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Techno-economic assessment and stakeholder perspectives on agrivoltaics in East Africa

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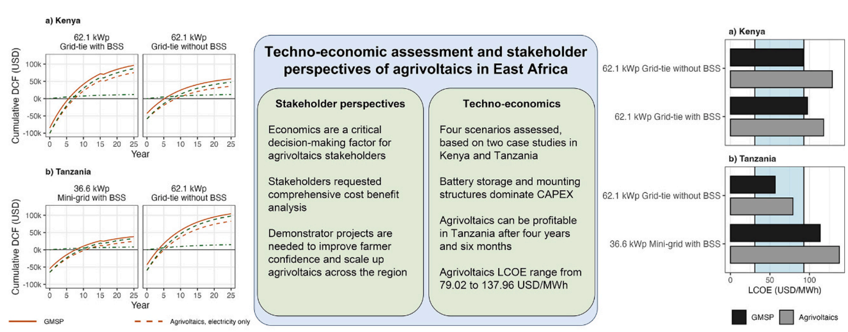
HIGHLIGHTS

- Economics are a critical decision-making factor for agrivoltaics stakeholders.
- Battery storage and mounting structures dominate CAPEX.
- Agrivoltaics can be profitable in Tanzania after four years and six months.
- Agrivoltaics LCOE range from 79.02 to 137.96 USD/MWh.
- A feed-in tariff in Kenya could improve ROI and reduce LCOE to 72.16 USD/MWh.

GRAPHICAL ABSTRACT



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ABSTRACT

Agrivoltaics (AV) can co-produce food crops and electricity while improving water conservation in East Africa; however, a lack of understanding of stakeholder perspectives and concerns over economic viability inhibits investment and uptake of the technology. This study addresses this knowledge gap by investigating stakeholder perspectives in East Africa and quantifying the financial economics – including a breakdown of CAPEX and OPEX, net present value, return on investment, internal rate of return, payback period and levelised cost of energy – of five AV scenarios based on two case studies in Kenya and Tanzania. Both AV and conventional ground-mounted solar parks are profitable in these scenarios, with net present values ranging 765–1680 USD/kWp. Mounting structures and battery storage systems dominate the CAPEX costs, with mounting structures comprised 45% of the CAPEX without battery storage, and conventional ground-mounted systems are 16–27% cheaper to install but income from crop sales partly compensates the higher CAPEX cost of AV and facilitates profitable co-use of land. While conventional ground-mounted solar parks breakeven approximately one to three years earlier than AV in the studied scenarios, the latter can be financially competitive, offer a diversified income source from the same area of land, and concomitantly benefit the food-energy-water nexus. A feed-in tariff in Kenya would boost economic viability of both PV and AV projects. These findings indicate that AV represent a

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viable land-use strategy for solar energy expansion in East Africa where co-benefits from land use in addition to electricity generation are valued.

Nomenclature

Abbreviations

AV	Agrivoltaics
BEI	Breakeven electricity income
BSS	Battery storage system
CAPEX	Capital expenditure
CV	Coefficients of variation
DCF	Discounted cash flow
DPP	Discounted payback period
EWURA	Tanzanian Energy and Water Utilities Regulatory Authority
FiT	Feed-in tariff
GHI	Global horizontal irradiation
GMSP	Ground mounted solar park
IRR	Internal rate of return
KES	Kenyan shilling
KPLC	Kenya Power & Lighting Plc
lat.	Latitude
long.	Longitude
LAS	Latia Agribusiness Solutions
LCOE	Levelised cost of energy
max	Maximum
min	Minimum
NPV	Net present value
OPEX	Operational expenditure
PPA	Power purchase agreement
PPP	Public-private partnership
PV	Photovoltaic
ROI	Return on investment
SAT	Sustainable Agriculture Tanzania
TZS	Tanzanian shilling
USD	United States Dollar
WACC	Weighted average cost of capital

Units and symbols

A	ampere
°C	degrees Celsius
GW	gigawatt
h	hour
kW	kilowatt
kWh	kilowatt hour
kWp	kilowatt peak
L	litre
m	metre
mm	millimetre
MW	megawatt
MWh	megawatt hour
w	watt
V	volt
$	United States Dollar

1. Introduction

The growing demand for renewable energy to mitigate the harmful impacts of fossil fuels puts pressure on land - a finite resource. The implementation of ground mounted solar parks (GMSPs) can lead to land use competition with other land uses such as food production, reflecting potential food-energy-land nexus trade-offs [1–3]. This competition is evident in East Africa, where agriculture supports food security and livelihoods [4] (54% and 65% of Kenyan and Tanzania labour forces, respectively, were employed in agriculture in 2019 [5]), yet where population growth and the increasing unpredictability of the climate [6] exert increasing pressure on both land resources and food.

Agrivoltaics – the integration of photovoltaic (PV) solar panels with agriculture to co-produce electricity and agricultural outputs simultaneously – have gained global interest over the past decade due to the potential to alleviate land use conflicts between solar energy infrastructure and agriculture [7,8]. The global AV market was valued at 4.59 billion USD in 2024 [9], and the concept has been deployed across six continents, primarily in Europe, Asia and North America. However, in some East African regions AV display some the greatest livelihood benefits, where entrenched energy access challenges, threatened food systems, and climate variability can be offset by harnessing substantial solar PV potential [10–13]. Agrivoltaics present a unique opportunity to improve socio-economic development outcomes in cases where urban and rural communities lack reliable electricity access exacerbated by prohibitive "last mile" costs and demand-side challenges for connecting centralised grids [10]. Despite notable national electrification efforts, 280 million people in East Africa still lack reliable access to electricity – almost half of the regional population [11]. Fluctuating fuel prices further exacerbate energy insecurity and hinder economic stability [12]. Abundant solar irradiation (5–7 kWh/m^2/day) could generate ample electricity in most populated regions of the continent [13], regardless of grid connection, and fixed generation prices offer stability over fluctuating grid or diesel costs. This is particularly promising for rural communities, as decentralised solutions such as PV mini-grids and pico-grids can electrify villages and households far from grid connection [14–16]. Despite this, solar PV only contributed 3.6% and 0.3% of electricity generation in Kenya, 2024 [17], and Tanzania, 2023 [18], respectively. Several government policy initiatives seek to capitalise on this opportunity, setting targets to increase electrification and solar PV deployments, which is already resulting in one of the fastest electrification rates in the world [11]. Both Kenya and Tanzania have national goals of achieving universal access to electricity by 2030 as well as increasing the share of renewable energy in the countries to 100% for Kenya and 75% for Tanzania [19,20]. To achieve 100% renewable energy, Kenya plans among other actions to create the required regulatory framework to expand the use of solar mini-grids and off grid systems for rural electrification.

Agrivoltaics offer a unique opportunity to address multiple UN Sustainable Development Goals (SDGs) [21–26]. By simultaneously supporting crop production, water conservation, and in some cases partial crop protection from extreme weather [27], multifunctional adaptation of solar PV technology provides additional advantages over conventional GMSPs, especially in terms of potential climate change resilience for farming in semi-arid locations. Agostini et al. [28] also note that the reduced impact on land occupation and stabilisation of crop production from AV are relevant added values that should be properly valorised in broader energy system planning under future climate scenarios. Further, a multi-dimensional AV rating system has been proposed to encapsulate the multitude of impacts and benefits for diverse stakeholders with various priorities [29].

Almost half of households in East Africa have experiences of food insecurity [30], and climate change is forecast to worsen this by decreasing major crop yields 8–45% by 2050 [6]. Indeed, it is the perceived "win-win" of AV that has led to burgeoning support from farmers, who view such systems as facilitating the diversification of their income alongside crop production [31,32]. Other studies have noted that increased production of power could lead to improvements in livelihoods, education and health [33]. However, techno-economic analyses in European regions present a note of caution, as shading effects on crop yields, higher machinery and labour costs and area lost due to the AV mounting structure can offset energy generation benefits [34]. As such, stronger financial gain is commonly found when growing high-value crops (e.g. vegetables or berries) compared to low-value crops (e.g. grains) unless electricity prices are sufficiently high to offset such costs [35].

At the policy level, adopting AV advances national agendas on renewable energy, agricultural and economic transformation, and climate resilience in East Africa [36–38], which is making the technology particularly attractive to governments, the private sector and donors among other actors.

The implementation of GMSPs depends on regulatory and permitting processes that relate to land use change, environmental approvals and acquisition of land [39,40]. Large-scale PV projects that require converting land classified for agriculture or urban development often involve complex processes such as land tenure verification, compliance with the existing national land-use policies and environmental and social impact assessments (ESIAs). In Tanzania and Kenya, for example, these complex processes are further complicated by fragmented governance structures, customary land tenure systems and fragmented governance structures which hinder or delay effective implementation [41]. This is exacerbated by the conflicting or overlapping functions and mandates among agriculture, energy, land and environment sector authorities, coupled with the high regulatory and transactional costs that many investors face [42]. Such institutional barriers are likely to inhibit the adoption and scaling of conventional PV systems and thus incentivise cross-cutting solutions such as AV, as they offer multiple benefits and address multiple SDGs.

At present, neither Kenya nor Tanzania has a dedicated agrivoltaics-specific regulatory framework governing the co-location of solar energy generation and agricultural production. Agrivoltaic projects are therefore regulated under existing renewable energy, land-use, environmental and agricultural policies, with no specific provisions regarding maximum land coverage by PV modules, minimum crop production requirements, or acceptable yield thresholds. Nevertheless, there is growing policy support for AV development in Kenya, through recognition of the value of low-carbon energy in meeting farm productivity and climate mitigation strategy [20,43]. Of note is the National Energy Policy of 2025–2034 [20], which aims to triple electricity capacity by 2030, with specific supports for renewable energy integration into agricultural systems. Emphasis within the policy documentation relevant to AV is the focus on solar powered irrigation and renewable applications for on-farm processing solutions directed at smallholder farmers. In Tanzania solar power is considered the most feasible source for electrifying rural regions due to its flexibility within mini grid infrastructure. Tanzania has the seen a recent flow of investment towards renewable energy, peaking at US$233 million in 2021, and the Tanzanian government has more recently created a more receptive regulatory environment for off- and mini-grid private developers relevant to AV development [44].

Proponents of AV expound the benefits across the nexus of water, energy, food and in increasing resilience to climate change challenges [45], and such benefits have been demonstrated in Kajiado County, Kenya and Morogoro, Tanzania [46]. The results from this study showed crop yields and morphologies varied, with some crops producing higher yields under the partial shade of AV. The survival of bean and maize plants increased under the partial shade of the solar panels when they were grown during a season relatively warm for the location, indicating potential resilience under future warmer climates. Soil retained water for longer and less irrigation was required – a significant finding for water-stressed regions. Rainwater harvesting channelling water running off the panels further reduced demand on centralised irrigation. The benefits of a grid-tied system saving money on energy bills and an off-grid system providing a new energy source were demonstrated, and land productivity was improved in all cases [46].

As with PV, AV systems are modular [47] that can be developed at any practical scale, ranging from <20 kWp systems for smallholder farmers to MW scale commercial systems for large agribusinesses. Examples of use cases and business models for AV include: systems privately owned by farmers for self-consumption of electricity and/or grid feed-in tariff (FiT) income; commercial systems with two distinct owners: agribusinesses operating the farmland and energy companies selling electricity to the national grid or mini-grids or with power purchases agreements (PPAs) with third parties; community-owned mini-grids with various payment schemes for installation and electricity consumption and agricultural management; and public sector installations, e.g. for schools and community spaces, supported by government grants, donor contributions or public-private partnerships (PPPs) [28,31,33,34].

Irrespective of scale or use case, AV must be economically viable for expansive uptake. Indeed, of considerable concern to stakeholders, identified in other regions, is the economic viability of such systems, including generating the upfront capital and the efficacy of payback for initial capital investment [48], the profitability of crops produced [49], and land use management costs related to hosting the systems [31]. Emergent research from East Africa is indicative that such concerns are pertinent there too [33]. As such, economic viability is crucial for a technology with substantial material costs deployed in a region where the costs of finance are typically high [50]. The systems should be cost competitive with alternative energy options, such as ground- or roof-mounted PV or diesel generators and should enhance broader social value such as by meeting additional SDGs. While conventional GMSPs require fewer materials for the mounting structures compared to raised AV [51,52], crop sale revenues provide additional income that can contribute to offsetting the higher material and installation costs for AV [34,53,54].

Despite the growing interest in development and investment opportunities in PV in Africa, and the significant potential for AV, there is a lack of empirical evidence concerning the financial viability of these systems and their potential benefits in comparison to conventional PV systems. This knowledge gap means the evidence needed to inform decisions on the investment and financial support to underpin any large-scale uptake of this technology is currently missing [55,56]. Further, studies based on different geographic contexts, e.g. European, Asian or American markets, have only limited application to regions with contrasting climates, agroecological and political conditions [57–60]. For example, regions may differ in potential crops, agricultural productivity, length and number of growing seasons, material and skilled labour costs and availability, and access to export markets. Design practices may also vary; for instance, regional differences in incoming solar radiation and evaporative water loss may warrant different panel densities. A meta-analysis recommends a panel density below 30% in temperate regions [61], while studies in East Africa reported yield increases under a 50% panel density [46]. To appropriately inform decision-making relevant to the specific context, there is an urgent need to thoroughly examine the techno-economic components of AV in-situ, alongside the broader socio-economic context in which they are deployed to determine if AV could be economically viable in this region [33,46,62,63].

The research questions addressed in this study are:

- **Stakeholder perspectives:** What are the stakeholder perceptions of AV in East Africa; what do they see as the most significant opportunities, challenges and concerns?

- **CAPEX and OPEX costs:** How much do AV systems cost compared to conventional ground-mounted PV systems, and what is the breakdown of the CAPEX and OPEX?
- **Cash flows:** Can AV be profitable: how long can it take for the initial investment to be returned, and what returns and cash flows can they offer?
- **Energy and system value:** What are the levelised costs of energy from GMSPs and AV?
- **Feed-in tariffs:** What effect do feed-in tariffs have on financial returns?

This mixed-methods study assesses the techno-economic aspects of relevant AV scenarios in East Africa, informed by stakeholder perspectives and grounded by empirical pilot studies. First, perceptions of the prevailing socio-economic, land use and policy conditions to facilitate deployment and upscaling of the technology are assessed. A financial model based on the case studies in Kajiado Country, Kenya and Morogoro, Tanzania then compares the cost and income/saving factors for grid-tied and mini-grid raised AV and GMSPs. The installation cost, return on investment, net present value, payback periods, breakeven electricity income, and levelised cost of energy are calculated, providing comparisons between AV, GMSPs, and an agriculture-only baseline. The various cost components of the energy sources are dissected to establish where cost-saving innovations would have the greatest impacts on expenditure. In addition to the case studies, an additional scenario is modelled for each country to assess highly relevant alternatives: 1) adding battery storage systems (BSS) in Kenya to mitigate curtailment; and 2) investigating a larger grid-tied system in Tanzania to test the effects of the two different FiT values for mini-grids and grid-tied systems. A fifth exploratory scenario was modelled to quantify the effects of a hypothetical FiT in Kenya. The findings from this study inform financial and policy decision making for solar energy developments in East Africa.

2. Methods

2.1. Study region

Study sites were selected to represent semi-arid agroecological farming conditions relevant in East Africa and areas that experience energy access constraints coupled with water shortage and land-use competition. Site selection was also based on the presence of existing and operational agribusiness institutions which provided infrastructure, human resources, agricultural expertise and access to farming markets.

The AV system in Kenya is located at Latia Agribusiness Solutions (LAS), Isinya, Kajiado County (lat. −1.6850, long. 36.8307) (Fig. 1a). The site is at an elevation of 1646 m and is characterised by clayey soils associated with gypsum, silicified lithics and limestone. The climate is tropical semi-arid, with a bimodal annual precipitation cycle. The mean annual temperature is 19.1 °C, ranging from 17.3 °C in July to 20.8 °C in February, and there is 687 mm of mean precipitation annually (max: 115 mm in April, min: 14 mm in September). The area receives an average of 7.5 h of sunshine a day, and 5.4 kWh/m^2/day of global horizontal irradiation (GHI).

The AV system in Tanzania is located at Sustainable Agriculture Tanzania (SAT)'s Farmer Training Centre, Morogoro (lat. −6.7414, long. 37.5494) (Fig. 1b). The site is at an elevation of 537 m, and the climate is tropical and semi-arid. The mean annual temperature is 22.6 °C, ranging from 20.4 °C in July to 24.4 °C in February, and Morogoro is characterised by a bimodal annual precipitation cycle with a mean of 972 mm (max: 199 mm in March, min: 15 mm in July). The area receives an average of 8.0 h of sunshine a day, and 5.2 kWh/m^2/day of GHI.

2.2. Stakeholder perspectives

Twenty two semi-structured interviews were conducted with key stakeholder participants from Kenya ($n = 11$), Tanzania ($n = 10$), and a pan-regional expert (n = 1). The interviewees included agricultural policy professionals, energy policy practitioners, private sector interests, international and regional development non-governmental organisations, research organisations, academic institutions, a land-use planner, and civil society organisations. Participants were selected through purposive sampling to ensure diversity across sectors and geographies relevant to AV implementation. Additional participants were selected through snowball sampling, whereby initial interviewees recommended other knowledgeable and relevant stakeholders within their professional networks to enrich the range of perspectives captured. Thematic analysis was used to interpret the English anonymised transcriptions of qualitative data, following the principles outlined by Braun and Clarke [64] and Squires [65]. Researchers read each transcript multiple times to develop familiarity with the content. Initial coding was conducted collaboratively using NVivo 13 (2020), with codes generated both inductively (bottom up) from the data and deductively (top down) based upon the study's focus on perceptions of the economic and social impacts related to AV deployment and uptake across the region.

Codes were organised into broader thematic categories through iterative discussion and themes to ensure internal coherence and distinctiveness and they were integrated into the mixed-methods framework to provide richness and context to the economic

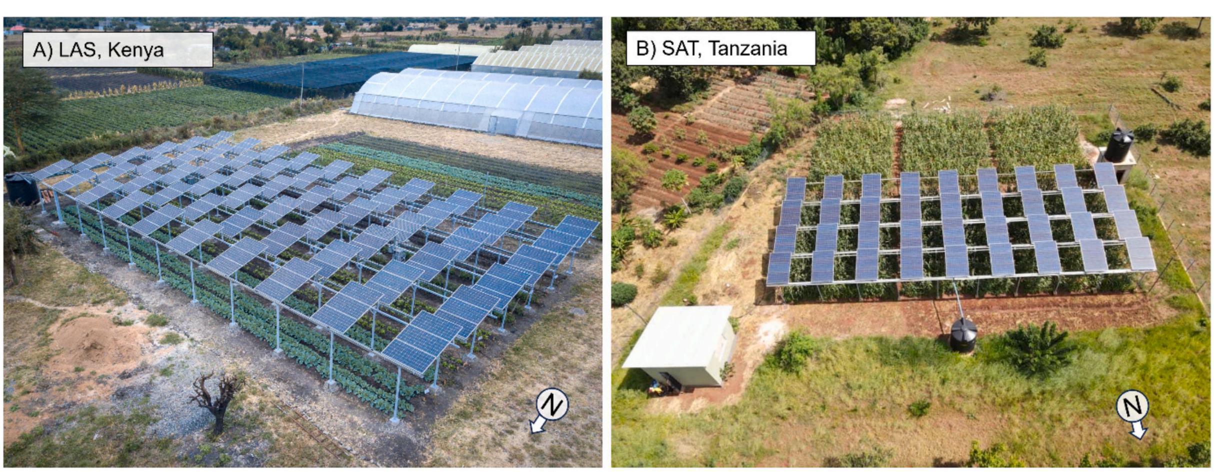

Fig. 1. Aerial photos of the two AV systems. A) The 62.1 kWp system grid-tie system at Latia Agribusiness Solutions (LAS), Kenya. B) The 36.6 kWp off-grid system at Sustainable Agriculture Tanzania (SAT). Photo credits: Chloride Exide Ltd.

modelling. This approach generated socially-grounded insights that complement the quantitative assessment of AV techno-economics, and individual quotes are shown to provide context to the emergent themes. Where direct quotes are shown, each is attributed to the anonymous interviewee expressed as [Country, X] and numbered sequentially as each appears in the text.

As an emergent technology in East Africa, AV are still a new concept, hence most stakeholder insights were based on limited first-hand exposure, experience and knowledge of the systems. As such, this novelty may have included some responses that were speculative, particularly with regards to various aspects such as financial viability (including financing models and cost of installation), technical optimisation, and scalability.

The qualitative data provides insight into key stakeholder perspectives to AV deployment across the regions studied. The stakeholder interviewees represent a relatively small, purposively selected sample, restricting representativeness and thus generalisability. However, given the diversity in stakeholder positions and characteristics leading to possibilities related to theoretical generalisability [66], the key findings may have wider purchase.

2.3. Scenarios and input data

2.3.1. Scenario descriptions

Five scenarios were assessed financially, derived from the case studies at LAS in Kenya (62.1 kWp) and SAT in Tanzania (36.6 kWp) [46] (Table 1). The capacity of the system in Kenya was determined based on the agribusiness' existing energy consumption profile. The capacity of the off-grid system in Tanzania was based on the forecast consumption together with representing an appropriate size for the scale of PV mini-grid implementation for rural electrification in sub-Saharan Africa, powering small-medium agribusinesses or a village of ~500 people (based on the trend of electricity demand per capita in Tanzania [67]).

In brief, the systems are raised 3 m above the ground at the lower edges of the panels and feature a 50% panel density, facing the equator at a 10° panel tilt. As feed-in tariffs are not currently offered in Kenya, both a grid-tied system with a reduced electricity income value of 56%, estimated from LAS' agrivoltaic:grid consumption rate, and a grid-tied system with a 88.2 kWh lithium-ion battery storage system (BSS) to utilise 100% of the electricity generated were modelled. Tanzania offers different FiTs for grid-tied and mini-grid PV systems and thus both systems were modelled for Tanzania. Here, a 52.0 kWh lead-acid BSS was included in the mini-grid scenario, but not the grid-tied scenario as all surplus electricity can be sold to the grid operator. The grid-tied system in Tanzania was modelled with the larger 62.1 kWp capacity deployed in Kenya to represent the larger grid-tied use case. The BSS capacities were derived from LAS' mean daily grid consumption in the month with the greatest grid consumption in the studied period, October 2023, to reflect a conservative upper value for BSS capacity needs. An additional scenario for Kenya, presented separately, featuring a FiT based on Tanzania's grid-tied FiT was also modelled; this represents a FiT 13.2% below Kenya's grid price.

Within each scenario a GMSP and an AV system were modelled. The GMSP and AV systems were modelled with equal capacities within each scenario, and the AV systems include the cost of raising the mounting structure to 3 m at the lower edges of the panels. The AV systems also feature a 10,000 L rainwater harvesting tank to supplement the existing irrigation systems. The agriculture baseline reflects the agricultural OPEX and income costs only, excluding the rainwater harvesting tank. The AV scenarios and agriculture baseline modelled small-scale vegetable farming for sale on the local urban market.

Table 1
Assessed scenarios. The five scenarios to which a financial assessment was conducted.

Scenario	Country	Use case	Electricity value source	Capacity
1	Kenya	Grid-tie w/o BSS	Bill savings	62.1 kWp
2	Kenya	Grid-tie w/ BSS	Bill savings	62.1 kWp
3	Tanzania	Grid-tie w/o BSS	FiT	62.1 kWp
4	Tanzania	Mini-grid w/ BSS	FiT	36.6 kWp
5	Kenya	Grid-tie w/o BSS	FiT	62.1 kWp

2.3.2. CAPEX and OPEX costs

The capital expenditure (CAPEX) costs are derived from quotes for a GMSP and a raised AV system, each with a 63.75 kWp installed capacity. They were provided in May 2025 by the East African solar developer that installed the case study sites. Prior to installation in 2021, quotes from three regional solar developers were obtained. Cabling and transmission costs were calculated from the panels to the inverter; grid connection costs beyond this were excluded. Reinvestments to replace BSS were applied, where applicable, in year 16 and at a 45% discounted cost derived from Mauler et al. [68] and Cole et al. [69]. System maintenance and farm labour operational expenditure (OPEX) costs were provided by the solar developer and by SAT, respectively. The costs for PV panels, the mounting structure, batteries, cabling, civil works and labour were converted to USD/kWp for scaling to the different scenario capacities (Table 2), as per guidance from the quote provider. The remaining costs were fixed.

Some costs that did not apply to the case studies, such as cost of land, may apply to other cases depending on the business model, while other costs like civil works will be site-specific. Decommissioning costs were not accounted for, although it is notable that reuse and recyclability of materials is high within the study region.

2.3.3. Electricity values

The electricity generated by each system was estimated using the European Commission's PVGIS (v5.3) international PV performance tool [70], based on the system's specifications. The financial assessment model includes a PV degradation rate (see section 0.5), thus the PV degradation rate was set to zero in PVGIS to avoid double-counting. The

Table 2
CAPEX and OPEX. The CAPEX and OPEX component prices for 63.75 kWp PV and AV systems, and whether those costs are scaled to kWp or fixed for the capacities studied. Most costs are equal for GMSP and AV, except for the mounting structure and system maintenance. The rainwater harvesting system and farm labour costs are only applied to the AV systems. Battery storage costs only apply to scenarios with BSS.

Item	Category	Cost scaling	Price (USD)
PV panels (625 W)	CAPEX	Scaled	7846
Inverter (50 KW)	CAPEX	Fixed	2473
Inverter shed	CAPEX	Fixed	824
Communication equipment	CAPEX	Fixed	621
DC breaker (32 A, 1000 V)	CAPEX	Fixed	824
DC cable	CAPEX	Scaled	1872
AC cable	CAPEX	Scaled	2473
Data manager	CAPEX	Fixed	440
Mounting structure^{GMSP}	CAPEX	Scaled	11,676
Mounting structure^{AV}	CAPEX	Scaled	23,352
Electrical integration gear	CAPEX	Fixed	2904
Civil works	CAPEX	Scaled	1099
Transportation	CAPEX	Fixed	916
Labour	CAPEX	Scaled	5254
Rainwater harvesting (10,000L)^{AV}	CAPEX	Fixed	2289
Batteries (90 kWh lithium ion)$^{Mini\text{-}grid}$	CAPEX	Scaled	42,844
Maintenance^{GMSP}	OPEX	Scaled	1125
Maintenance ^{AV}	OPEX	Scaled	1680
Farm labour^{AV}	OPEX	Scaled	276
Land preparation^{AV}	OPEX	Scaled	25
Weeding^{AV}	OPEX	Scaled	7
Planting/sowing^{AV}	OPEX	Scaled	6
Biopesticide application^{AV}	OPEX	Scaled	1
Manure application^{AV}	OPEX	Scaled	34

undegraded generation amounts were 112.3 MWh/year for a 62.1 kWp system at LAS, and 103.7 MWh/year and 61.1 MWh/year for 62.1 kWp and 36.6 kWp systems at SAT, respectively.

The unit price of electricity in Kenya, 0.19 USD/kWh (24.5 KES/kWh), was derived from LAS' energy bills and reflects the potential for savings from grid-supplied energy bills. Although national electricity provider Kenya Power & Lighting Plc (KPLC) offers off-peak rates between 22:00 and 06:00 [71], these were not modelled as PV would not generate electricity during these hours, and consumption from BSS will primarily fall outside these hours.

Feed-in tariffs of 0.165 USD/kWh (436 TZS/kWh) and 0.181 USD/kWh (476 TZS/kWh) were applied to grid-tied and mini-grid systems in Tanzania, respectively. Feed-in tariffs are set by the Tanzanian Energy and Water Utilities Regulatory Authority (EWURA), and systems <100 kWp are unregulated, with operators free to set their own electricity tariff to connected customers; the FiTs used in this study were therefore based on those set by EWURA for grid-tied and mini-grid systems ≥100 kW up to 1 MW [72].

The model assumes full consumption of the forecast electricity generation for all scenarios except the systems without BSS in Kenya; this is suitable for grid-tied systems where FiTs are applicable, or consumption exceeds PV generation and battery storage, but if consumption is below storage capacity then excess electricity will be curtailed and value lost.

2.3.4. *Crop values*

Crop sale values were provided by LAS and SAT and applied to mean yield results reported in Randle-Boggis et al. [46] (Table 3). Beans were excluded due to their low-income value. Intercropping and crop rotation combinations were based on growing schedules at the respective case studies. The empirical data based on the case study observations reflect the spatial and temporal snapshots of the experiments, and regional and market price fluctuations of materials and crop sales will affect the results.

2.4. *Financial assessment*

A discounted cash flow (DCF) approach was used to assess the financial feasibility of each scenario over a 25-year lifespan. The model assesses return on investment (ROI), internal rate of return (IRR), net present value (NPV), discounted payback period (DPP), levelised cost of energy (LCOE) and breakeven electricity income (BEI). A 0.99% PV degradation rate was applied [73]. A discount rate of 8.75% was applied, based on an International Energy Agency survey of the cost of capital of large-scale solar projects in Kenya in 2022 [74]. The internal rates of return (IRR), i.e. the maximum profitable discount rates, were calculated for each scenario, along with the IRR margin (the IRR minus the baseline discount rate). All cash flows were modelled in real terms, assuming constant annual values for costs and incomes over the project lifetime. Accordingly, the discount rates represent real WACC, and inflation was not explicitly modelled. Values are stated in USD using conversion rates of 0.0077 KES and 0.00038 TZS from July 2025 where applicable.

Table 3
Crop seasonal rotations, intercropping and values. The season(s) each crop was studied within a year and the annual crop sale values, with yields and growing combinations derived from Randle-Boggis et al. [46].

Crop	Season(s) studied	Crop value (USD/ha/year)	Plot value (USD/year)
800 m^2 grid-tie, LAS, Kenya			
Coriander	1, 3	1687	135
Kale	1, 3	1138	91
Cabbage	2, 4	4764	381
Onion	2, 4	11,358	909
800 m^2 grid-tie, SAT, Tanzania			
Maize	1	3108	249
Eggplant	2	3116	249
Onion	2, 3	9343	748
Sweet pepper	3	4708	377
Swiss chard	3	2589	207
442 m^2 mini-grid, SAT, Tanzania			
Maize	1	3108	137
Eggplant	2	3116	138
Onion	2, 3	9343	412
Sweet pepper	3	4708	208
Swiss chard	3	2589	114

A two-factor income sensitivity analysis identified how combined variations in electricity and crop values affect financial returns and vulnerability to price fluctuations, and a discount rate sensitivity analysis revealed the effects of different discount rates on NPV. As AV combine two traditionally distinct sectors – PV development and farming, several AV business models exist that have varying degrees of ownership and separate and/or combined revenue streams [75]; for example, energy revenue streams may be independent from farming revenue streams [76]. Therefore, for the AV scenarios studied, each financial metric was modelled both excluding and including the agricultural values, providing two sets of results: 1) “electricity only” (AV^{elec}) and 2) “with agriculture” (AV^{agri}). This is to present the cashflows for 1) solar energy developers/investors that are handling only the energy related cash flows, i.e. they receive no benefit from any crop sales, and 2) holistic ownership approaches that cover both the energy and agricultural values.

2.4.1. *Return on investment*

The discounted return on investment (ROI) [53,77] (Eq. (1)) measures the net present value (NPV) of cumulative discounted cash flows relative to the initial investment. The internal rate of return (IRR) [77] (Eq. (2)) is the discount rate that sets the NPV of cash flows to zero, i.e. the maximum profitable discount rate. Subtracting the discount rate from the IRR presents the IRR margin.

Equation 1. Return on investment.

$$\text{Discounted ROI}\,(\%) = \frac{\sum_{t=1}^{T}\frac{(I-O)}{(1+r)^t} - C_0}{C_0} \times 100$$

where ROI the discounted return on Investment (%), T is the project lifetime (years), I is the annual income value (USD/year), O is the annual OPEX (USD/year), r is the discount rate, and C_0 is the initial CAPEX (USD).

Equation 2. Internal rate of return.

$$0 = \sum_{t=1}^{T}\frac{(I-O)}{(1+r_{\text{IRR}})^t} - C_0$$

where rIRR is the internal rate of return (IRR) such that the NPV equals zero, T is the project lifetime (years), I is the annual income value (USD/year), O is the annual OPEX (USD/year), rIRR is the internal rate of return, and C_0 is the initial CAPEX (USD).

2.4.2. *Net present value*

The NPV [53,77] (Eq. (3)) represents the total value generated from a project at present day values. The metric is discounted to account for the time cost of money. A positive NPV indicates a profitable project over the project's lifespan, while a negative NPV indicates value loss.

Equation 3. Net present value.

$$\text{NPV} = \sum_{t=1}^{T}\frac{(I-O)}{(1+r)^t} - C_0$$

where NPV is the net present value (USD), T is the project lifetime (years), t is the year index from 1 to T, I is the annual income value (USD/year), O is the annual OPEX (USD/year), r is the discount rate, and C_0 is the initial CAPEX (USD).

2.4.3. Discounted payback period

The DPP [53,77] (Eq. 4) shows how long it will take for CAPEX to be recovered, discounted for the time cost of money.

Equation 4. Discounted payback period.

$$\text{Find DPP such that } \sum_{i=1}^{t} \frac{(I-O)}{(1+r)^i} \geq C_0$$

where DPP is the discounted payback period t is the number of years required to recover the initial investment (CAPEX) through discounted net cash flows, i is the index for each year from 1 to t, I is the annual income value (USD/year), O is the annual OPEX (USD/year), r is the discount rate, and C_0 is the initial CAPEX (USD).

2.4.4. Levelised cost of energy

The LCOE [53,78] (Eq. 5) represents the total cost of energy per unit consumed, discounted over a project's lifetime. This metric enables comparisons of energy costs across different energy technologies.

Equation 5. Levelised cost of energy.

$$\text{LCOE} = \frac{C_0 + \sum_{t=1}^{T} \frac{O}{(1+r)^t}}{\sum_{t=1}^{T} \frac{G_t}{(1+r)^t}}$$

where LCOE is the levelised cost of electricity (USD/MWh), C_0 is the initial CAPEX (USD), T is the project lifetime (years), t is the year index from 1 to T, O is the annual OPEX (USD/year), Gt is the generated electricity delivered in year t, accounting for degradation (MWh/year), and r is the discount rate.

2.4.5. Breakeven electricity income

The BEI (Eq. 6) reflects the required income from electricity sales/savings for a project to break even, discounted for the time cost of money. The equation is derived from NPV breakeven calculations [77]. The BEI is also presented as a percentage of the calculated electricity income value to indicate sensitivity to risk.

Equation 6. Breakeven electricity income.

$$\text{Find } E^* \text{ such that } \sum_{t=1}^{T} \frac{(E^* + C - O)}{(1+r)^t} = C_0$$

where E^* is the breakeven annual electricity income (USD/year), t is the year index from 1 to T, T is the project lifetime (years), C are the annual crop sales (USD/year) (excluded in the "electricity income only" analysis), O is the annual OPEX (USD/year), r is the discount rate, and C_0 is the initial CAPEX (USD).

2.5. Sensitivity analysis

A two-factor sensitivity analysis was conducted to evaluate the effect of variations in electricity value and crop sale income on NPVs. Each income source was independently and jointly adjusted in 5 % step changes to +/− 30% of their baseline values. This reveals how sensitive the NPVs are to individual and combined variations in the two income sources. The resulting NPVs are presented as heatmaps displaying the percentage change in NPV from the baseline. For GMSPs the crop sale factor is fixed as 1. For AV, the electricity:crop value ratio indicates the relative impact of each income source on NPV. Coefficients of variation (CV) quantify the variability in NPV across all six scenario-system combinations (Eq. (7)), where higher CVs indicate greater sensitivity. A sensitivity analysis was also conducted to assess the effects of different discount rates on NPV, from 0% up to the maximum calculated IRR, in 0.5% increments.

Equation 7. Coefficient of variation.

$$\text{CV}_{\text{NPV}} = \frac{\sigma_{\text{NPV}}}{\mu_{\text{NPV}}} \times 100$$

where CV_{NPV} is the coefficient of variation for NPV, σ_{NPV} is the standard deviation and μ_{NPV} is the mean NPV across all sensitivity combinations.

3. Results

3.1. Stakeholder perspectives

The qualitative thematic analysis of stakeholder interviews revealed considerable concern over the CAPEX cost for AV infrastructure, reflecting the relatively high costs for mounting structure compared to ground-mounted alternatives:

"Maybe I am looking at the investment, the investment cost... unless we have some sort of a firm that is supporting this in terms of the costing... the cost of the panel and even installation could be something that we need to look at." Kenya 1.

"So I think the issue it here will be capital issue so if the project can try to link up with these finance institutions like banks, microfinance or something so that even when someone is ready to take up the technology they can get maybe like a loan." Tanzania 1.

Moreover, there was concern that high CAPEX cost would limit opportunities for farmers to invest in other aspects of their business, potentially reducing their overall farm efficiency due to the opportunity cost of AV investment compared to, for example, fertilisers, pesticides, climate change-resistant crop varieties, water saving measures or other sustainable alternatives, particularly under conditions of financial stress:

"The cost of production is high, and if farmers are not careful, they end up... not producing a crop successfully because of the cost of production." Kenya 2.

Though there was a commonly expressed caution around AV specifically, other stakeholders expressed that the high initial investment cost is a feature of any rural renewable energy transition, and is thus not an exclusive challenge to AV deployment:

"We were doing biogas units and one of the things that we find a big challenge is the initial investment." Kenya 1.

"I think most of the challenges especially in these renewable solar technologies... are still the same. Most of products here they don't last long, and their investment cost is very high. That is very difficult for small farmers to afford." Tanzania 2.

Agrivoltaics could thus be a potential transition pathway for farm sustainability, but this is highly dependent upon accurate cost-benefit analysis.

"You need to do... a cost benefit analysis, that is very key for any project so that you understand the gross margins... does it bring to the farmer or whoever person is adopting... So, it is ensuring that we break down not only costs but also the benefits." Kenya 3.

Access to affordable finance, and to appropriate markets across an array of sustainable technologies was repeatedly mentioned as a key barrier to farm productivity and AV specifically. There was an expressed need for innovative financing models, for instance through pay-as-you-go, or results-based financing to balance CAPEX and OPEX considerations, and the second concerns the availability of appropriate labour to support operations and maintenance of the AV system.

"First is the finance or the capital base to be able to purchase these that is the first one. The second one is the availability of the personnel it will take time to train the personnel who can be able to maintain this." Kenya 4.

The overall economic viability of AV systems was therefore perceived as being subject to broader socio-economic and farm productivity conditions. Many stakeholders called for a detailed assessment of socio-economic impacts. To ensure financial sustainability, stakeholders called for a thorough cost-benefit analysis that simultaneously accounts for CAPEX costs from mounting and OPEX costs related to maintenance, crop yields, and energy generation, drawn together into a holistic analysis:

Among these costs was a concern for the supply chain of solar PV cells, their availability and quality control, with a strong sense that cost reductions can only be made through purchasing imported PV from China:

"[AV] is capital intensive and when you are producing the solar panels of the materials your market should not be only one country maybe Tanzania or Kenya it should be for the global market. There is no way you are going to break even if you are targeting the local market because you cannot have economies of scale. Which means you can produce solar panels in Kenya but still the panels which are coming from China can be sold in Kenya at a very competitive price, you cannot beat them." Tanzania 3.

Moreover, cost-benefit evaluation must integrate not just CAPEX costs but also how AV integrate with broader agricultural value chains, including post-harvest processing, packaging, and distribution, can enhance returns by adding value to raw produce and improving market

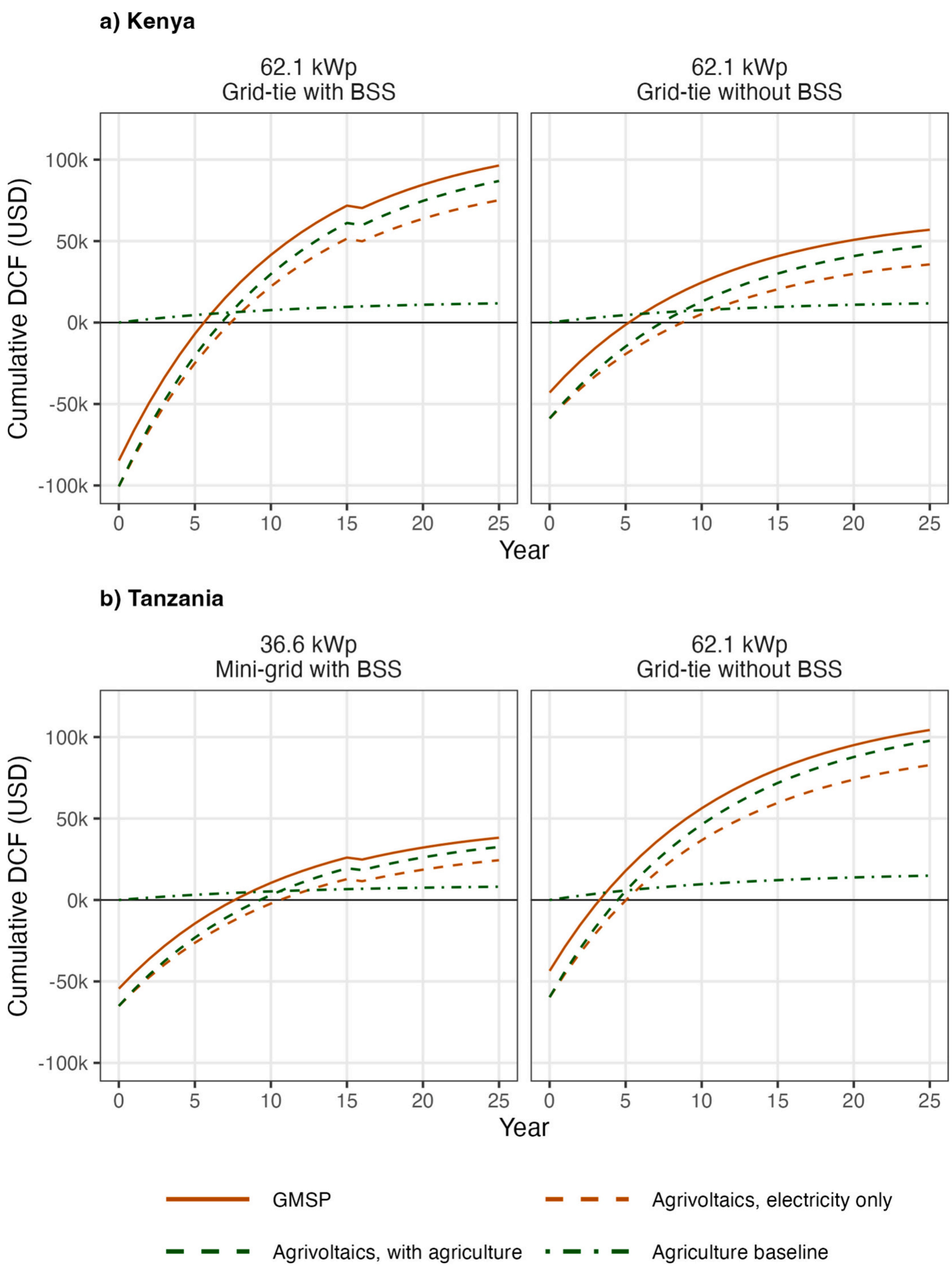

Fig. 2. Cumulative discounted cash flow. The cumulative DCF from ground-mounted solar parks (GMSP, solid line) and agrivoltaics (dashed line) across the four scenarios. Green lines denote the inclusion of agricultural cash flows, while orange lines represent electricity cash flows only. The green dash-dot line represents the farming-only agriculture baseline. Intersecting the horizontal black line represents the breakeven point (payback period). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

competitiveness. This holistic approach helps maximise both agricultural and energy outputs, making AV a more attractive investment for farmers and stakeholders worthy of scaling-up to a broader market. Stakeholders in the sample also expressed a clear need for pilot projects and demonstration sites to build trust and raise awareness about new technologies and practices. They viewed these pilots as essential for showcasing real-world benefits, addressing uncertainties, and providing tangible evidence of feasibility – particularly in communities unfamiliar with AV. Demonstration sites were also seen as valuable for engaging local actors and fostering a sense of ownership and confidence in the project:

"Having these what we call demonstration classes the farmers field demos where farmers can learn, where farmers can see... " Tanzania 4.

In addition, participants emphasised the importance of stakeholder engagement and policy alignment. They noted that early and inclusive consultation with local communities, industry representatives, and policymakers is critical to ensure that projects reflect local needs and priorities. Alignment with existing regional development strategies and national policy frameworks was seen to streamline implementation, secure funding, and avoid regulatory bottlenecks:

"We need to look into ways that we are not just selling it as a package technology, but we are walking with the customers up to the end." Kenya 5.

Finally, technical capacity and infrastructure challenges in rural areas were identified as significant barriers to successful deployment. Stakeholders highlighted issues such as limited grid connectivity, inadequate transport networks, and a shortage of skilled labour. These constraints were seen as requiring targeted investment and support, including training programmes, infrastructure upgrades, and partnerships with local institutions to build long-term capacity:

"We have also had suggestions... that if we could also have the local village polytechnics... the renewable energy lessons could be introduced." Kenya 6.

Thus, although there is a strong concern about the feasibility of small-scale farmer adoption based upon CAPEX risks, but there remains also potentially strong market demand for this technology and potential to scale beyond its existing technological niche:

"The challenge is the capital I would say, but the opportunity it is there for up-scaling and it is huge and you can see that people are eager to engage in agriculture." Tanzania 4.

3.2. Financial assessment

3.2.1. Financial summary

Agrivoltaics and GMSPs both generate profitable returns on investment (ROI) in all scenarios studied, with initial CAPEX investment returned in approximately three to 10 years (four to 15 years with a discount rate of 13.5%) (Fig. 2, Table 4). Within each scenario, GMSPs offer greater ROI, shorter payback periods and higher NPVs than AV due to the lower mounting structure CAPEX costs; however, scenario context has a greater impact on the results than the system type, with some AV systems offering greater returns than GMSPs in different contexts. The results indicate that the grid-tied system in Tanzania offers a lower financial risk than the mini-grid system in Tanzania, with the two scenarios in Kenya falling in-between. In the case of grid-tied systems in Tanzania, the NPV difference between AV and GMSPs is relatively low, suggesting that AV could be a viable option for solar energy infrastructure to benefit multiple SDGs concomitantly.

Table 4
The financial results for ground-mounted solar parks (GMSP) and agrivoltaics (AV) across the four scenarios modelled in Kenya and Tanzania.

Scenario	Metric	GMSP	AV Electricity only	AV With agriculture
Kenya 62.1 kWp Grid-tie with BSS	ROI (%)	113.8%	74.7%	86.4%
	IRR (%/year)	22.5%	18.0%	19.3%
	IRR margin (%/year)	13.7%	9.2%	10.5%
	NPV (USD)	$96,393	$75,120	$86,910
	Payback period	5 years, 7 months	7 years, 4 months	6 years, 9 months
	Breakeven electricity income (USD)	$10,954	$13,245	$11,975
	Breakeven electricity income (% of forecast)	51.3%	62.1%	56.1%
	LCOE (USD/MWh)	$97.54	$117.95	$117.95
Kenya 62.1 kWp Grid-tie without BSS	ROI (%)	132.6%	60.7%	80.7%
	IRR (%/year)	24.1%	16.1%	18.3%
	IRR margin (%/year)	15.3%	7.3%	9.5%
	NPV (USD)	$56,972	$35,699	$47,489
	Payback period	5 years, 3 months	8 years, 9 months	7 years, 5 months
	Breakeven electricity income (USD)	$5812	$8194	$6834
	Breakeven electricity income (% of forecast)	48.6%	67.8%	57.2%
	LCOE (USD/MWh)	$92.42	$128.86	$128.86
Tanzania 36.6 kWp Mini-grid with BSS	ROI (%)	70.2%	37.5%	50.0%
	IRR (%/year)	17.5%	13.5%	15.0%
	IRR margin (%/year)	8.7%	4.8%	6.3%
	NPV (USD)	$38,220	$24,411	$32,541
	Payback period	7 years, 7 months	10 years, 7 months	9 years, 3 months
	Breakeven electricity income (USD)	$6942	$8430	$7554
	Breakeven electricity income (% of forecast)	62.8%	76.2%	68.3%
	LCOE (USD/MWh)	$113.62	$137.96	$137.96
Tanzania 62.1 kWp Grid-tie without BSS	ROI (%)	239.6%	138.8%	163.8%
	IRR (%/year)	35.7%	24.8%	27.4%
	IRR margin (%/year)	27.0%	16.0%	18.6%
	NPV (USD)	$104,327	$82,782	$97,709
	Payback period	3 years, 3 months	5 years, 0 months	4 years, 6 months
	Breakeven electricity income (USD)	$5873	$8194	$6586
	Breakeven electricity income (% of forecast)	34.3%	47.9%	38.5%
	LCOE (USD/MWh)	$56.64	$79.02	$79.02

3.2.2. Upfront CAPEX components

Battery storage systems (BSS) are the greatest CAPEX cost factor where applicable, contributing between 41.3 and 49.4% of the total installation cost (Fig. 3). The mounting structure was the second greatest cost, or greatest for systems without BSS, especially for AV where the increase in steel required to raise and support the panels doubles the mounting structure CAPEX. For the AV systems without BSS the mounting structure comprises 45.1–45.2% of the total installation cost. The GMSPs without BSS cost the least to install, \$692 – \$701/kWp, while those with BSS cost almost double: \$1364 – \$1487/kWp. The studied AV without BSS cost \$947 – \$961/kWp while those with BSS cost \$1619 – \$1777/kWp. This 19–37% increase in CAPEX to develop AV instead of GMSPs reflects the higher mounting structure costs, although BSS dominates the installation cost regardless of system type (GMSP or AV). Cabling and transmission, the third greatest cost, comprises between 9.6 and 22.6% of the CAPEX. The solar panels follow closely at 9.0–17.9%, notably lower than the BSS and mounting structure costs.

3.2.3. Return on investment

The grid-tied systems in Tanzania offer the greatest ROI (GMSP: 239.6%, AV^{agri}: 163.8%; AV^{elec}: 138.8%) because of the valuable feed-in tariffs and the lack of CAPEX-intensive BSS (Table 4). The grid-tied GMSP in Kenya offers the next greatest ROI, first without BSS (132.6%) and then with BSS (113.8%). Here, the reduced electricity utilisation (thus income) is compensated by the lower CAPEX without BSS. In contrast, AV with BSS offer greater ROI (AV^{agri}: 86.4%; AV^{elec}: 74.7%) than those without BSS (AV^{agri}: 80.7%; AV^{elec}: 60.7%) in this scenario. This reversal in order of ROI between systems with BSS and without BSS demonstrates that the higher electricity utilisation provided by BSS has greater value in Kenya when the CAPEX includes both BSS and a raised AV mounting structure. The smaller mini-grids in Tanzania

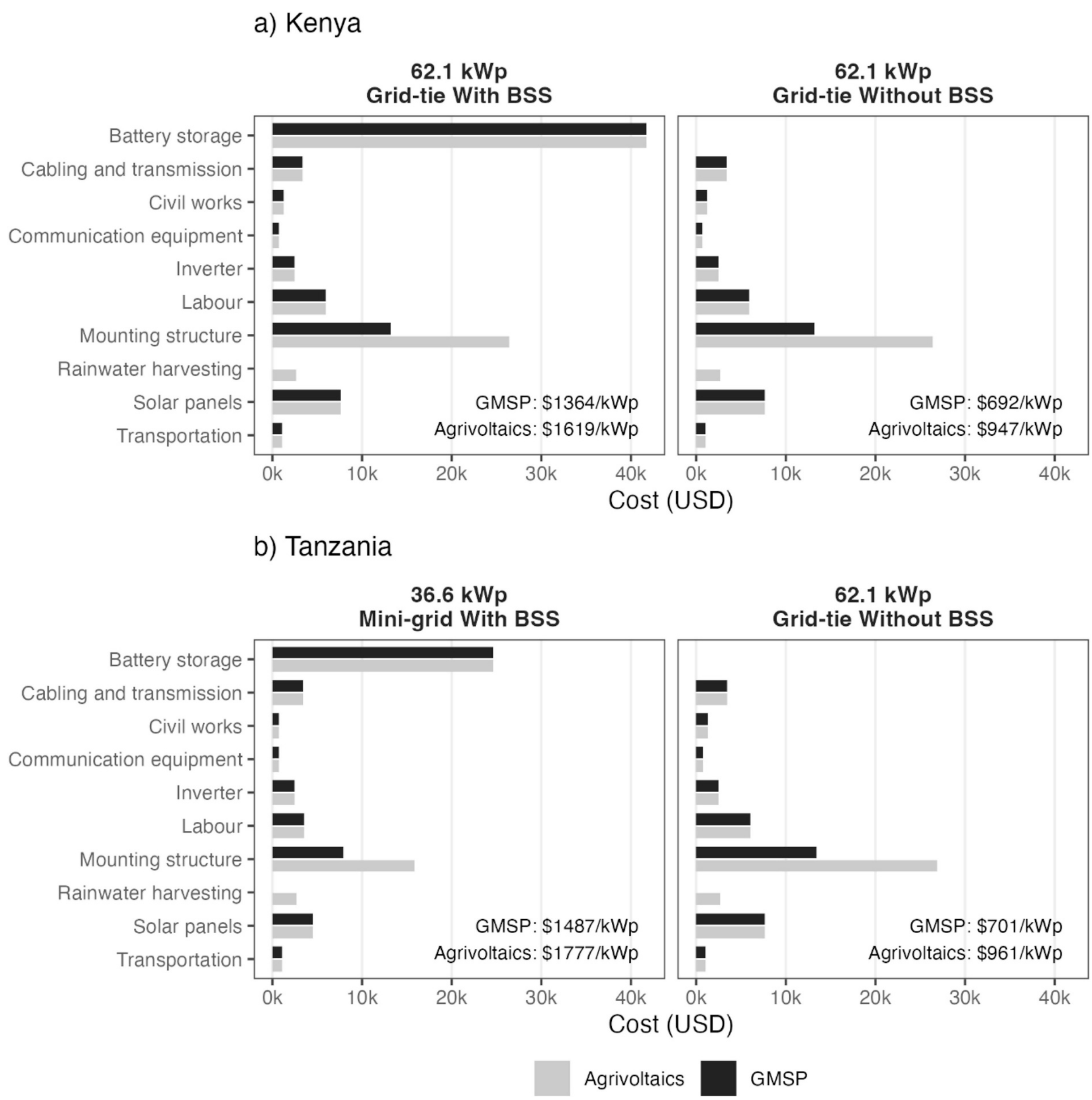

Fig. 3. Installation CAPEX costs. The costs of the components required for each ground-mounted solar park (GMSP) and agrivoltaics scenario in a) Kenya and b) Tanzania, with the total installation cost per kWp annotated. Mounting structures were raised to 3 m for the agrivoltaic systems, which also include guttering and 10,000 L rainwater harvesting tanks. Battery storage was excluded from the grid-tied system in Tanzania as surplus electricity could be sold to the grid with feed-in tariffs.

offer the lowest ROI (GMSP: 70.2%; AV^{agri}: 50.0%; AV^{elec}: 37.5%). This is because they require both BSS and raised mounting structures (thus high CAPEX) while the lower generation capacity provides less income.

3.2.4. Net present value

The grid-tied GMSP without BSS in Tanzania is the most profitable, followed closely by the AV equivalent with an NPV 6.3% lower than the GMSP (GMSP: $104,327; AV^{agri}: $97,709) (Fig. 2). This relatively small difference between the two system types is also notable for systems with BSS in Kenya (GMSP: $96,393; AV^{agri}: $86,910; difference: −9.8%). The differences in NPV of GMSP and AV in mini-grid systems in Tanzania and grid-tied systems without BSS in Kenya are greater, at −14.9% and − 16.7%, respectively (Tanzania mini-grid: GMSP: $38,220, AV^{agri}: $32,541; Kenya grid-tie w/o BSS: GMSP: $56,972, AV^{agri}: $47,489). These differences reflect the greater ROI offered by GMSP, but they do not represent the additional sustainability benefits offered by AV. While the GMSPs offer higher NPVs due to lower mounting structure CAPEX costs, they do not maintain farming practices and income sources, and the AV options present NPVs 349–793% higher than the agricultural baselines. This indicates that AV can be a profitable investment for farmers if they can secure financing to cover the infrastructure investment. While the mini-grid in Tanzania provides the lowest NPV in absolute terms, they offer a higher NPV scaled to capacity than the grid-tied systems without BSS in Kenya (Tanzania mini-grid with BSS: 889–1044 USD/kWp; Kenya grid-tied without BSS: 765–917 USD/kWp) (Supp. mat. Table 1).

3.2.5. Payback period

The cumulative DCFs reveal the breakeven point and ongoing cash flows for each scenario (Fig. 2). In all cases it takes approximately one to three years longer to breakeven with an AV system than with a GMSP. Each grid-tied system without BSS - both GMSP and AV - in Tanzania breaks even in just over three to five years, offering profitable returns for the remaining 20+ years of the predicted lifespan (Fig. 2, Table 4). The payback periods for each system type within the two studied scenarios in Kenya are comparable, where the greater electricity income from the system with BSS negates the higher CAPEX of the BSS. The mini-grid system with BSS in Tanzania takes the longest to breakeven at nine years and three months if agriculture income is included and 10 years and seven months if this income is excluded.

3.2.6. Levelised cost of energy

The levelised costs of energy (LCOE) are notably higher with AV, between 20.9 and 39.5% higher than GMSPs (Fig. 4) due to the higher CAPEX costs. Battery storage has only a marginal benefit for the modelled LCOE in Kenya, as the higher CAPEX costs negate the improved electricity utilisation. The larger grid-tied systems without BSS CAPEX in Tanzania offer the lowest LCOEs, regardless of system type.

3.2.7. Financial security: breakeven electricity income, income sensitivity and discount rate robustness

The 62.1 kWp grid-tied GMSP without BSS in Tanzania requires just 34.3% of the forecast electricity generation to breakeven, while the 36.6 kWp mini-grid AV^{elec} with BSS in Tanzania requires 76.2% (assuming all other values remain unchanged) (Table 4). The former indicates a reduced risk of negative returns from insufficient electricity income in most scenarios, while the latter reveals a higher exposure to reductions in electricity income; the mini-grid scenario in Tanzania only has a 23.8% buffer in electricity income before the system no longer profitable at the end of its 25-year lifespan.

Variations in electricity income/savings have a notable impact on the net present value (NPV) (Fig. 5), while crop sales contribute significantly less to the combined income than electricity sales in all AV scenarios (Kenya grid-tie with BSS: 6.6%; Kenya grid-tie without BSS: 11.3%; Tanzania grid-tie: 9.7%; and Tanzania mini-grid: 8.4%); thus, the NPV of the systems are only marginally sensitive to variations in crop sale values. Mini-grid PV systems in Tanzania are more sensitive to

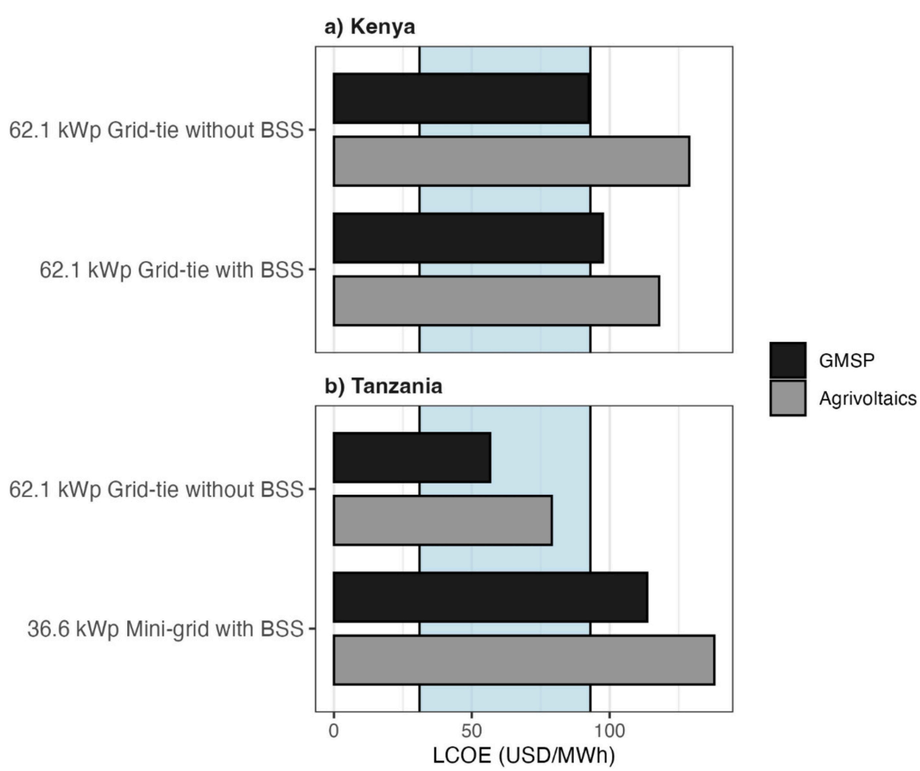

Fig. 4. Levelised cost of energy. The LCOE generated by the two scenarios of ground-mounted solar parks (GMSPs) and agrivoltaics in a) Kenya and b) Tanzania. The blue shaded area represents the forecast LCOE's for solar parks in Africa [56]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

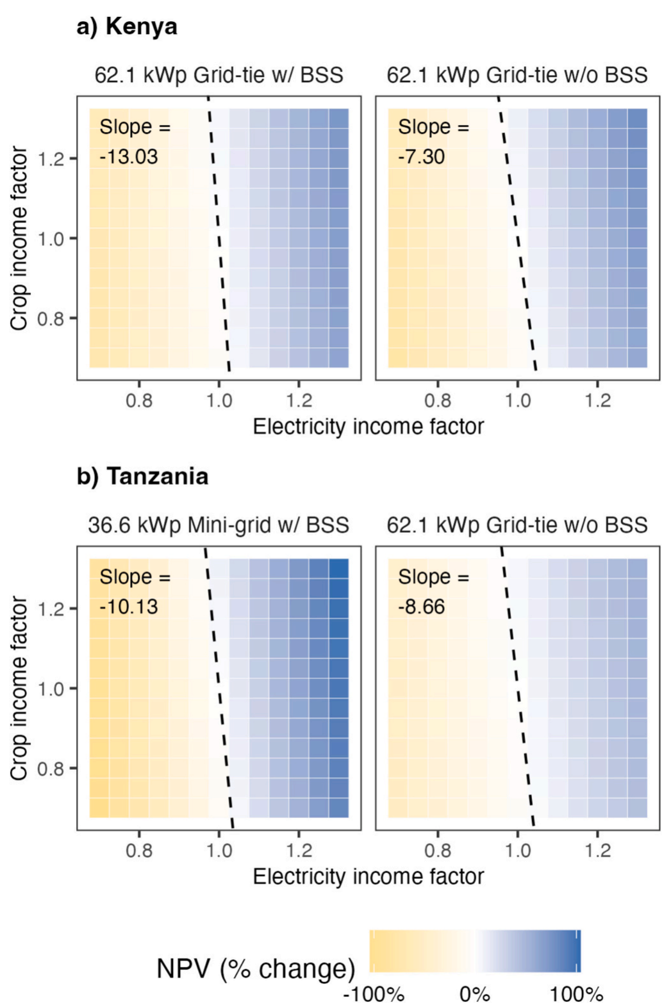

Fig. 5. Agrivoltaics net present value sensitivity. The effects of varying electricity income and crop sale income in 5% increments, up to 30%, on the NPV of agrivoltaic systems from four scenarios in Kenya and Tanzania. The slope is the ratio between the two income factors, signalling a much greater effect of variations in electricity income on NPV compared to variations in crop sales.

variations in income than the other three scenarios, while grid-tied systems without BSS in Tanzania are the least sensitive to income variations (Supp. mat. Fig. 1). The two scenarios in Kenya fall between the Tanzanian scenarios in terms of income sensitivity, with the system without BSS being slightly more sensitive. Agrivoltaics are more sensitive to income variations than GMSPs, but less so when considering both energy and agriculture income sources.

The internal rate of return (IRR) margins for grid-tied PV systems in Tanzania are 18.6% and 27.0% for AV and GMSPs, respectively, presenting a low risk of value destruction. The margins for mini-grids, however, are 6.3% and 8.7%, presenting higher financial risk. The margins for system in Kenya are between these values, and lower for AV (Agrivoltaics without BBS: 9.5%, and with BSS: 10.5%; GMSP without BSS: 15.3%, and with BSS: 13.7%).

The financial results are inherently dependant on the discount rate applied to the model. With a discount rate of 13.5%, the NPV on grid-tied systems without BSS in Tanzania is almost halved, from $104,327 to $62,890 (−39.7%) for GMSPs and $97,709 to $53,494 (−45.3%) for AV with agricultural income included (Fig. 6). For the Kenya systems the value loss is greater: NPVs are 60.0% lower on average. For mini-grids in Tanzania, the IRR range from 17.5% for GMSPs to 13.5% for AV excluding agricultural cash flows. For the latter, the project would simply breakeven after 25 years, while the former generates a low NPV of $13,007. Testing the reported European discount rate of 3.5% for AV projects [79], on the other hand, approximately doubles the NPVs compared to using the surveyed 8.75%, and in the case of mini-grids in Tanzania it is almost tripled.

3.2.8. *Implementing a feed-in tariff in Kenya*

Implementing a feed-in tariff for grid-tied systems in Kenya, negating the need for battery storage or curtailment, improves the economic viability of GMSPs and AV significantly (Fig. 7). The NPVs increase 22–25% compared to systems with battery storage, and 107–129% compared systems with 44% curtailment (Fig. 7a). Such systems breakeven in almost half of the time compared to those without FiTs: after two years, 11 months (GMSP) to four years, one month (AV^{agri}); without FiTs the breakeven points range from five years, three months to seven years, five months. The LCOEs are also 53.0–61.2% lower than without FiTs because the ability to export excess electricity eliminates curtailment and the need for CAPEX-intensive BSS, thereby increasing the useful electricity delivered while reducing system costs (Fig. 7b).

4. Discussion

4.1. *System economics: stakeholder perspectives and financial results*

Our combined economic and qualitative stakeholder perception analysis demonstrates the financial economics of both GMSPs and AV, with or without battery storage systems (BSS), in Kenya and Tanzania. In all scenarios, both AV and GMSPs offer profitable returns on investment. Ground-mounted solar parks are more profitable than AV equivalents, but in some scenarios the difference is not substantial and the AV systems needed just over one additional year to breakeven; thus the latter may be attractive for investors and developers seeking PV initiatives that tackle multiple sustainable development goals. This corresponds with findings from Austria that GMSPs are more profitable than AV [80]. For AV to be attractive, however, the electricity income needs to be great enough to justify the higher CAPEX to raise the systems. Where this is achieved, for example with grid-tied systems in Tanzania where feed-in tariffs utilise all electricity generated and negate the need for costly BSS, AV can be developed with low financial risk. In cases where AV with agricultural income offer NPVs close to GMSPs, financial incentives that fill the NPV gap by valuing the multifunctional land use AV offer could make them a financially attractive alternative to the single-use provided by GMSPs.

It is notable that stakeholders interviewed raised concerns about potentially high upfront CAPEX costs – particularly the mounting costs of AV arrays. They called for a comprehensive cost-benefit analyses to assess AV CAPEX and OPEX costs, and they stressed the important of access to finance to support them. The energy components of AV dominate the OPEX and income values, a common finding with AV economics [34,53], although the sale of crops — especially high value items such as onions — provide a valuable income stream for farmers. While installation costs are higher for AV than for GMSPs, the differences between scenarios are greater than the differences between the two PV applications (GMSP and AV) within each scenario, highlighting the impact that installation context (grid-tied or mini-grid), BSS requirements, feed-in tariffs (FiTs) and electricity prices have on solar park CAPEX. Despite the high cost, BSS have a vital role in modern energy systems. The increasing contribution from renewables to the grid presents both benefits and challenges; while on one hand they offer low-carbon, local and renewable electricity, on the other they generate variable and intermittent supply that can contribute to grid instability and needs appropriate management and mitigation [81–83]. This is the case globally, and especially so in countries with underdeveloped grid infrastructure. Extensive BSS integration with grid-tied systems could mitigate these generation and load imbalances, thus adding stability to the grid [84,85].

The benefits of FiTs for encouraging investments in energy

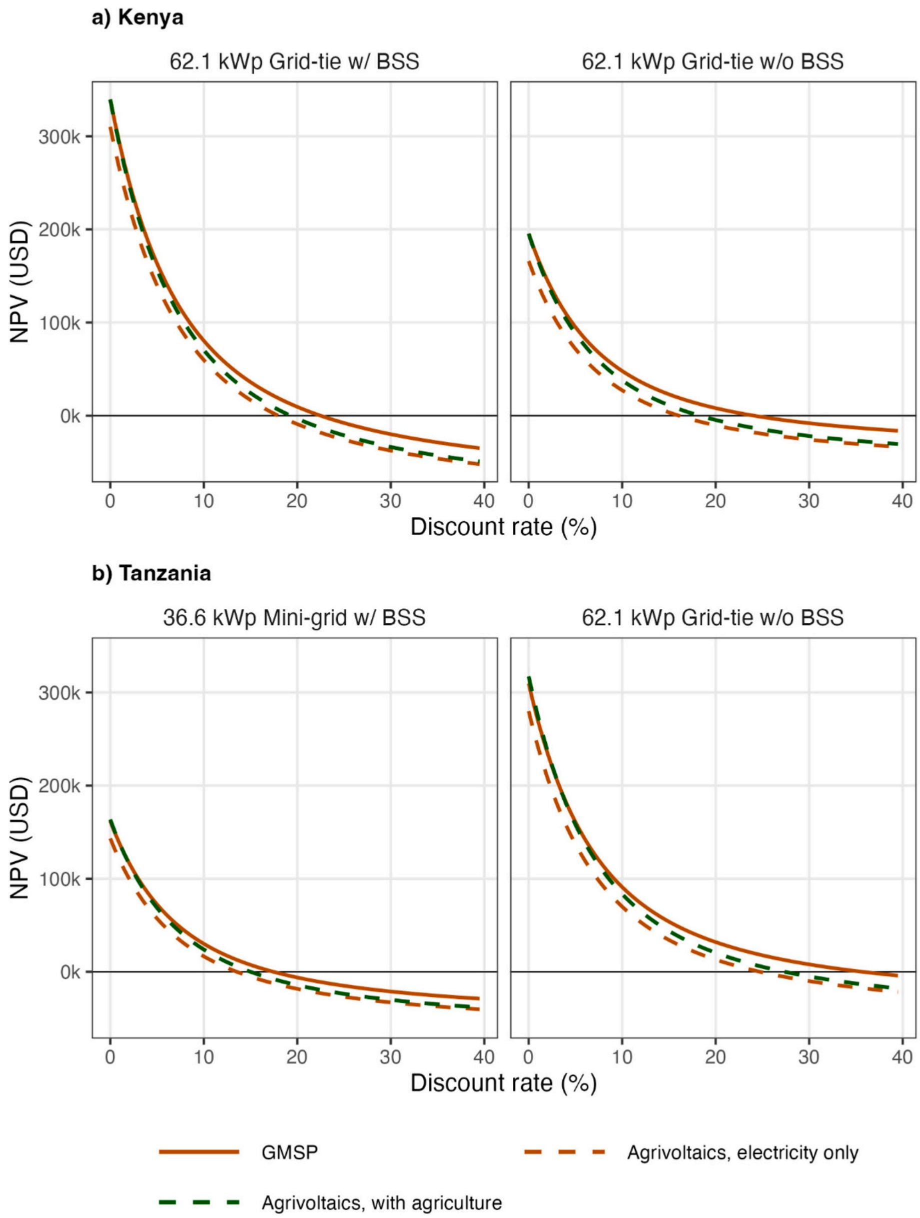

Fig. 6. Discount rate robustness. The relationship between discount rates and net present value (NPV). Discount rates resulting in a NPV below 0 result in value loss.

infrastructure are widely reported [86,87]. In this assessment, the profitability of grid-tied systems in Tanzania without BSS is largely due to conducive FiTs that support and encourage PV developments. Conversely, the lack of FiTs in Kenya either increases the risk of curtailment – wasting valuable energy – or necessitates BSS with sufficient storage capacity to maximise energy utilisation, significantly escalating CAPEX and risk of unaccounted OPEX maintenance. Kenya has been reported as an attractive location for energy investments [86], but the lack of FiTs limits the financial returns that are offered to investors in neighbouring Tanzania where FiTs are available. Including FiTs boosts the financial returns and investment appeal of GMSPs and AV in Kenya, which could encourage investment and development of the technologies that add supply to the grid while simultaneously offering a revenue source for the national energy provider, KPLC. On the other hand, FiTs are susceptible to changes in policy that reduce returns, increasing the risk for investors. Where PV is owned by the end-user instead of an investor or developer, however, the stability of local electricity generation for self-consumption can buffer against energy price shocks [88], the latter which can consequently drive food price shocks [89]. This is important because interviewed stakeholders identified challenges related to farmer access to finance, and thus affordable and innovative financing models (e.g. pay-as-you-go, results-based financing) were identified as essential to support farmer adoption and farm productivity. Fixed FiTs can potentially improve returns and buffer against price shocks, improving system economic performance and potentially increasing farmer access to finance due to the de-risking of the investment.

The levelised costs of energy for GMSPs are within the range, or marginally above, the $31–93/MWh for solar PV in Africa presented by the International Energy Agency (IEA) in 2020 [56]. Levelised costs of energy for AV vary, generally at the upper end or above this range, but in the case of Tanzanian grid-tied systems - which benefit from FiTs and lack costly BSS (unlike the mini-grid scenario) - the LCOE for AV are at the lower end of the reported range, positioning the technology as an attractive PV investment. The IEA forecasts the LCOE of PV in Africa to decrease 42–47% to $18–49/MWh by 2030, and AV would likely see a cost reduction. The modelled LCOEs for GMSPs and elevated AV in Africa are within a factor of two of comparable systems in Europe [53] and

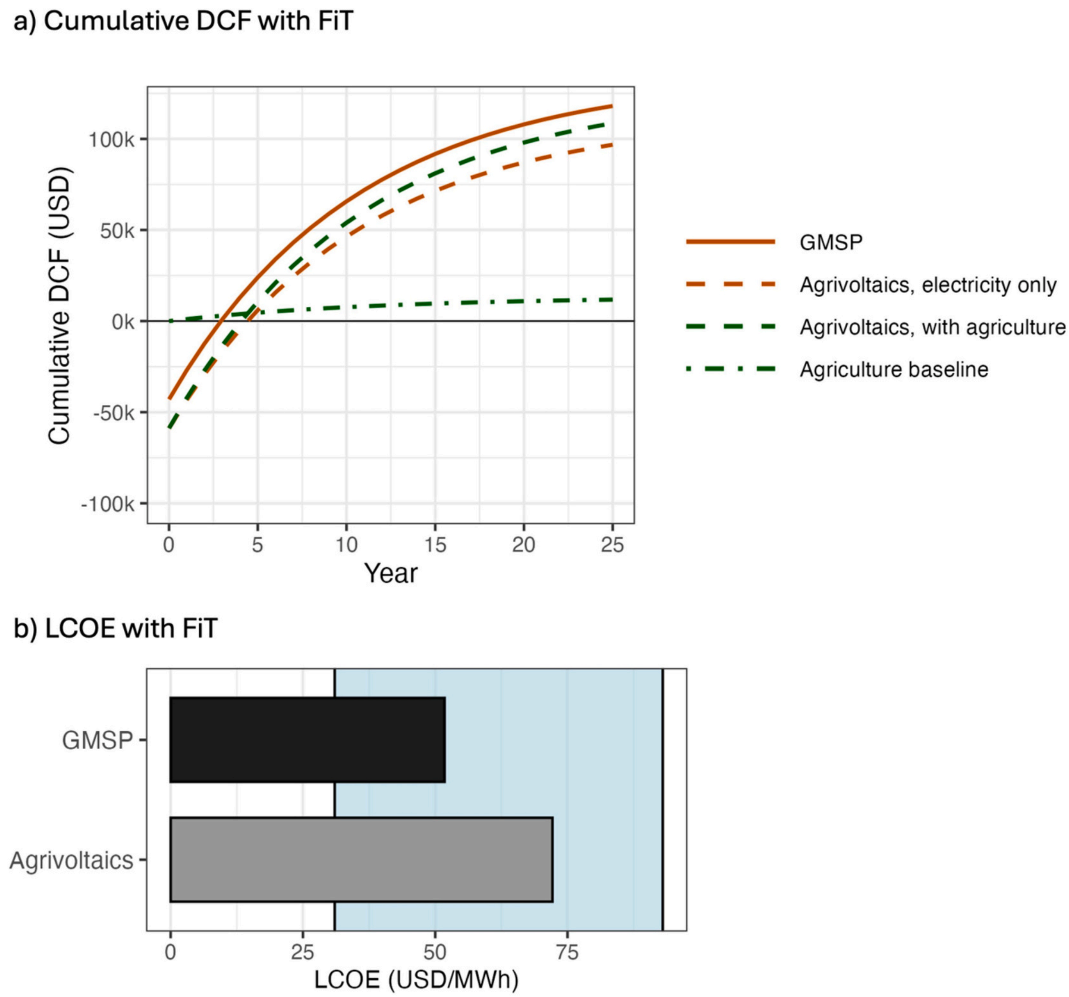

Fig. 7. The effects of a feed-in tariff on cash flows and levelised cost of energy in Kenya. The cumulative discounted cash flow (a) and the LCOE (b) for 62.1 kWp grid-tied systems in Kenya without BSS when modelled with a 0.165 USD/kWh feed-in tariff applied to 100% of the electricity generation. The blue shaded area represents the forecast LCOE's for solar parks in Africa [56]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a tensile-supported AV system in Italy [28], highlighting the higher costs of energy in Africa. The NPVs of each of these studies also forecasts profitability for AV, and, like the findings presented here, are marginally lower than the NPVs of GMSPs. The mounting structure contributes a significant portion of the CAPEX and thus impact on LCOE, representing a focus point for innovation and cost-reduction. As noted by stakeholder interviewees, pilot projects are deemed necessary to demonstrate different build types, and to foster farmer and community engagement with the technology. New AV pilots could thus experiment with the design of mounting arrays and different materials to improve this engagement process and lead to greater uptake while also presenting an opportunity for innovating and testing optimised mounting structures. For example, wood structures may be cheaper than steel and thus reduce LCOE for small-scale applications [90], although require more maintenance. Market-wide improvements in BBS technologies and costs will also bolster rural uptake by reducing CAPEX costs for off-grid and mini-grid systems.

The modelled financial returns are directly tied to the discount rates set, and the internal rates of return (IRR) reveal that mini-grids with costly BSS in Tanzania are a higher risk for investors, despite the lucrative FiTs. Conversely, the grid-tied systems without BSS offer a much high buffer between the discount rate and the IRR, indicating lower risk. The variability between the scenarios reveals that some AV specifications are likely to be attractive for investors while others are not. The payback periods for AV are slightly longer than those for GMSP, approximately one to three years extra for each scenario. The longest payback period, a 36.6 kWp mini-grid AV system with BSS in Tanzania, takes nine years and three months to breakeven - almost half of the project's forecast lifespan. On the other hand, a 62.1 kWp grid-tied AV system without BSS in the same country breaks even after four years and six months, i.e. within the first fifth of the project's lifespan. These payback periods align with other modelled systems, such as 3–3.5 years for AV with tomatoes in Botswana [91] and 7.9 years for AV with tomatoes in India [92]. Longer PV lifespans are reported in Europe for PV, up to 30 years [93], and if achieved in East Africa this would increase profitability for all scenarios. Combined with the additional land use sustainability and potential climate-change resilience benefits for crops [46], AV could be an attractive investment for investors seeking profitable and sustainable infrastructure projects and for agribusinesses seeking new energy solutions.

4.2. *Business models and use cases*

One barrier facing AV uptake is the complexity of operating across two distinct sectors - energy and agriculture. This can be exacerbated by economic imbalances between the sectors. How different stakeholders will operate and benefit from the technology depends on the business models and use cases, which can be complex due to the sectoral distinctions. Multiple business model structures can be applied to the ownership and operation of AV, with single or combinations of stakeholders [94]. These can build on traditional business models for PV, such as power purchase agreements or FiTs, with the sale of electricity combined with agricultural revenue streams. In single-ownership models, the land/farm owner and the panel owner are the same. The owner may be an individual, a business, or a cooperative, and energy generated may be for own use or for income generation via FiTs if available. In dual-ownership models, the land/ farm owner and the owner of the panels are different. Typically, the panel owner is an energy developer or a power company who rents the land or has a PPA with the landowner.

The energy components of AV dominate both cost and income values, with electricity values tenfold greater than crop values for food crops. However, the magnitude of income disparity between energy and agricultural production is dependent on the scale of the system, the value of crops produced, and local energy market prices; a small 0.675 kWp household system growing high value crops in India demonstrated energy and crop costs within the same order of magnitude [95]. For farmers, AV profitability is perceived to be linked to strategic crop selection, reliable market access and the integration of AV into broader agricultural value chains to enhance returns and increase farm competitiveness.

The multifunctionality of AV diversifies income streams, with the split of the income streams (energy and agriculture) among the stakeholders being dependant on the business model of each case. For singular owners operating both the energy and the farming system, this can provide valuable resilience to income shocks, such as changes in electricity or crop prices due to policy change, market fluctuations or environmental disasters [96]. However, it was noted by the stakeholder interviewees that investment in AV could potentially divert farm funds from other critical sustainability measures such as fertilisers, pesticides, climate-resilient crops or water-saving technologies, thus the financial risk-benefit equation from investment choices needs to be clearer for farm managers.

Cooperatives present a potentially valuable ownership model, particularly applicable to mini-grids, where the members of the cooperative pay for the system through joint financing to de-risk investment. Cooperatives can enable a rural community to install a PV or AV system with high upfront CAPEX by reducing the financial burden on individuals [97]. This is valuable, as the stakeholder interviewees highlight continued limitations to farmer access to finance. However, in practice, cooperatives can overburden community members paying for the system [98] and lead to potential intra-community conflicts around consumption, repayments and equality.

The added CAPEX of AV compared to conventional GMSPs needs to be accounted for to attract investment. For dual stakeholder-operated systems, this could be achieved by land-owning farmers offering reduced costs of land for energy developers in exchange for a share of electricity income or reduced electricity prices in return. External benefits such as additional subsidies, tax incentives or low-interest loans for energy developers that benefit multiple SDGs through AV could also be offered by governments to attract investment and reduce LCOE [99]. Carbon credits offer an incentive for sustainable energy solutions [100], and another innovative approach to make AV attractive would be to account for the environmental value of directly combining low-carbon electricity generation with agricultural production for multifunctional land use. While the concept of natural capital – economically valuing the benefits provided by ecosystem services to society – has been discussed for decades [101,102], the full value of sustainability initiatives is often under looked. The need to address energy-agriculture land use conflicts and associated community and political resistance arising from the rapid expansion of solar PV also makes AV an attractive option for developers, as it can avoid such conflicts [31,103,104], particularly when developed through an inclusive decision-making process [105].

Financial support is particularly necessary for rural electrification where the lack of established income streams adds uncertainty and risk to financial viability [15]. Aside from subsidies, stakeholder interviewees also highlighted the need for early and inclusive stakeholder engagement with rural communities to demonstrate construction practices, cost-benefit, and clear alignment of AV planning with regional and national policy frameworks as enablers to attract potential farmer uptake. They also noted, however, that technical capacity and infrastructure limitations in rural areas, such as grid connectivity, transport, and skilled labour, are significant challenges requiring targeted investment and support.

This study modelled single-owner AV systems operating on medium-scale vegetable farms with direct-to-consumer sales, a common agribusiness in the region. The NPV of AV was relatively insensitive to the value of crop sales in these scenarios; however, as several interviewed stakeholders suggested, switching to higher value crops could make the business model for AV more attractive. Cash crops such as coffee, a shade tolerant crop highly sensitive to the changes in rainfall and temperature predicted under climate change [106,107], can fetch prices of 100× or more the market price of vegetables such as maize, cabbage or tomatoes in Kenya [108]. Ample energy provided by AV can also expand the range of agricultural activities available to farmers, such as drying, cold storage, post-harvest processing, or value addition activities, further adding to the income from AV. Stakeholder interviewees similarly highlighted the need for broader supply chain integration, and these value-added approaches were perceived to improve farmer uptake of AV.

Although the benefits of rainwater harvesting and reduced evapotranspiration were not tested in this study, results from the pilot study in Kenya indicate that these features alleviate demands on local water resources for irrigated systems and protect crops from heat stress [46] – the latter being notably valuable for rain-fed systems, where crop survival during periods of drought are directly linked to incomes and livelihoods.

4.3. Future research, development and policy steps

The perspectives presented here provide an insight into the views of relevant stakeholders from two East African countries. Further quantitative survey research across the broader East African geographic scope to ascertain views of individuals and groups from different locations and organisations would strengthen this understanding. The economic model is based on two case studies of market-scale vegetable farming in Kenya and Tanzania, expanded to include relevant contexts of BSS to increase electricity utilisation in Kenya and grid-connection with FiTs in Tanzania. The findings have relevance beyond East Africa to other regions with similar environmental conditions and energy markets, and the study can contribute to development decision making in other tropical and semi-arid locations, especially those elsewhere in Africa. Appropriate data from different system designs (e.g. panel densities) and capacities (of several hundred kW to 10s of MW) in other locations in the region with different microclimate and soil conditions, and with alternative agricultural models including livestock [109], would enable a fuller assessment of the performance, economics and potential of the technology across the broader East Africa region. Optimising designs in terms of construction materials and panel densities will improve the economics of the systems, appealing to developers and investors while also improving the lifecycle sustainability of the installations [52].

Exploring how the technology aligns with national and regional policies would highlight potential avenues for government and international support for the technology, key for advancing nascent climate technologies from demonstration phase to commercial uptake in a region where public-private partnerships are common in infrastructure development [110,111].

This study highlights the grounded economic benefits offered by FiTs in Tanzania for PV and AV deployment and showcases the positive impacts that introducing FiTs in Kenya could have for both PV and AV uptake and for KPLC (the national electricity provider). Such policies could boost PV expansion, delivering several economic, social and sustainability objectives such as rural electrification [112,113], economic development associated with energy security, and decarbonisation of energy sources [114].

Building local knowledge and capacity will also foster uptake and self-sufficiency by local businesses and entrepreneurs, avoiding pitfalls of technology transfer and supporting technology absorption [115]. The stakeholder interviewees recognised the importance of pilot projects, demonstration sites and accurate cost-benefit analyses for different sizes of agribusiness in building trust, showcasing feasibility, and providing this platform for further engaging local communities before widespread regional rollout and upscaling of the technology takes place.

5. Conclusion

Agrivoltaics is rapidly expanding in Europe, North America and Asia but is understudied in Africa, where some of the greatest benefits for improved energy security and climate change-resilient food systems could be realised. This mixed-methods work combines stakeholder perspectives with economic modelling, based on empirical and modelled data, to inform investment and policy decision-making for PV and AV deployment in East Africa. Economic factors are notably important for stakeholders, with concerns over CAPEX costs being too high and a need for financial support. The stakeholder-requested financial comparison between conventional GMSPs and AV reveals that both systems are profitable in the four modelled scenarios, with varying returns on investment and payback periods reported. Ground-mounted solar parks are more profitable than AV, but AV still offer returns on investment that, combined with addressing other social and sustainability objectives, may position AV as an attractive option for investors, governments, energy companies and agribusinesses. Levelised costs of energy are slightly higher than reported ranges for PV in the region, reflecting the higher CAPEX required. Factoring in crop sales improves the economics of AV. Business models that are viable for both the energy and agriculture components of the system need to be established, especially where multiple stakeholder groups span the two distinct sectors. Further, stakeholders emphasise the need for the complete value chain of AV to be understood. Introducing a feed-in tariff in Kenya improves the financial incentives for PV and AV development, as observed in Tanzania, suggesting such a policy would be beneficial if adopted. It is clear from this study that knowledge awareness, financial incentives and capacity building mechanisms are necessary to support uptake. With multifunctionality, diversified income sources, and improved stakeholder support, AV present a potentially viable alternative to GMSPs, delivering scalable energy sources to on- and off-grid communities simultaneously with climate change-resilient food production and water conservation.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT and Copilot to review and consolidate python and R code. After using these tools, the authors reviewed the code and edited it if necessary. The authors take full responsibility for the content of the published article.

CRediT authorship contribution statement

R.J. Randle-Boggis: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **A.W. Kuria:** Writing – original draft, Investigation, Formal analysis, Data curation. **M. Cotton:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K. Parkhill:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Lamanna:** Writing – original draft. **S.E. Hartley:** Writing – review & editing, Funding acquisition, Conceptualization.

Ethics statement

Ethical approval for the stakeholder perspective study was obtained from the Department of Environment & Geography's (University of York) Ethics Committee in accordance with institutional and General Data Protection Regulation (GDPR) requirements. All participants interviewed received detailed information about the study objectives, procedures, data handling, and their rights, prior to participation. This was accompanied by a written informed consent, which was obtained from all interviewees prior to the interviews, where they were requested to choose their preferred level of anonymity or attribution.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2026.128450.

Data availability

Data will be made available on request.

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