implications for electricity generation and energy access. Ultimately, this study provides context-specific insights into the viability of local perovskite PV manufacturing in Ethiopia, addressing an underexplored yet critical pathway for deploying affordable, clean energy solutions in regions lacking conventional grid infrastructure.

This work not only advances the understanding of the economic challenges associated with perovskite PV commercialization but also provides valuable insights for establishing sustainable manufacturing strategies in Ethiopia and Africa. It highlights the potential for perovskite PV to drive renewable energy adoption in regions with significant energy access challenges, thereby contributing to global climate change mitigation and sustainable development goals.

Before this study, performance and stability analysis of perovskite solar cells under outdoor conditions in Bahir Dar, Ethiopia, was conducted, addressing how environmental factors such as dust accumulation, elevated temperatures, strong irradiance, shading effect, soiling, and wind significantly affect the performance and long-term stability of perovskite PV modules[17,18]. Additionally, we have conducted review work on the recent advancements in the outdoor performance of perovskite photovoltaic cell technology demonstrating many of these effects [19].

Enabling environment and appraisal criteria

The Ethiopian government has identified key priority areas for development, focusing on food security, climate change mitigation, and sustainability, recognizing their significant impact on the overall economy. These priorities are reflected in the government's policies and strategies outlined in various frameworks such as the Growth Transformation Plan (GTP), Rural and Agricultural Development Plan, National Climate Resilience Growth Strategy and Action Plan, and the Water Sector Strategy. These initiatives aim to promote energy-efficient growth and address critical challenges facing the country. Fig. 1 presents the geographical map of the country and its neighboring territories where the case study was conducted.

Ethiopia's market presents significant opportunities for improving electricity access, particularly through off-grid energy solutions. Achieving this requires collaboration between the public and private sectors. Various donors, including the Scaling-Up Renewable Energy Program (SREP) of the Climate Investment Funds, support initiatives to enhance lighting access in the country. Germany, for instance, has established the first solar energy operation in least developed countries (LDCs), including Ethiopia, aiming to alleviate poverty by promoting solar energy use.

To achieve its long-term goal of becoming a middle-income country within 15–25 years, Ethiopia needs to aggressively pursue strong industrial development, which in turn requires a reliable energy supply. However, the country currently lacks an adequate energy supply for

Fig. 1. Geographical map of Ethiopia (https://www.mapsofindia.com/world-map/ethiopia/).

industrialization, with energy access rates even lower than the Sub-Saharan African average. To reach its ambitious development goals, Ethiopia must expand its use of renewable energy sources, such as solar energy.

The country faces significant challenges due to food shortages resulting from irregular rainfall patterns, occasional droughts even during rainy seasons, steep increases in oil prices, and persistent inflationary pressures, despite having experienced double-digit economic growth in previous years. To sustain this growth momentum, mitigate price hikes, and achieve its vision of attaining middle-income status through industrialization, nation shall prioritize the enhancement of its energy sector [20]. In recent years, Ethiopia has witnessed alarming inflation rates: 33.9 % in 2023, 19.2 % in 2021, 18.7 % in 2020, and approximately 34.6 % in 2022. This underscores the urgent need for proactive measures to stabilize prices and ensure sustainable economic development [21].

This high inflation rate reported in Ethiopia can significantly affect the cost structure and viability of local manufacturing operations of perovskite PV modules. In our analysis, we have considered the impact of inflation on key cost drivers such as labor, raw materials, utilities, transportation, and maintenance, which are all vulnerable to local price volatility. The inflation-adjusted cost escalation was incorporated into our financial modelling through sensitivity analysis on the real discount rate and operating cost projections. The LCOE is calculated taken into consideration of these assumptions.

Ethiopia boasts of abundant sunshine throughout the year, making it ideal for solar power generation. The country receives solar radiation ranging from 4.5 kWh/m^2 to 7.5 kWh/m^2 per day, with an average of 5.26 kWh/m^2. The amount of useful sunshine available for the panels on an average day during the lowest insolation month is taken to ensure the system will work year-round without a shortage of power. The total annual solar energy potential of the country is estimated to be 2×10^6 TWh; however, it needs only 0.003 % of this potential to cover the annual energy demand of the country [22–25]. Despite this potential, the adoption of solar PV systems and solar thermal technologies in rural communities remains limited [23]. The country's minimum energy consumption per capita is 25 kWh/year, which is below the consumption of sub-Saharan country and the world, which is 550 kWh/year. This means the country is expected to harness more energy to achieve even the minimum standards [25].

Ethiopia possesses significant solar energy potential, particularly during the dry season, which constitutes over 75 % of the annual seasonal variations. However, despite this abundant renewable resource, its utilization remains below its potential due to constraints such as limited technology, affordability issues, and inadequate maintenance. To fully tap into this resource and address the scarcity of rural electrification, a concerted effort involving governmental, non-governmental organizations, and the private sector is imperative [26]. Furthermore, Ethiopia has set a policy goal to enhance its industrial capacity to produce energy source minerals by 2030, signalling a commitment to advancing its energy sector. The government policies encourage private sector participation in the industry [27,28].

Expanding off-grid solar power coverage faces challenges such as high costs associated with foreign currency and a lack of clear module importing policies [29]. Local manufacturing of low-tech PV systems, like Perovskite Solar Cells (PSCs) modules, could help overcome these challenges. Ethiopia possesses minerals such as aluminium, gold, copper, iron, nickel, manganese, and lead that can be used as raw materials for manufacturing PSCs. Many minerals used to synthesize the required chemicals for local manufacturing of perovskite PV are available in Ethiopia. For instance, $TiO_{2,}$ the proposed ETL is available with recommended techniques of extraction. Ethiopia is well endowed with gold and copper ores, which promote the potential to use these noble metal as a back electrode. Additionally, it has silica sand and feldspar for glass plate fabrication, necessary for PSC production [30-33].

The advantages of PV technology over other alternatives, particularly traditional sources, are immense, driven by its decreasing costs, reliability, and established models of technology diffusion. Due to the growing demand in the local market and an expanding workforce, Ethiopia stands poised to cultivate a sustainable PV technology market. However, despite some progress, PV system installations have primarily been limited to projects owned by governmental and non-governmental organizations (NGOs), falling short of meeting the demand and expansion targets.

Different researches have been conducted on the SWOT (strength, weakness, Opportunity, and threat) analysis and concluded that fast growth solar energy development in Ethiopia needs a great attention to work on producing skilled manpower for maintenance and installation, reducing the cost of solar power [25]. Shifting to emerging PV technologies, such as Perovskite PV cells, can reduce the cost of solar power generation. Perovskite PV cells offer a more environmentally friendly and sustainable option compared to traditional silicon-based technology, with a lower energy payback period [34]. To reduce manufacturing costs further, researchers are exploring new materials and device configurations, including tandem structures, for PSCs. Ethiopia's focus on research and development of emerging solar PV technology aligns with its government policies and local context, indicating a promising future for solar energy production in the country [15].

The main cost items for local manufacturing of Perovskite PV modules include:

i. **Manufacturing Equipment**: Large-area manufacturing facilities are required for perovskite PV module manufacturing, with capital costs associated.
ii. **Consumables/Chemicals**: Various chemicals are needed for the substrate, perovskite absorber layer, charge transport layers, electrodes, encapsulation, and other essential components.
iii. **Labour**: Skilled and semi-skilled human resources who can work as technical experts and project administrators are required for local manufacturing.
iv. **Utilities:** Expenses for the electricity and other utilities required to run the manufacturing plant.
v. **Research and Development (R&D):** R&D investments to improve the efficiency and durability of the perovskite PV modules.
vi. **Policy-related costs:** Costs associated with complying with relevant policies and regulations (see supporting information).

Appraisal criteria such as payback period (PBP), accounting rate of return, discounted cash flow (DCF) methods NPV, Internal Rate of Return (IRR), profitability index (PI) or Benefit Cost Ratio (BCR), and LCOE are used to determine the viability of local manufacturing of Perovskite modules in Ethiopia.

Local manufacturing of Perovskite PV modules in Ethiopia introduces a new technology, promoting technology adaptation and employment. It aligns with the country's priority areas, such as the Growth and Transformation Plan, Sustainable Development Goals, climate change initiatives, and investment policies. The economic and social benefits are substantial, encouraging sectors to support the project.

Despite being recognized as the largest PV market in the region [35], Ethiopia still grapples with significant energy access challenges, with approximately 80 % of its rural population lacking electricity and relying on biomass energy sources. This underscores the untapped potential of abundant renewable energy sources that could substantially contribute to the country's economic growth [36]. Ethiopia's heavy reliance on biomass energy underscores the importance of clean, affordable, and renewable energy sources to meet the growing energy demand driven by population growth, urbanization, and industrialization [37,38].

Expanding energy coverage and diversity is a national priority, with an emphasis on renewable and affordable energy supply to achieve the government's goal of becoming a lower-middle-income country. Up scaling energy is identified as one of the economic strategies for this growth and transformation plan [39]. Energy research in Ethiopia aims to assess alternative energy pathways for their economic contribution, in addition to their impact on climate and the environment [37]. Ethiopia has significant solar energy potential [24], enabling the privatization of off-grid electrification.

Perovskite PV modules

Perovskite PV cells have emerged as a promising technology with high PCE. It offers many advantages over silicon PV such as low-cost manufacturing at relatively low temperatures. Unlike silicon PV, which relies on high-tech, low-throughput processes, perovskite PV fabrication can utilize simple, high-throughput techniques, including roll-to-roll methods for large-area module production.

Perovskite materials have low processing energy requirements, and tunable band gap properties. These features make them promising candidates for various applications, particularly perovskite/silicon tandem solar cells [16,22,40]. Though scalability and stability remain a challenge, perovskite PV modules are anticipated to revolutionize the solar energy landscape, offering a superior alternative to traditional silicon modules. Notably, perovskite modules boast ease of integration into various structures and devices, serving as efficient power sources [40]. Research efforts are focused on overcoming these challenges to enable local manufacturing and commercialization of perovskite PV technology [9]. Significant progress has been made in stability, with some perovskite/silicon tandem cells achieving one year of outdoor stability, making them viable for local manufacturing [41].

In order for perovskite PV modules be competitive in the market, it is necessary to reduce the manufacturing costs by using cheaper materials as the back electrode, electron transport layers (ETLs), and hole transport layers (HTLs). With various research efforts perovskite mini-modules with an area of about 100 cm^2, achieving a certified PCE of 15 % have been fabricated. The manufacturing cost of a simple geometry perovskite PV module, excluding back-sealing glass, junction box, and wiring, ranges from $\$30/m^2$ to $\$41/m^2$ in the United States [16]. Researchers have also conducted manufacturing cost assessments for perovskite PV modules of different structures [14]. In comparison to the cost estimates in the United States, the manufacturing costs in Ethiopia are expected to be lower, primarily due to reduced labor expenses and improved access to locally available materials.

Methodology

Model description and assessment parameters

This study utilizes a bottom-up model to analyze the techno-economic potential and calculate viability metrics for manufacturing perovskite PV modules [41]. The analysis is based on several assumptions relevant to a hypothetical perovskite module manufacturer in Ethiopia. Key parameters considered include the quality and local availability of raw materials, annual solar insolation, labor costs, land availability, taxes, and comparisons with silicon PV and other energy sources. The analysis also incorporates procedural assumptions for process design, process modeling, equipment sizing, capital cost estimation, operating cost estimation, and cash flow analysis.

The methodology includes calculating the initial capital expenditure for the perovskite PV module's MSP. The study models an average medium-scale production line (100 MW/year) and estimates module costs using standard engineering costs, taking into account similar analyses as input [42,43]. Initially, the analysis assumes that perovskite/silicon tandem modules, which have demonstrated a PCE of 34 % at cell level, can enter the market.

The techno-economic analysis of the perovskite PV module considers essential components for large-area module manufacturing, including glass plates, interconnection busbars, sealants, laminating film, edge sealing frames, junction boxes, and wiring [16]. The quality of glass used is crucial to prevent moisture ingress and avoid degradation effects on the perovskite device [44].

Manufacturing procedure and cost development

The study assumed a standard module size of 1 m x 1.4 m, with an area of 1.4 m2, and utilized a monolithic perovskite-silicon tandem PV configuration. The module's PCE was considered at 24 %, corresponding to an output of 240 W/m2. Various operational assumptions included a 25-year module lifespan, 20 % shading loss, and 3 % annual degradation. The study has taken into account the stability and degradation concerns associated with perovskite PV modules in our techno-economic analysis. We have incorporated degradation rates by normalizing the degradation rates from multiple outdoor testing published literature rather than direct long-term measurement data, due to the evolving nature of perovskite stability research and the absence of standardized outdoor degradation datasets for large-area modules. Our assumptions were guided by conservative estimates that reflect realistic expectations for commercially scalable perovskite technologies. Furthermore, we used the silicon PV modules' degradation rate as a baseline for comparison in terms of performance and operational lifetime.

In this study, a module PCE of 24 % was assumed for the perovskite-based tandem technology. This value was determined by applying a 70 % module-to-cell derating factor to a lab-scale tandem cell efficiency of above 34 %, which aligns with recent advancements in tandem perovskite-silicon solar cells. The derating accounts for performance losses during module fabrication, encapsulation, and real-world operating conditions.

Manufacturing perovskite PV modules involves selecting the desired module architecture, followed by fabrication using low-temperature deposition techniques on a large scale. Electron and hole transport layers are prepared through screen printing and heat treatment, with screen printing also preferred for depositing the perovskite layer. The perovskite composition used in this analysis includes cesium and formamidium double cations for the A-site, lead for the B-site, and iodide and bromide anions (with 25 % bromide) for the X-site, dissolved in a 4:1 mixture of DMF:DMSO [45]. Front ITO and back gold/copper electrodes are deposited using industrial-scale magnetron sputtering [46,47]. Various techniques, such as doctor blading, slot die coating, and ultrasonic spraying, can be employed for large-area PV module manufacturing. These coating methods, however, exhibit significant differences in both capital and operational expenditures. Factors such as scalability, precision requirements, and process-specific energy demands play a critical role in determining their suitability. Each technique offers unique advantages and trade-offs depending on the production scale, desired film properties, and long-term operational costs, making the choice of method highly context-dependent [48–51].

The manufacturing cost (MC) per unit area of the perovskite module can be calculated by summing the costs of raw materials (M_i), utilities (U_i), labor (L_i,), equipment maintenance (E_i), and depreciation (D_i) in the ith step of the process [16]:

$$MC = \sum_i (M_i + U_i + L_i + E_i + D_i) \tag{1}$$

The device configuration used for manufacturing determines the materials and utilities costs [16]. Labor costs vary across different parts of Ethiopia and are influenced by the inflation of the cost of living in each location. For this analysis, the estimated labor cost in Bahir Dar city was used, where pilot performance and stability tests of perovskite devices have been conducted. Maintenance costs can be calculated as a fixed percentage of equipment and building costs [52], while depreciation costs depend on the depreciation time of the PV module. The proposed module cost is calculated using the linear depreciation method, with costs distributed evenly over each year of production throughout the operational lifetime.

The analysis consists of capital expenditure (CAPEX) for setting up a perovskite PV manufacturing facility such as equipment, manufacturing operational expenditure (OPEX) for a 10 year manufacturing period (see the supporting information), and power generation operational expenditure (PV OPEX) for 25 years, with the first manufactured PV modules assumed to start power generation on year 2.

Direct costs analysis encompassed materials, equipment, labor, utilities, and rent, totaling approximately $29.1 million over 10 years. Indirect costs, such as operation and maintenance (5 %), overhead (20 %), and depreciation (2 %), contributed approximately to an additional 8.2 million in manufacturing costs over the same period.

Key parameters influencing the analysis included a weighted average cost of capital (WACC), discount rate, tax, depreciation rates, and utility costs. Perovskite PV module is a newly emerging technology; as a result, there is no adequate information on its cost and price from companies. In this study, most of the cost assumptions were taken from chemical/equipment vendors, online sources, academic literature, and official government reports. The analysis also highlighted the impact of inflation rates and insolation levels specific to Bahir Dar.

Minimum sustainable price (MSP)

The Minimum Sustainable Price (MSP) model is a key parameter used to estimate the total manufacturing cost of a perovskite module [53]. It is determined by equating the minimum selling price, at which the IRR for the PV manufacturer is equal to the WACC.

To reduce uncertainties in the model assumptions, a normal distribution with a growth rate of 5 % and standard deviation of 1 % is applied to the manufacturing cost, overheads, and WACC. The WACC is calculated as the sum of the cost of equity (Ce) and the cost of debt (Cd), weighted by their respective proportions in the capital structure [54].

$$WACC = \frac{E}{D+E}C_e + \frac{D}{D+E}C_d(1-TR) \tag{2}$$

where E is the value of equity, D is the value of debt, Ce and Cd are the costs of equity and debt respectively, and TR is the corporate tax rate (if applicable).

Once the average module MSP is determined, it can be used in the calculation of the LCOE, which considers the discount rate specific to each technology using the WACC. A high WACC is required to run very large power plants [55].

The MSP can be expressed as [16]:

$$MSP = \frac{1}{PCE^{*}I_0}(MC + OH + WACC) \tag{3}$$

where MC is the direct manufacturing cost of the module, OH is the overhead cost associated with module manufacturing (including sales, general, and administrative costs, research and development, taxes & interest), and the required WACC. Companies typically specify the cost of PV modules in terms of peak power (Wp) rather than module area (m^2). Thus, the PCE of the module and the incident irradiance I_0 are the important parameters to be estimated [56]. Thus, the cost per unit area can be calculated by dividing the product of the module's PCE and the incident solar irradiance (I_0) at AM 1.5 G illumination by the MSP.

$$\mathrm{Cost}/Wp = \left(\mathrm{Cost}/m^2\right)/(PCE^{*}I_0) \tag{4}$$

The assumed OH equivalent to 20 % of operating revenue and factoring in taxes on operating profit, along with the recommendations of commonly experienced rates of debt (8 %) and equity (10 %) for WACC calculations, which serves as the expected IRR for the PV manufacturing industry [42,53,57], we can establish a financial framework. For a perovskite PV module, the power dissipated at a given irradiance I_0 (depends on the site) can be represented in relation to the module's PCE, its area (A), and the rate of degradation (r) over its operational lifespan (n). This relationship can be expressed mathematically through an equation.

$$P = \sum_{t=1}^{n} I_o \times PCE \times A \times r^t \tag{5}$$

Levelized cost of energy (LCOE)

Levelized Cost of Energy (LCOE) is a critical metric for evaluating the economic viability of PV electricity compared to other sources [58]. It facilitates a long-term cost comparison with conventional generation, informing grid parity assessments. LCOE depends on system size, supplier, and geographical factors [59,60]. Accurate LCOE values are essential for informed technological decisions and policy direction at local and global levels.. Contrary to misconceptions, PV costs have declined significantly, reaching competitiveness with conventional sources in many regions [58]. Electricity cost also hinges on the marginal cost of generation and market regulations [61].

The LCOE method offers a technology-agnostic benchmark for cost-effectiveness. It considers future cost assumptions, lifetime energy generation, and estimated cost per unit of energy produced, excluding risk factors and specific financing methods [43,54,62,63]. Accurate assumptions are crucial for effective policymaking. Several factors influence LCOE, including location, generation capacity, efficiency, and operational capacity [58].

By calculating the LCOE of a PV system, we can estimate the long-term cost per unit of electricity produced by the system over its lifetime.

$$\mathrm{LCOE}\ (\$/\mathrm{MWh}) = \mathrm{life\ time\ of\ cost}\ (\$)/\mathrm{life\ time\ of\ energy}\ (\mathrm{MWh})$$

If C_t is the total cost, and E_t is the energy in kWh in the t^{th} year, DR is the discount rate, and n is the life span of the PV system, then the LCOE is [13,58,59]:

$$LCOE = \frac{\sum_{t=0}^{n}\frac{C_t}{(1+DR)^t}}{\sum_{t=0}^{n}\frac{E_t}{(1+DR)^t}} \tag{6}$$

The energy produced per year (Et) for a PV power plant depends on the power rating (P) of the PV array, the annual solar insolation (Q), the loss factor (L), and the rate of degradation (r). This can be expressed mathematically as:

$$E_t = Q^{*}PCE^{*}A^{*}(1-L)(1-r)^t \tag{7}$$

The total energy generated throughout the lifespan of the PV power plant can be calculated as:

$$E = Q \times PCE \times A \times (1-L)\sum_{t=1}^{n}(1-r)^t \tag{8}$$

For this study, insolation data from previous literature conducted by Benti et al. [64,65] (supplemental information) was used. Losses can occur due to shading and connecting elements of the circuit, while degradation of the perovskite PV module can result from intrinsic and extrinsic exposures.

The annual cost of the system (C_t), can be expressed in terms of the initial installation cost (I_t), the operating cost (O_t), maintenance cost (M_t), and the financial cost (F_t) in year t year:

$$C_t = I_t + O_t + M_t + F_t \tag{9}$$

It should be noted that the initial cost presented in Equation (9) was annualized during the analysis.

The initial installation cost includes the costs of the PV modules, inverters, wiring, labor, overhead costs, grid interconnection, land fees, and taxes, and contributes significantly to the total cost of the PV system.

By substituting equations (9) and (8) into equation (6), the LCOE can be expressed as [58]:

$$LCOE = \frac{\sum_{t=0}^{n}(I_t + O_t + M_t + F_t)/(1+DR)^t}{\sum_{i=0}^{n}\left(Q \times PCE \times A \times (1-L)((1-r)^t\ )/(1+DR)^t\right.} = \frac{NPV_{CAPEX} + NPV_{OPEX}}{NPV_{generation\ CAPEX}} \quad (10)$$

Equation (10) defines the NPV as a function of the NPV of CAPEX and NPV of OPEX over a specified period of time. The PV CAPEX describes the present value of the expenditure required to setup the manufacturing facility. The PV OPEX expresses the present value of all operational costs over the defined time period, including manufacturing costs, overheads, and other operating expenditures.

The manufacturing cost of a PV module includes the initial investment cost and other associated costs, while the LCOE depends on manufacturing cost reductions and the financing system [66–68].

Other parameters used in the techno-economic analysis of a PV system include the energy payback time (EPBT) and the energy return on energy investment (EROI), which can be expressed as [69]:

$$EPBT(year) = \frac{E_{in}}{E_{out}} \quad (11)$$

$$EROI = \frac{Lifetime}{EPBT} \quad (12)$$

where E_{in} is the primary energy demand of the PV module, and E_{out} is the annual energy generated.

The EPBT can also be simply referred to as “payback time.” It is defined as the ratio of the total primary energy required to produce the PV system to the annual energy output of the system. Although both the numerator and denominator represent energy quantities, the numerator refers to the total energy input (in kWh), while the denominator represents the annual energy generation (in kWh/year). As a result, the unit of EPBT is expressed in years. The EPBT can be less than or greater than one year, depending on how quickly the system can recover the energy invested in its production. This depends on both the total energy invested and the annual energy generated by the system.

The energy output per year (Eout) for a PV power plant depends on the incident irradiance (I_0), the PCE, the performance ratio (PR) of the actual energy output to the theoretical energy output, and the efficiency conversion factor from energy to electricity (ε), which can be expressed as.

$$E_{out} = I_0 \times PCE \times PR \times \varepsilon \quad (13)$$

The energy output also depends on the rate of degradation and other losses due to shading. The performance and sustainable lifetime to operate at the maximum power output determine the viability of PV projects. Reports show that PV systems with an annual degradation rate of 0.5–1.0 % can still be financed [58,70]. However, perovskite PV has higher rate of degradation with lower manufacturing cost to compensate it. For this analysis, a PCE of 24 %, a degradation rate of 3 %, and a lifespan of 25 years were assumed. Most PV modules stabilize immediately after very fast degradation at the initial stage of illumination [15,71,72].

The efficiency conversion factor ε (epsilon) in equation (13) refers to the overall system conversion efficiency, which accounts for not only the PCE of the perovskite PV cell itself, but also other losses associated with module integration, balance of system (BOS), and operational conditions such as temperature, soiling, and degradation. While the PCE is just specific the perovskite PV cell-level efficiency under standard testing conditions. In estimating total energy generation, the use of ε offers a more practical and realistic approach.

Manufacturing costs include materials, equipment, utilities, labor, building, maintenance, and overheads, while operating costs include the annual cost of maintaining and repairing damaged parts of the PV system, such as modules and inverters. Financial costs include debt interest, insurance tax, incentives, and the internal return of capital investment. One important parameter used to describe the viability of local manufacturing is the payback period, defined as the investment cost per return per year. A lower payback period indicates a more viable project. Therefore, the analysis includes the cost incurred in each step of the process, broken down into main components. Identifying the materials required for manufacturing is integral for each step. Information about the required materials, equipment items, and existing manufacturing costs has been collected from various sources, such as vendors, literature, policy documents, and case reports [15].

Another important parameter used for comparison with the selling price of electricity to check viability is the LCOE. To assess the potential economic viability of a 100 MW/year of PSC power plant to be installed in Ethiopia, we calculated its LCOE based on estimated costs for 2023 [42,73]. However, it’s important to consider that perovskite technology is still under development and may take several years before commercialization [74]. The LCOE is particularly sensitive to the lifespan of the PSC modules, with lower LCOE values indicating greater cost-effectiveness. Some studies have assumed a module efficiency of 70 % relative to cell efficiency for their LCOE calculations [56]. Fig. 2 illustrates the perovskite-silicon tandem device architecture utilized as the basis for the techno-economic analysis.

A techno-economic analysis of perovskite PV module manufacturing reveals challenges to their viability. Traditional materials like gold electrodes and mesoporous structures inflate costs due to expensive components like gold, Spiro-OMeTAD, and TiO_2. To address this, research is shifting towards more cost-effective alternatives. Promising options include carbon/copper electrodes (demonstrating a PCE of 20.8 %) and planar device architectures. Additionally, exploring alternative hole transport materials beyond Spiro-OMeTAD is crucial. By targeting a 25-year lifespan and a module PCE of 24 % (a 34 % improvement over perovskite-silicon tandems cells [76]), this approach aims to achieve cost competitiveness with the established silicon PV market. [56,76,77].

Considering a wastage rate of 5 % for a 100 MW/year production line [56], material costs are estimated through extrapolation from lab-scale costs, utilizing prices from various grades and suppliers, with relevant equipment sets sourced accordingly [78]. The analysis employs Monte Carlo simulation to assess manufacturers’ decisions probabilistically through random number generation, conducting ten thousand iterations to derive mean values for key techno-economic metrics.

Efforts are directed towards modeling risks and associated policy issues for inclusion in the analysis calculation. Notable assumptions include the discount rate, average system price, financing method, expected lifespan, shading loss of PV modules, and degradation rate, all crucial in calculating the LCOE. Financial parameters such as interest rates, equity-to-debt ratios, and discount rates must be factored in, alongside considerations of inflation, incentives, tax credits, depreciation, and carbon credits, tailored to the specific analysis model employed [58].

The manufacturing cost of Perovskite modules encompasses several components, including consumables and chemicals required for the desired device architecture, equipment costs, and depreciation. Additionally, there are expenses related to building rent or purchase, labor, maintenance and operations, utilities, research and development (R&D), and selling, general, and administrative (SG&A) costs. A techno-economic analysis model conducted in 2020 for Perovskite-silicon tandem devices utilized module power conversion efficiency (PCE) of 18 %, while the cell PCE stood at 29 %. However, with advancements, the PCE of such tandem devices has been increased to 34 %, prompting the adoption of a 24 % model for the PV module in current analyses [77].

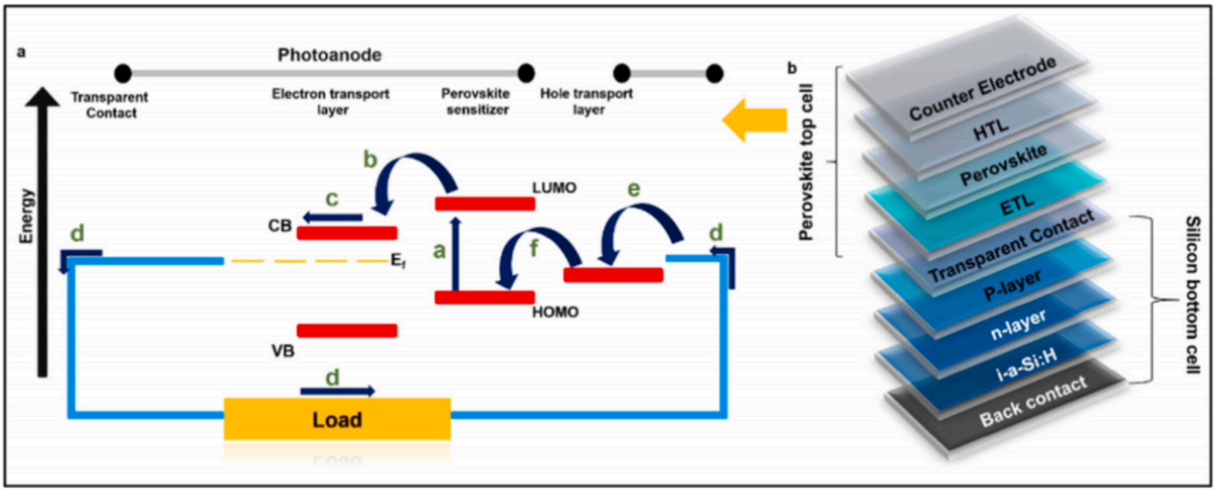

Fig. 2. Perovskite-silicon tandem device architecture. Reprinted from [75] copy right 2021, with permission from Elsevier.

Results and discussion

Cost breakdown and economic metrics

In this study, we have conducted a comprehensive analysis of the manufacturing cost and viability metrics for perovskite PV modules. The manufacturing cost is calculated to be \$0.29/Wp or \$6**9.6** /m^2, inclusive of materials, utilities (such as water and electricity), labor, equipment, and maintenance (see supporting information). The reported cost of \$30–41/m^2 in the U.S. reflects optimized, large-scale production under mature industrial conditions with well-established supply chains and infrastructure. However, this figure does not include several key economic metrics considered in our analysis.

In contrast, our estimated cost of approximately \$70/m^2 for Ethiopia accounts for realistic local conditions, incorporating additional factors such as higher indirect costs (e.g., labor training, capital depreciation, inflation, and limited infrastructure). These contextual differences do not contradict the U.S. estimate but rather reinforce the objective of this study to critically assess the techno-economic viability of production in emerging markets like Ethiopia.

The MSP is determined to be \$0.38Wp or \$91.2/m^2. Comparing these costs with manufacturing costs in the United States, it is evident that establishing perovskite PV manufacturing in Ethiopia is highly cost-effective, especially when considering direct costs. The US cost analysis does not consider depreciation and overhead cost [16].

The material and labor cost components of the perovskite-silicon tandem device are significantly higher than other costs (equipment, utilities, and rent). Material cost, accounting for 55 %, emerges as the dominant cost factor for a perovskite PV module (Fig. 3a). This finding is supported by a techno-economic analysis of perovskite module manufacturing conducted by Song et al. [16]. The material cost includes components for direct PSCs manufacturing and other parts necessary for module operation, known as the balance of module (BOM).

The BOM components protect the device from degradation caused by moisture ingress into the perovskite. The cost of the absorber layer is higher than that of the transport layer and the electrode costs (Fig. 3b). This suggests that replacing Spiro-OMeTAD and gold with alternative HTL and metallic electrode, respectively, can reduce the manufacturing cost of perovskite PV modules. Utilizing materials with high absorption coefficients can further reduce the cost required for the absorber layer.

Various metrics were used in this techno-economic analysis to assess the viability of local manufacturing of perovskite PV modules. These metrics include NPV, IRR, PBT, PI, and LCOE. Using Monte Carlo simulation, the net present value of the project was found to be positive, with an internal rate of return of approximately 12 %. The payback period was estimated to be between 7 and 8 years, and the profitability index of the project is 1.2. The average rate of return is on observed to be 10.5 %, which is higher than the calculated WACC rate (9.1 %). These economic metrics indicate that local manufacturing of peroskite PV in Ethiopia is financially viable project.

Levelized cost of energy (LCOE)

In our cost model calculation, the LCOE for perovskite PV is estimated to be \$0.019/kWh. Comparing this to the selling price of electricity from the Ethiopian Electric Power Authority, which is \$0.027/kWh, the LCOE of perovskite PV is below the selling price. This indicates that local manufacturing of perovskite PV modules in Ethiopia is highly

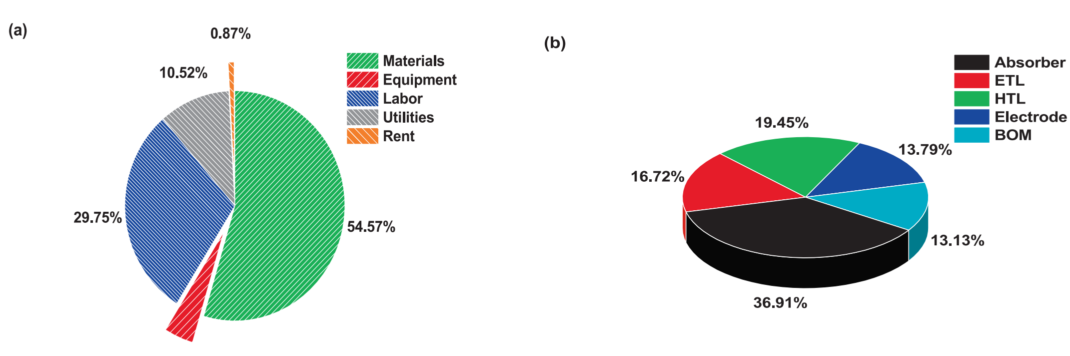

Fig. 3. A pie chart depicting the breakdown of the capital expenditure (CAPEX) and operational expenditure (OPEX) percentages for manufacturing Perovskite PV modules.

viable from an economic point of view. One of the key factors contributing to this viability is the availability of minerals necessary for the local manufacturing of perovskite PV cells in Ethiopia, along with proposed extraction techniques. Additionally, the cost of skilled and semi-skilled labor is relatively lower in Ethiopia, further supporting the economic feasibility of local manufacturing.

The LCOE of perovskite PV decreases as the lifespan of the PV module increases, as shown in Fig. 4. This relationship is expected, as a longer lifespan means the energy generation from the device can be maintained for a longer period, leading to a lower LCOE. This indicates that customers can benefit from using perovskite PV technology at an affordable cost, lower than the selling price of electricity.

Stability remains a major challenge for perovskite technology, but considering the lifespan as a variable parameter in the techno-economic analysis is promising. It allows for a more accurate assessment of the economic viability of perovskite PV technology by accounting for its potential for long term and sustainable energy generation.

It is important to note that the LCOE calculation incorporates both the initial PCE and its degradation over time, as described by Equations (8) and (10). A performance degradation rate has been incorporated into the LCOE model to represent the annual decline in energy output per PV module due to reduced PCE, aging, and operational losses. This rate is applied to the annual energy generation across the system's lifetime, ensuring that the LCOE accurately reflects the diminishing output as the module ages.

LCOE and related parameters

The LCOE is influenced by many factors, including the lifespan of the PV module and its PCE. A longer lifespan allows for returns over a longer period, even at a low LCOE, as the two parameters are inversely related. Fig. 5 illustrates the relationship between the life span PCE of a perovskite PV module. The exponential decline in PCE over the module's operational lifetime directly influences its energy output, which, in turn, affects the LCOE. This indicates the significant role of both efficiency and stability in determining the economic viability of perovskite PV technologies. The degradation of PCE can be modeled by the exponential function:

$$\eta = \eta_0 \exp(-(t/\tau))$$

where η represents the PCE at any time and η_0 denotes the initial PCE, τ is the characteristic lifetime constant, which quantifies the rate of efficiency degradation over time.

Besides, the LCOE is impacted by the PCE of the PV module. A higher PCE results in increased energy generation, leading to a decrease in the LCOE. Perovskite PV modules exhibit a lower LCOE compared to silicon PV technology and hydropower, as shown in Fig. 6, indicating that perovskite PV can be manufactured at a more affordable cost compared to silicon counterparts. The results presented in the bar graph are consistent with current trends in the respective technologies: the lower LCOE values for perovskite PV align with the optimistic projections for its future commercialization, the LCOE for silicon PV reflects typical costs for existing manufacturing processes, and the value for hydropower is representative of small-scale irrigation projects, where initial capital costs and site-specific conditions influence the overall cost-effectiveness.

The reference device, perovskite/silicon tandem, can achieve a PCE of 34 %, although the module PCE drops to 24 %. Fig. 7a demonstrates that as the PCE increases, the LCOE decreases, suggesting a shorter payback period and viability even at lower selling prices for electricity.

Inflation plays a critical role in the LCOE. As inflation increases, manufacturing costs rise, leading to an increase in the LCOE to compensate. This increase in the selling price of the technology can make local manufacturing more expensive for customers, underscoring the importance of managing inflation in policy considerations (Fig. 7b).

Initiating the technology with sufficient initial investment can lead to the design of highly efficient perovskite modules, as shown in Fig. 8a, which can decrease the LCOE. Conversely, reducing the initial investment may result in a lower efficiency and higher LCOE, impacting the expected return for the WACC.

In Fig. 8b, we illustrate how the LCOE varies with the WACC. As WACC increases, the cost of financing capital investments also rises, leading to a higher annual capital cost component of the LCOE. This effect is particularly significant for emerging technologies like perovskite photovoltaics, which involve substantial upfront costs.

Fig. 9 illustrates two key aspects of the economic performance of perovskite PV modules. Fig. 9a shows that the LCOE increases significantly with higher degradation rates, indicating the reduced energy output over time. It means that stable perovskite PV modules with long-term stability offer greater economic viability for local manufacturing. This implies that even modest improvements in long-term stability can substantially enhance the overall economic performance. This reaffirms that enhancing the intrinsic stability of perovskite materials, along with improved encapsulation techniques, can significantly contribute to the economic viability of local manufacturing. Fig. 9b illustrates the relationship between capital investment cost and module lifespan. The

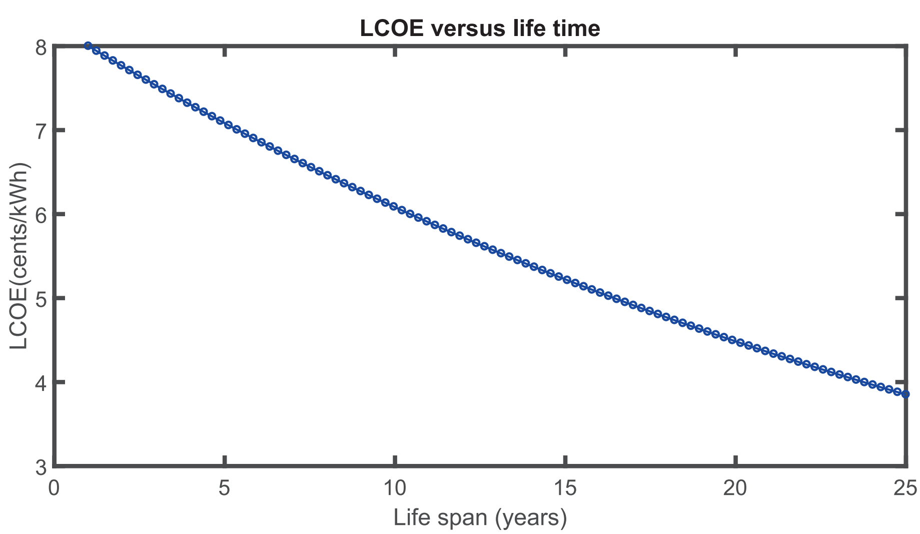

Fig. 4. Levelized cost of energy versus life span of a perovskite PV module. This relationship illustrates how extending the module's lifespan reduces LCOE by distributing initial capital costs and operational expenditures over a longer period, while considering degradation, discount rates, and annual maintenance costs.

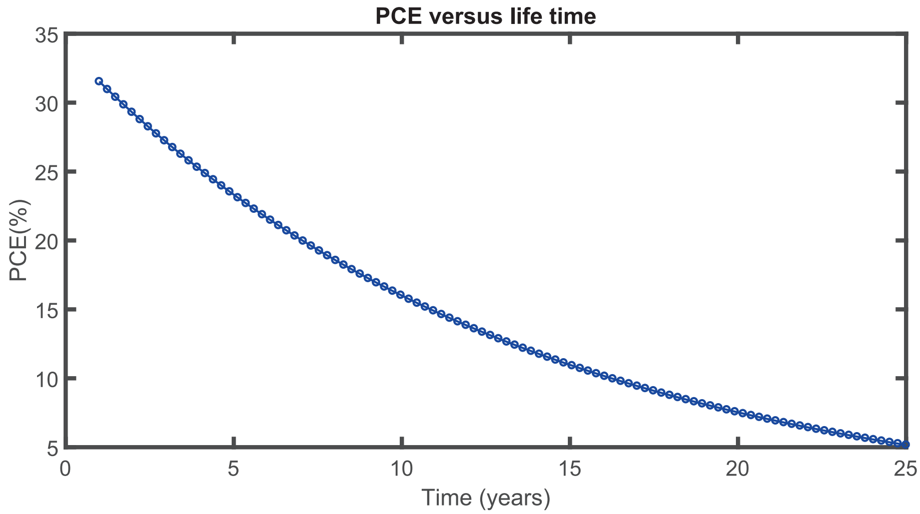

Fig. 5. Life span versus PCE of a perovskite PV. It describes the relationship between the operational lifetime PCE of a perovskite photovoltaic module, illustrating the exponential degradation of PCE over time.

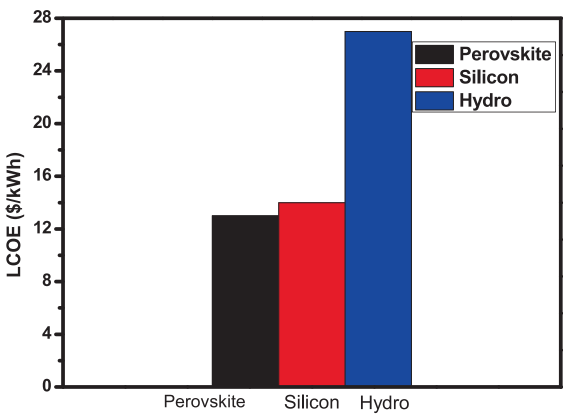

Fig. 6. LCOE of different power plants consisting of perovskite PV, silicon PV, and hydropower.

result indicates that extending the module lifespan enables capital costs to be distributed over a longer period of energy generation, thereby enhancing economic viability. This trend emphasizes the importance of achieving longer operational lifespans for cost competitiveness, especially in high-inflation or capital-constrained settings. Collectively, these findings highlight the strong interdependence between technological durability and economic feasibility in emerging photovoltaic technologies.

Reducing production costs by half could significantly promote the market for perovskite technology if the PCE and lifespan are comparable to conventional c-Si modules. The high PCE, along with low-tech production using cost-effective materials, makes PSCs economically viable for local manufacturing and commercialization. The decreasing LCOE of PSCs facilitates their commercialization [76]. Achieving equilibrium between perovskite-silicon tandems poses a challenge due to their disparate manufacturing methodologies. Perovskite fabrication often employs a cost-effective solution processing approach, offering lower capital expenditure. Conversely, silicon manufacturing demands substantial capital investment [77].

In conclusion, the analysis suggests that local manufacturing of perovskite PV modules in Ethiopia is highly viable due to factors such as availability of minerals, skilled labor, and lower costs. However, careful consideration of factors such as inflation, initial investment, and electrode materials is crucial for ensuring the economic viability of these projects. Recently, solar manufacturing costs significantly decreases rapidly, the life time of inverters prolonged, installation are supported by technologies and their costs reduced [79]. The utility cost of electricity in Ethiopia, categorized under the business sector, stands at $0.027 kWh [80]. This rate is notably lower than the benchmark assumed in Martin et al.'s study on the techno-economic analysis of PSC [81].

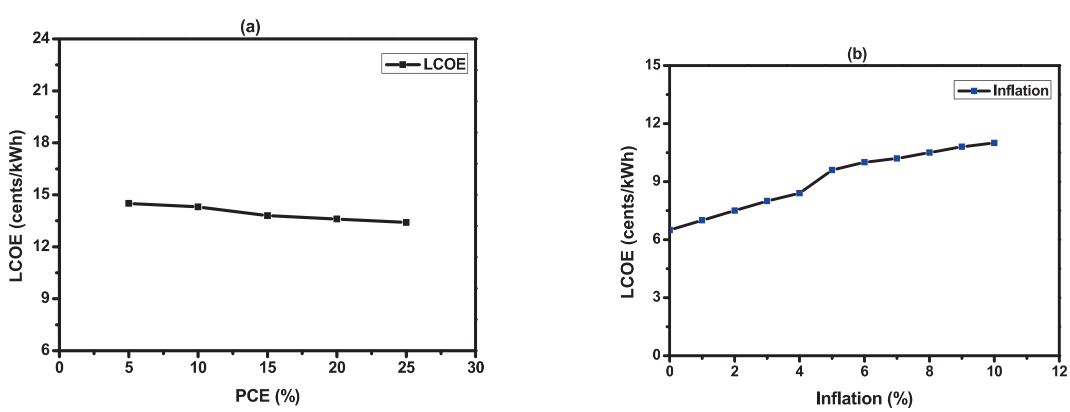

Fig. 7. Analysis of LCOE for Perovskite Photovoltaics. (a) Impact of PCE on LCOE, and (b) Variation of LCOE with inflation of Perovskite PV.

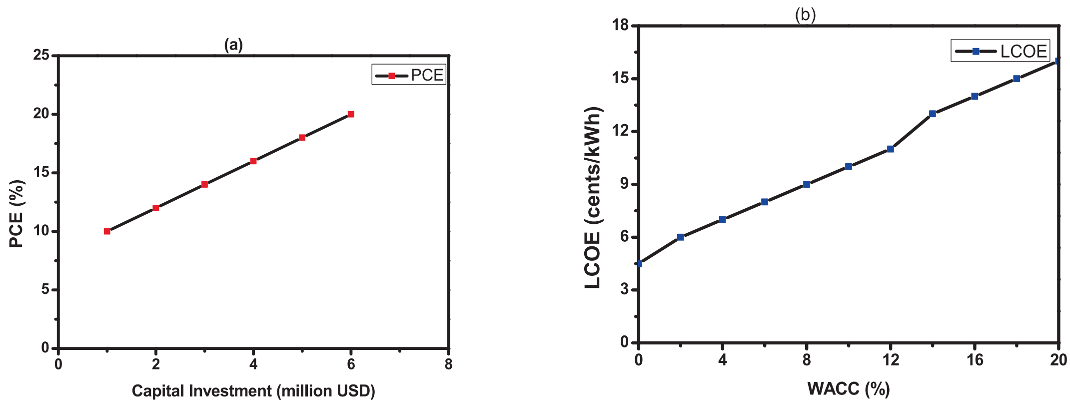

Fig. 8. Economic Analysis of Perovskite Photovoltaics. (a) PCE versus capital investment cost (b) variation of LCOE with WACC.

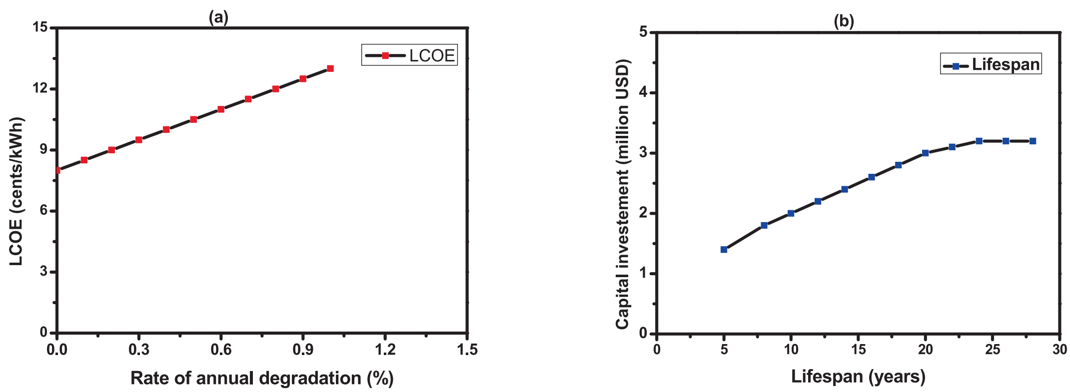

Fig. 9. Impact of Degradation and Lifespan on the Economics of Perovskite Modules. (a) Variation of LCOE with rate of degradation and (b) capital investment cost versus lifespan of a perovskite module.

Limitations of the study

Multiple metrics have been taken into consideration in this comprehensive techno-economic analysis of perovskite PV manufacturing. Nevertheless, several important limitations are associated with this analysis, including the reliance on assumptions and extrapolations from lab-scale cost data and vendor inputs, uncertainties related to technology adaptation and learning curves, and the absence of real-world data for validation.

Assumptions and extrapolations from lab-scale costs and vendor data is observed to be the primary based cost estimates used in this study. However, these may not accurately reflect the realities of large-scale manufacturing. Lab-scale technologies often overlook real-world challenges such as equipment scaling, yield losses, and the complexities of handling high production volumes. As a result, there is an inherent uncertainty in how these extrapolated figures will translate into actual manufacturing costs when the technology is deployed at a commercial scale. Moreover, vendor data is subject to significant market fluctuations and rapid technological advancements, making it difficult to use for reliable future cost predictions. The prices of materials, equipment, and related components often vary due to changes in global supply and demand, as well as geographic and logistical factors. Additionally, the assumptions used in this analysis do not fully account for the complexities of technology transfer and the localization of perovskite production in Ethiopia, which may result in discrepancies between the projected and actual cost structures.

Another key limitation is the uncertainty related to technology adaptation and learning curves. While the learning curve for perovskite manufacturing is expected to follow a trajectory similar to that of other photovoltaic technologies, there is currently no clear strategy outlining how local manufacturers in Ethiopia plan to adopt perovskite technology to achieve the desired cost reductions compared to conventional silicon PV. Critical factors such as workforce skills, availability of training programs, and the level of technical expertise within the country will significantly influence the extent and pace of these cost reductions.

Since perovskite technology is still in the research and development phase, there is currently no real-world operational data available for validation. Most of the data used in this study is derived from limited pilot-scale testing. Although some performance and stability studies exist at the cell level, there is a lack of large-scale, real-world data on perovskite module performance, particularly under Ethiopia's unique environmental and economic conditions. As a result, assumptions regarding module efficiency, degradation rates, and long-term material stability remain uncertain and may change as more empirical data becomes available. This represents an additional limitation of the study.

Conclusion

In this study, we conducted a detailed and comprehensive techno-economic analysis aimed at evaluating the potential for local manufacturing of perovskite PV modules in Ethiopia. A bottom-up approach to cost modeling was employed, which allows for an in-depth assessment of all cost components and assumptions such as raw material, equipment, labor, and financial parameters using recently updated data. The focus was on perovskite-silicon tandem PV modules, which are recognized for their advanced performance characteristics. These modules are reported to achieve a cell efficiency of 34 % and a module efficiency of 24 %. Furthermore, their output power is expected to reach 240 W/m^2 under standard air mass 1.5 G conditions.

To ensure that the perovskite PV modules remain competitive with existing PV technologies, we considered key performance parameters such as a module lifespan of 25 years and an annual degradation rate of 3 %. These assumptions reflect realistic operating conditions while highlighting areas where further technological advancements could enhance performance. The analysis incorporated a wide range of cost factors associated with manufacturing. These include the cost of raw materials, specialized equipment, labor, utilities, and rent, as well as financial considerations such as the discount rate, overhead costs, depreciation, and ongoing operation and maintenance expenses. By accounting for these variables, we provided a holistic understanding of the economic landscape for manufacturing perovskite PV modules locally.

To support the economic viability of local manufacturing, we recommended several policy measures designed to mitigate financial barriers and attract investment. These measures include reducing inflation and income tax rates and setting favorable values for the weighted average cost of capital (WACC) and internal rate of return (IRR). Such interventions would be important for establishing sustainable production line with an annual capacity of 100 MW. By implementing these strategies, Ethiopia can create a conducive environment for the growth of its PV manufacturing sector, ultimately supporting the broader adoption of renewable energy technologies.

The financial analysis of the project also involved calculating the net present value (NPV) of the capital expenditure (CAPEX). This calculation took into account all relevant cost components, including site-specific factors like insolation levels, the power conversion efficiency (PCE) of the modules, degradation rates, and other performance-related losses. These inputs allowed us to estimate the net present value of energy generation over the module's operational lifespan. From this analysis, we have obtained a LCOE of \$0.019/kWh, which is significantly lower than the current national average electricity cost of \$0.027/kWh. This demonstrates that locally produced perovskite PV modules can provide cost-competitive renewable energy solutions while reducing dependence on imports. The results highlight the potential for Ethiopia not only to meet its domestic energy demand but also to support industrial growth through affordable, high-efficiency solar technologies. With its abundant solar resource and availability of key raw materials, Ethiopia is well positioned to leverage perovskite PV manufacturing to achieve significant cost reductions in energy generation.

Future research should focus on enhancing the module the performance and durability, extending the module lifespan by reducing the rate of degradation, and optimizing tandem configurations to further improve performance and drive down costs. These advancements would lower costs, strengthen the competitiveness of perovskite PV in Ethiopia's energy mix and accelerate progress toward long-term sustainability and energy security. The scope of this analysis can be extended to evaluate the financial viability of perovskite-silicon tandem solar cells in greater detail. Future studies could model the potential of these advanced modules to reduce PV manufacturing costs further and support the expansion of renewable energy markets. Additionally, the use of bottom-up cost modeling and sustainable growth calculators can provide valuable insights into scaling production and identifying suitable funding mechanisms. These tools are especially useful for start-ups and emerging enterprises in the technology manufacturing sector, offering a pathway to sustainable and economically viable operations.

In general, this study provides a robust framework for assessing the local manufacturing potential of perovskite PV modules in Ethiopia. By addressing both technological and economic considerations, this analysis lays the groundwork for the successful integration of advanced PV technologies into Ethiopia's energy landscape, thereby contributing to sustainable development and energy independence.

CRediT authorship contribution statement

Getnet M. Meheretu: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ababay Ketema Worku:** Writing – review & editing, Supervision. **Moges T. Yihunie:** Writing – review & editing, Supervision. **Richard K. Koech:** Writing – review & editing, Supervision. **Getasew A. Wubetu:** Writing – review & editing, Supervision.

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.

Acknowledgements

This work was supported by the Intra-Africa Academic Mobility Scheme under Mobility for Renewable Energy Technologies (MIRET) (grant number 2019–1973/006–001), and Bahir Dar University. Thus, the author acknowledges the support of both institutions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2025.101274.

Data availability

Data will be available upon request from the corresponding author.

References

[1] Cariou R, et al. III-V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration. Nat Energy 2018;3(4):326–33. https://doi.org/10.1038/s41560-018-0125-0.

[2] Roy P, Khare A. An analysis of an efficient and eco-friendly CsGeSnI3 based perovskite solar cell: A theoritical study, vol. 44. 2021.

[3] Ghosh A, Dipta SS, Nikor SSS, Saqib N, Saha A. Performance analysis of an efficient and stable perovskite solar cell and a comparative study of incorporating metal oxide transport layers. J Opt Soc Am B 2020;37(7):1966–73. https://doi.org/10.1364/JOSAB.391817.

[4] Wang Y, et al. Recent progress in developing efficient monolithic all-perovskite tandem solar cells. J Semicond 2020;41(5):1–11. https://doi.org/10.1088/1674-4926/41/5/051201.

[5] Zhao Y, Fei Ma AJY, Gao F, Yin Z, Zhang X. Research progress in large-area perovskite solar cells. Photonics Res 2020;8(7):1–15. https://doi.org/10.1364/PRJ.392996.

[6] Park NG, Zhu K. Scalable fabrication and coating methods for perovskite solar cells and solar modules. Nat Rev Mater 2020;5(5):333–50. https://doi.org/10.1038/s41578-019-0176-2.

[7] Zhao B, et al. Efficient light-emitting diodes from mixed-dimensional perovskites on a fluoride interface. Nat Electron 2020;3(11):704–10. https://doi.org/10.1038/s41928-020-00487-4.

[8] Keremane KS, et al. Improving the performance of carbon-based perovskite solar modules (70 cm2) by incorporating cesium halide in mesoporous TiO2. ACS Appl Energy Mater 2021;4(1):249–58. https://doi.org/10.1021/acsaem.0c02213.

[9] Aldo Di Carlo, Outdoor performance evaluation of a 2D materials-based perovskite solar farm,Nat Energy 2022;7(7):580–1. https://doi.org/10.1038/s41560-022-01037-2.

[10] Pescetelli S, et al. Integration of two-dimensional materials-based perovskite solar panels into a stand-alone solar farm. Nat Energy 2022;7(7):597–607. https://doi.org/10.1038/s41560-022-01035-4.

[11] De Bastiani M, et al. Efficient bifacial monolithic perovskite/silicon tandem solar cells via bandgap engineering. Nat Energy 2021;6(2):167–75. https://doi.org/10.1038/s41560-020-00756-8.

[12] Edition S. International Technology Roadmap for Photovoltaic (ITRPV) 2015, no. October, 2016.

[13] Asif AA, Singh R, Alapatt GF. Technical and economic assessment of perovskite solar cells for large scale manufacturing, J Renew Sustain Energy 2015;7(4), 10.1063/1.4927329.

[14] Cai, et al. Cost-Performance Analysis of Perovskite Solar Modules. Advanced Science 2016;news.":1–6.

[15] Barkhouse DAR, Gunawan O, Gokmen T, Todorov TK, Mitzi DB. Yield predictions for photovoltaic power plants:empirical validation,recent advances and remaining

uncertainties. Prog Photovolt Res Appl 2015;20(1):6–11. https://doi.org/10.1002/pip.
[16] Song Z, et al. A technoeconomic analysis of perovskite solar module manufacturing with low-cost materials and techniques. Energy Environ Sci 2017;10(6):1297–305. https://doi.org/10.1039/c7ee00757d.
[17] Meheretu GM, Yihunie MT, Wubetu GA. Performance and stability of hybrid organic-inorganic perovskite photovoltaics in outdoor illuminations conditions. Mater Res Express 2024;11(5):1–10. https://doi.org/10.1088/2053-1591/ad495b.
[18] Meheretu GM, Yihunie MT, Wubetu GA. The impact of charge carrier dynamics on the outdoor performance of cesium-lead-halide perovskite photovoltaics. Phys Scr 2024;99(11):115982. https://doi.org/10.1088/1402-4896/ad85af.
[19] Meheretu GM, et al. The recent advancement of outdoor performance of perovskite photovoltaic cells technology. Heliyon 2024;10(17):e36710. https://doi.org/10.1016/j.heliyon.2024.e36710.
[20] A. E. version translated by the E. of J. in E. based on an original report written in Japanese, "Study on the Energy Sector in Ethiopia," Proj. Apprais. , pp. 1–16, 2008.
[21] UNDP, "Quarterly Economic Profile of Ethiopia", no. March, 2023.
[22] Roose et al, Local manufacturing of perovskite solar cells, a game-changer for low- and lower-middle income countries?†, Environ Sci 2022;3571–3582, 10.1039/d2ee01343f.
[23] Kebede KY, Mitsufuji T, Islam MT. Building innovation system for the diffusion of renewable energytechnology: practices in ethiopia and Bangladesh, Procedia Environ Sci 2015; 28(SustaiN 2014);11–20, doi: 10.1016/j.proenv.2015.07.003.
[24] Glob. Photovolt. Power Potential by Ctry. 2020. https://doi.org/10.1596/34102.
[25] BA, "The study on the SWOT Analysis of Solar Energy in Ethiopia," Plast. Reconstr. Surg., vol. 136, no. 4, pp. 502e-510e, 2015, [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/26397269%0Ahttp://journals.lww.com/00006534-201510000-00032.
[26] Benti NE, Tadesse G. Feasibility study of solar photovoltaic (PV) Energy systems for rural villages of ethiopian somali region (a case study of Jigjiga Zone), Http://Www.Sciencepublishinggroup.Com, vol. 1, no. 2, p. 42, 2017, doi: 10.13140/RG.2.1.2860.5042.
[27] FDRE Planning and Development Commission, "Ten Years Development Plan: A Pathway to Prosperity," ten Years Dev. Plan A Pathw. to Prosper., vol. 2, no. ten years development plan., p. 86, 2021.
[28] Delhi N. Investment Opportunity in the Pharmaceutical Sector in Ethiopia, pp. 0–13, 2014.
[29] Lakew H, Hailu B, Hailu T, Carter S. A climate for solar power : Solutions for Ethiopia's energy poverty, no. December 2017, pp. 1–4, 2017.
[30] Assefa G. The mineral resources potential of Ethiopia. Bull Chen Soc Ethiop 1991;5(2):111–37.
[31] Power M. The goal MLAP organizational structure. Depression 1970.
[32] MoMP, Ministry of Mines and Pertoleum, Mining in Ethiopia, Investor Guide, 2020.
[33] Guesh K. Preparation , Characterization and Photocatalytic Application of TiO 2 Supported on Zeolites for Textile Wastewater Treatment, 2016.
[34] Zaky AA, et al. Energy efficiency improvement of water pumping system using synchronous reluctance motor fed by perovskite solar cells. Int J Energy Res 2020; 44(14):11629–42. https://doi.org/10.1002/er.5788.
[35] Ethio Research Group. Solar energy vision for Ethiopia : Opportunities for creating a photovoltaic industry in Ethiopia. 2012. p. 1–30.
[36] Hailu AD, Kumsa DK. Ethiopia renewable energy potentials and current state. AIMS Energy 2020;9(1):1–14. https://doi.org/10.3934/ENERGY.2021001.
[37] Yalew AW. The Ethiopian energy sector and its implications for the SDGs and modeling. Renew Sustain Energy Transit 2022;2(July 2021):100018. https://doi.org/10.1016/j.rset.2022.100018.
[38] Wazza MT. review on achievement of the sustainable development goals in Ethiopia By PBT Africa college, no. February, 2022, doi: 10.13140/RG.2.2.18854.80967.
[39] National Planning Commission (NPC), "Federal Democratic Republic of Ethiopia Volume I : Main Text," World Bank Gr., vol. I, no. GTP II, p. 236, 2016.
[40] Roose B. Perovskite Solar Cells, Energies. 2022. p. 14–6.
[41] Babics M, et al. Report One-year outdoor operation of monolithic perovskite / silicon tandem solar cells One-year outdoor operation of monolithic perovskite / silicon tandem solar cells, Cell Reports Phys Sci, vol. 4, no. 2, p. 101280, doi: 10.1016/j.xcrp.2023.101280.
[42] Horowitz KAW, Fu R, Woodhouse M, Renewable N, Parkway DW. an Analysis of Glass-Glass CIGSManufacturing Costs 2016.
[43] Paquin F, Rivnay J, Salleo A, Stingelin N, Silva C. Multi-phase semicrystalline microstructures drive exciton dissociation in neat plastic semiconductors. J Mater Chem C 2015;3:10715–22. https://doi.org/10.1039/b000000x.
[44] Sheng Huang HZ, Huang P, Wang L, Han J, Chen Y. Halogenated-methylammonium based three dimensional halide perovskites, Adv. Mater., pp. 1–24, doi: 10.1002/)).
[45] Ahn N, et al. Highly Reproducible Perovskite Solar Cells with Average Fabricated via Lewis Base Adduct of Lead (II) Iodide Highly Reproducible Perovskite Solar Cells with Average Efficiency of 18 . 3 % and Best Efficiency of 19 . 7 % Fabricated via Lewis Base Ad- duc, no. Ii, 2015, doi: 10.1021/jacs.5b04930.
[46] Krebs FC. Fabrication and processing of polymer solar cells: a review of printing and coating techniques. Sol Energy Mater Sol Cells 2009;93(4):394–412. https://doi.org/10.1016/j.solmat.2008.10.004.
[47] Hösel M, Dam HF, Krebs FC. Development of lab-to-fab production equipment across several length scales for printed energy technologies, including solar cells. Energy Technol 2015;3(4):293–304. https://doi.org/10.1002/ente.201402140.
[48] Razza S, et al. Perovskite solar cells and large area modules (100 cm2) based on an air flow-assisted PbI2 blade coating deposition process. J Power Sources 2015;277 (2015):286–91. https://doi.org/10.1016/j.jpowsour.2014.12.008.
[49] Schmidt TM, Larsen-Olsen TT, Carlé JE, Angmo D, Krebs FC. Upscaling of perovskite solar cells: fully ambient roll processing of flexible perovskite solar cells with printed back electrodes. Adv Energy Mater 2015;5(15):1–9. https://doi.org/10.1002/aenm.201500569.
[50] Mohamad et al, "Spray-Cast Multilayer Organometal Perovskite Solar Cells Fabricated in Air,Advanced Energy Materials." pp. 1–7, 2016, doi: 10.1002/aenm.201600994.
[51] Hösel, et al. Development of Lab-to-Fab Production Equipment Across Several Length Scales for Printed Energy Technologies Including Solar Cells. Energy Technology. 2015:293–304. https://doi.org/10.1002/ente.201402140.
[52] Walker A, et al. Model of Operation-and-Maintenance Costs for Photovoltaic Systems, Technical Report NREL, Nrel, no. June, 2020.
[53] Powell DM, Fu R, Horowitz K, Basore PA, Woodhouse M, Buonassisi T. The capital intensity of photovoltaics manufacturing: Barrier to scale and opportunity for innovation. Energy Environ Sci 2015;8(12):3395–408. https://doi.org/10.1039/c5ee01509j.
[54] Darling SB, You F, Veselka T, Velosa A. Assumptions and the levelized cost of energy for photovoltaics. Energy Environ Sci 2011;4(9):3133–9. https://doi.org/10.1039/c0ee00698j.
[55] Kost C, Shammugam S, Fluri V, Peper D, Memar AD, Schlegel T. Levelized cost of electricity- renewable energy technologies 2021, no. June, pp. 1–45, 2021, doi: 10.13140/RG.2.2.22457.08800.
[56] Chang NL, Ho-Baillie AWY, Vak D, Gao M, Green MA, Egan RJ. Manufacturing cost and market potential analysis of demonstrated roll-to-roll perovskite photovoltaic cell processes. Sol Energy Mater Sol Cells 2018;174(August 2017):314–24. https://doi.org/10.1016/j.solmat.2017.08.038.
[57] Fu R, James TL, Woodhouse M. Economic measurements of polysilicon for the photovoltaic industry: Market competition and manufacturing competitiveness. IEEE J Photovoltaics 2015;5(2):515–24. https://doi.org/10.1109/JPHOTOV.2014.2388076.
[58] Branker K, Pathak MJM, Pearce JM. A review of solar photovoltaic levelized cost of electricity. Renew Sustain Energy Rev 2011;15(9):4470–82. https://doi.org/10.1016/j.rser.2011.07.104.
[59] Joglekar N, Graber-Lopez E. A Countdown towards Solar Power at Grid Parity: Evolution of Price-Performance, Proc. 27th Int. Conf. Syst. Dyn. Soc., no. July, 2009.
[60] Denholm P, Margolis RM, Ong S, Roberts B. Break-Even Cost for Residential Photovoltaics in the United States: Key Drivers and Sensitivities Break-Even Cost for Residential Photovoltaics in the United States: Key Drivers and Sensitivities, Tech. Rep. NREL/TP-6A2-46909, no. December, p. 33, 2009, [Online]. Available: http://www.nrel.gov/docs/fy10osti/46909.pdf.
[61] International Energy Agency, "Canada 2022 - Energy Policy Review," Int. Energy Agency, p. 121, 2022, [Online]. Available: www.iea.org/t&c/.
[62] Koch W, Endrös AL, Franke D, Häßler C, Kalejs JP, Möller HJ. Bulk Crystal Growth and Wafering for PV 2005.
[63] Zweibel K, Mason J, Fthenakis V. By 2050 solar power could end U.S. dependence on foreign oil and slash greenhouse gas emissions. Sci Am 2008;298(1):64–73. https://doi.org/10.1038/scientificamerican0108-64.
[64] Benti NE, Aneseyee AB, Asfaw AA, Geffe CA, Tiruye GA, Mekonnen YS. Estimation of global solar radiation using sunshine-based models in Ethiopia, Cogent Eng, vol. 9, no. 1, 2022, doi: 10.1080/23311916.2022.2114200.
[65] Tanashu M. Innovative energy & research solar and wind resource assessment fo r technoeconomic. Feasibly Study 2021;10(2):2–6.
[66] Agency IE. Technology Roadmap Solar photovoltaic energy. 2010.
[67] Singh PP, Singh S. Realistic generation cost of solar photovoltaic electricity. Renew Energy 2010;35(3):563–9. https://doi.org/10.1016/j.renene.2009.07.020.
[68] U. M. D. E. C. D. E. Los, U.S. Department of Energy (DOE). Solar energy technologies program: multiyear program plan 2007–2011. Washington, DC; 2006. p. 1–66.
[69] Celik I, et al. Energy payback time (EPBT) and energy return on energy invested (EROI) of perovskite tandem photovoltaic solar cells. IEEE J Photovoltaics 2018;8 (1):305–9. https://doi.org/10.1109/JPHOTOV.2017.2768961.
[70] Cambell M. The Drivers of the Levelized Cost of Electricity for Utility-Scale Photovoltaics, Sunpower, p. 21, 2008, [Online]. Available: sunpowercorp.com.
[71] Realini A. MTBF - PVm Mean Time Before Failure of Photovoltaic Modules, Supsi, Dacd, Leee-Tiso, no. June, pp. 1–58, 2003.
[72] Ruther R, Cuet J, Montenegr AA. Climates - Year Four: Progress In Understanding Exposure History, 2010.
[73] Albertus, et al. Technology advances needed for photovoltaics to achieve widespread grid price parity. Progress in Photovoltaics. 2016:1272–83.
[74] Battaglia C, Cuevas A, De Wolf S. High-efficiency crystalline silicon solar cells: status and perspectives. Energy Environ Sci 2016;9(5):1552–76. https://doi.org/10.1039/c5ee03380b.
[75] Akhil S, et al. Review on perovskite silicon tandem solar cells: Status and prospects 2T, 3T and 4T for real world conditions. Mater Des 2021;211:110138. https://doi.org/10.1016/j.matdes.2021.110138.
[76] Roy A, et al. Certified high-efficiency 'large-area' perovskite solar module for Fresnel lens-based concentrated photovoltaics. iScience 2023;26(3):106079. https://doi.org/10.1016/j.isci.2023.106079.
[77] Mathews I, et al. Economically sustainable growth of perovskite photovoltaics manufacturing. Joule 2020;4(4):822–39. https://doi.org/10.1016/j.joule.2020.01.006.
[78] Krebs FC, Tromholt T, Jørgensen M. Upscaling of polymer solar cell fabrication using full roll-to-roll processing. Nanoscale 2010;2(6):873–86. https://doi.org/10.1039/b9nr00430k.

[79] A. C. F. and C. R. E. I. A. Sustainable Energy for All, supported by Bloomberg Philanthropies, ClimateWorks Foundation, “Africa Renewable Energy Manufacturing: OPPORTUNITY AND ADVANCEMENT,” 2022.
[80] Utility EE. Current High-Level Electricity Tariffs by different user categories. 2016.
[81] Martin B, Amos D, Brehob E, van Hest MFAM, Druffel T. Techno-economic analysis of roll-to-roll production of perovskite modules using radiation thermal processes. Appl Energy 2022;307:1–38. https://doi.org/10.1016/j.apenergy.2021.118200.