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Harnessing the sun for agriculture: Pathways to the successful expansion of Agrivoltaic systems in East Africa

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ABSTRACT

Agrivoltaic systems (AVS) (elevated solar arrays enabling energy and rainwater harvesting alongside crop production), have been gaining increasing traction globally. Most research has focused on the technical efficacy of AVS, with less attention paid to social dimensions and few studies in East Africa (EA). This research had two aims; firstly, to identify the critical enabling factors, institutions and support required to successfully widen AVS adoption across EA. Secondly, could widening adoption help address increasing climate-energy-food production-population growth challenges predicted for the coming decades. We present findings from two case study farms where AVS was installed (Kenya and Tanzania). We undertook user journey mapping with 14 participants associated with the case study farms, to monitor their experiences, building narratives that identify critical enabling factors and support required to successfully widen East African AVS adoption. The case studies are supplemented by additional farmer interviews ($n = 44$) and two end of project workshops with diverse regional stakeholders. Our findings indicate AV technology could be beneficial to a range of agricultural systems and contribute to addressing climate-energy-food nexus issues in EA, but innovations are needed to enable this uptake. Specifically, widening AVS adoption equitably requires: government interventions to deal with land tenure uncertainties particularly for small-holders and cooperative farms; provision of appropriate finance mechanisms for different types of beneficiaries; reforming the current regulatory framework for energy investments and payments for surplus distribution of AV electricity; and, developing assistance from additional supporting agencies (e.g. regulatory, agricultural and technical) at key touch-points in the adoption process.

1. Introduction

East Africa (EA)[1] is one of the fastest transforming regions globally. Projections show that these countries are undergoing the most rapid population growth with rates for many EA countries at around 3 % per year [1]. Population are projected to grow from 458 million (2021) to 861 million (2050), a 53 % increase [2]; a massive shift bringing development and sustainability challenges alongside potential economic opportunities.

Concurrently the region has pressing food security issues with increasing extreme weather events leading to droughts and floods whilst exacerbating impacts of pests and diseases for both crops and livestock [3]. The EA agriculture and livestock sector is dominated by rain-fed crop production and animal husbandry meaning climate shocks can severely disrupt local food production and supply. This disproportionately affects low-income communities with less resilience and lower adaptive capacity to respond to these disruptions. These impacts combine to exacerbate malnutrition, particularly for the most vulnerable [4]. Recent climate change projections [3] indicate increasing risks from these extreme weather events that will intensify challenges for agricultural production needed to satisfy the growing regional demand. Key changes include increasing extreme heat, particularly affecting human health and agricultural production in existing semi-arid environments. Conversely in the Blue Nile region enhanced rainfall extremes are likely to disrupt agriculture with severe flooding.

Alongside these environmental and demographic changes, demand for energy across the region is increasing with both population and economic growth. However, energy access remains an overarching

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[1] Composed most broadly of Burundi, Comoros, Djibouti, Ethiopia, Eritrea, Kenya, Rwanda, Seychelles, Somalia, South Sudan, Sudan, Tanzania, and Uganda.

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challenge in sub-Saharan Africa with only 19 % of the population connected to a national electricity supply in rural areas [5]. Yet the potential for improving access to sustainably produced electricity remains high with more than 55 % of the East African population not connected to reliable electricity supplies [6]. In rural areas these energy deficits exacerbate food insecurity issues during both production and post-harvest by reducing the ability to pump irrigation water and prevent the refrigeration or post crop processing.

To increase EA agricultural productivity by improved energy access, distributed solar photovoltaic (PV) systems have been promoted as a possible solution, particularly addressing the need to increase yields through irrigation [7]. Geographic assessments of the hotspot locations where PV would be particularly effective for electricity generation identify East Africa as one of six regions with the highest opportunities based upon solar irradiance levels [8]. These conditions are predicted to persist despite future climatic scenarios indicating irradiance changes with increased cloud cover that will decrease PV potential by up to 10 % in some parts of this region [9].

Despite this EA environmental and infrastructure conditions still make the region particularly well suited to deploy this technology to address energy access, particularly in rural areas. However, pure solar developments bring with them challenges of land conflicts through tensions between releasing land for power generation and the need for food production. To overcome this trade-off agrivoltaic systems (AVS) have been gaining increasing traction globally and in EA as a way of enabling both improved availability of electricity whilst maintaining access to land and improving agricultural yields [7,10]. Sarr et al. (2023; pg. 3) [7] define AVS technology as a “land-use concept that directly integrates solar energy production and agricultural activities, which are practiced under the photovoltaic field installation, both of which are highly dependent on sunlight”.

According to Wydra et al. [11] an AV system can be classified on the basis of the following aspects:

- application (agriculture, livestock)
- system (open, closed [greenhouse])
- construction (high, slightly elevated, vertical, and others)
- type of agricultural use (horticulture, arable crops, fruits, permanent grassland)
- flexibility (mobile, permanent system; plant/energy-optimized tracking).

AV systems typically elevate the PV panels above the ground enabling crop cultivation or livestock production to be continued. The shading from the panels can also provide production co-benefits by reducing evapotranspiration from soil and crops, reducing temperatures and improving growing conditions for specific crops. This reduced heat potentially also benefits human, crop and animal health. AV co-benefits can include harvesting rainwater falling on the panels for storage with solar generated electricity being used to enable pumping of this increased supply for crop irrigation under the panels or in neighbouring fields.

To date, most research has focused on engineering design and technical efficacy of AV systems [12], with far less attention paid to the social dimensions including stakeholder perceptions, despite the importance of these for the successful diffusion of innovations [13]. However, the following section outlines insights generated by previous research about stakeholder attitudes and perceptions to AV systems.

Literature Review: Stakeholder attitudes towards AVS.

Devine-Wright and Wiersma (2020) [14] note the importance of understanding the social acceptability of new developments, in advance of their contestation during their implementation. Other research has outlined how social conflicts can pose development challenges and significantly delay or impede the diffusion of innovation [13]. Thus, it is integral to understand how stakeholders view technological innovations like AVs.

Past studies have found that in general there are positive attitudes towards AVs by: German farmers [15]; Tirkeye farmers [16]; US farmers and communities [17,18]; German, Belgium and Denmark stakeholders (including farmers) [19]; and, Greek farmers [20]. Such positive attitudes relate to the perceived “win-win” of AVs whereby farmers can diversify their incomes through electricity generation combined with production of food [15,19].

The perceived “usefulness” [15] of AVs goes beyond the use the production of renewable energy to diversify incomes. Stakeholders across a number of studies are optimistic that AVS could provide cost savings through reducing the need for vegetation management [18], producing electricity to run irrigations systems or foods processing plants or cooling systems for animals, or reduce water costs via increased water conservation through the provision of more shade, and reduce crop losses from extreme weather through shielding and sheltering crops [15,16,19], However, significant concerns related to costs were also raised, including how to fund the required upfront capital demand of such systems and the economic efficacy to payback the initial capital investment [16], whether the crops produced would be economically viable [21], and whether the presence of the panels may require more vegetation management and an increased need for pesticides [19].

A significant potential benefit of AVs put forward by solar industry experts [17] and farmers [15] was that such developments may increase the social acceptability of solar developments, which are becoming increasingly contested by rural communities [17]. This includes improving perceptions of developers to be seen as helping local ventures (i.e. farms). However, US studies also show increased support is dependent on nuanced factors, such as the arrays not being visible from residences, not placed on public land and not publicly subsidized [18]. Stakeholders (farmers in Germany [22], 2022; stakeholders in Germany, Belgium and Denmark [19]) noted that AVS incorporating fruit crops would likely be more aesthetically pleasing and socially acceptable than current processes using plastic or hail nets. East African concerns from the present study seem markedly different to this European and US perspective with access to electricity and creating more hospitable crop growth conditions of concern, rather than increasing social acceptability.

Previous work has outlined how attitudes towards innovations can be mediated by environmental governance policies [13]. Alqasa and Talt (2023: 142) [13] state that “when government policies align with innovative practices, organisations experience enhanced sustainability from both environmental and social standpoints”. This is significant as an enduring concern by stakeholders across multiple studies relates to institutional challenges created by complexities or uncertainties within political frameworks including bureaucracy, revolving legislation, regulation, planning processes [15,17,19]. Such concerns were seen as significant barriers for the uptake of AVs.

Whilst co-location of farming with agriculture was generally perceived as beneficial, farmers across several studies, raised significant concerns regarding the permanency of AV structures and how these may interfere with, or impede, long-term land productivity plans and framing practices [16,21] Operational issues such as AVS inhibiting agricultural machinery use, were also potential barriers [15,19,21,22]. However, some studies argue that AVS “would allow farmers to choose a tailor-made set-up to meet their farm’s specific energy demand curve” and preferred agricultural processes (Torma and Aschemann-Witzel, 2023: 616) [19], thus underpinning the strong potential for AVS to be successfully developed if designed and operated *by*, or at the very least, in partnership with farmers.

Importantly, Pascaris et al. (2021:3) [17] assert that “the effective diffusion of the agrivoltaic innovation is strongly related to the acceptance of farmers” (2022a: 2; also see: [16,18]). Whilst we do not disagree, a significant difference between such studies and ours is that they are largely viewing farmers’ role as landowners or working the land [17,18], rather than as (co)developers or operators of such energy production developments. In addition, unlike our research, the other studies reviewed have detailed stakeholders' perceptions of hypothetical or proposed developments (often by way of contrast with solar arrays), rather than lived experiences of developing, operating and owning AVS. A final key difference between existing studies and ours is the geographical location. Most previous work has taken place in the Global North [16], whereas ours is in the Global South specifically East Africa, which to our knowledge has not been the location of any previous AVS research.

Addressing these issues this paper presents findings from two EA case study locations (Kenya and Tanzania) tracking the installation and use of AVS to identify the critical enabling factors, institutions and support that would be required to successfully widen the adoption of this technology across the region to address the energy access-food security under a changing climate-population growth challenges. The case study findings are supplemented by additional interviews with farmers adjacent to the test sites. Insights are further expanded upon from Kenya and Tanzania workshops that brought together stakeholders from across the region to explore this technologies potential.

2. Methods

2.1. Case study sites and AV installations

Two relatively large-scale test AV systems were built and installed; one in Kenya at Latia Agri-business Centre and the other in Tanzania at Sustainable Agriculture Tanzania (SAT) (see Figs. 1 and 2).

Latia Agri-business Centre (afterwards called Latia Farm) is a training centre delivering technical and vocational courses to students to improve their agricultural knowledge and business skills. Latia Farm also grows crops for sale to local and Kenyan national markets. Latia is in Kajiado county with a tropical wet and dry or savanna climate (Köppen-Geiger climate classification: Aw). SAT is primarily an educational establishment upskilling farmers in agro-ecology concepts through practical hands-on training. The atmospheric conditions prevailing in this region are tropical with drier winters and wetter summer seasons (Köppen-Geiger climate classification: Aw). Both sites are experienced in running experimental crop trials and evaluating their performance so were ideally suited to explore the AVS impacts on the nexus of food, water and energy.

The SAT AVS is off-grid with a lead-acid battery storage system, providing electricity to the farmer training centre that previously relied on diesel generators. The system at Latia is grid-tied, supplementing the existing electricity supply. Respectively, the sites have peak capacities of 36.6 kWp (SAT) and 62.1 kWp (Latia). The photo-voltaic (PV) arrays are supported by steel mounting structures fixed into concrete foundations. Both systems are structured with a 50 % panel density, with the gaps to improve sunlight distribution to underlying crops. Guttering at the lower edges of the PV panels channels rainwater and panel cleaning water runoff into 10,000 L storage tanks for later irrigation use.

2.2. User journey mapping

To understand the experiences of the AVS at our test sites and identify issues and opportunities for introducing and upscaling the adoption of these systems more effectively we utilized a service design method known as 'user journey mapping' (UJM) or customer journey mapping [23–25]. UJM not only allows the exploration of the 'use' but also the 'experience' of a system or service [26]. This experience is dynamic and evolves over time based on perceptions and actual practice of utilizing a system and supporting services. Applying a UJM approach to the development, installation and use of the AV system allows us to explore beyond the purely technical outputs. This method can generate rich insights into the barriers and opportunities resulting from the introduction of a technology that can help shape more successful approaches to upscaling the installation of an innovation to a wider community [27].

We utilized UJM to track, map, visualize and build narratives around the experiences of our case study farms through the development and working with the AVS. This was supplemented with additional UJM interviews with the solar installers and the system developer (see Table 1 below). The interviews were undertaken in three phases: (i) before accessing the AVS when the stakeholders were in the discovery and planning phase in order to understand how they become aware of the concept as well as their expectations; (ii) after the initial construction and initial use of the AVS, and; (iii) finally after a longer timeframe to explore their more reflexive understandings following mature experience as well as their future concerns or aspirations for the technology and service [27]. The final interviews included questions to explore perceptions on which types of farming system would be most suitable for adoption of AV, from our two case study farms participants perceptions in both countries.

User journey perspectives were explored in semi structured interviews. The interviews were recorded, transcribed, coded and analysed using NVivo software. The coding framework was conceptually developed by a project team investigating international, national, local, as well as user journey perspectives, on agrivoltaics before the interviews were undertaken. The coding framework was then empirically tested against the data by the team through comparison of independent blind coding of selected texts to assess their reliability. There were 46

Fig. 1. Case study AV trial systems (Left: Latia Agri-business Centre, Kenya; Right: Sustainable Agriculture Tanzania).

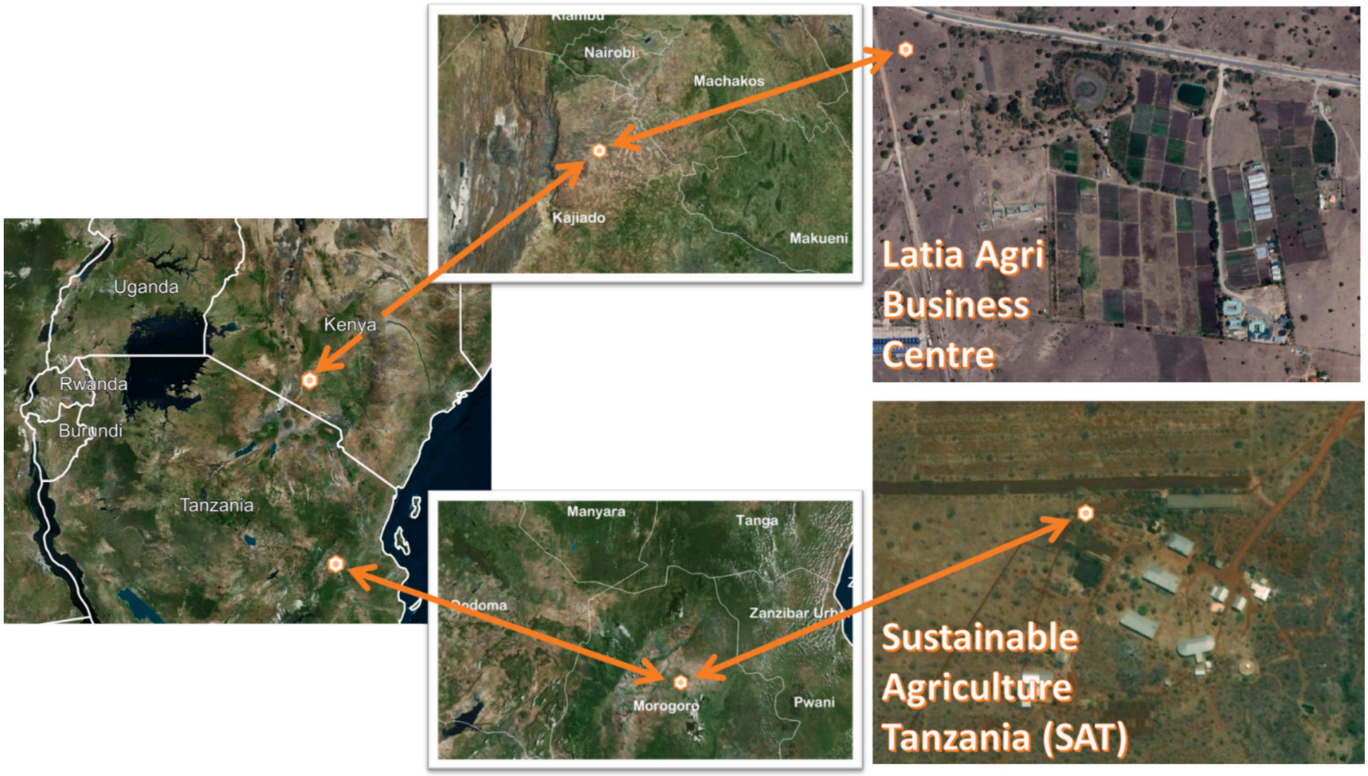


Fig. 2. Case study site locations.

Table 1
List of Interviews and participants in the UJM. Note: Interviews participants and numbers differed between case studies due to the phasing of the AV system construction and availability of participants.

Country	Participants	UJM Stage – Number of interviews			Total
		(i) Before (Pre-install)	*(ii) Year 1–2 (Post-install)*	*(iii) Year 3+ (Medium term)*	
Kenya	Technology Champion	👍			1
	Farm Owner & Business Manager	👍	👍	👍	3
	Farm Manager	👍	👍	👍	3
	Solar Developer & Installer	👍		👍	2
Tanzania	Farm Manager	👍		👍	2
Both	Solar Researcher	👍	👍	👍	3
TOTALS		6	3	5	14

codes identified relating to issues and concepts such as age, gender, land use and justice as well as barriers, opportunities and benefits of development. Three codes for classifying the user journey as before, during or after the development took place were applied to track changes. Each code was given a definition and an example of the data to be coded to that node.

The UJM can highlight key "touch-points" [23–25] along the adoption of a service that could be critical in determining initial investment or long-term use of technology. These "touch-points" represent positive or negative experiences or the key considerations for participants at different steps that could lead to different outcomes for other adopters of AVS. They can also be used to highlight which agencies or service providers were utilized or should be involved at these different critical moments, particularly when they are currently absent.

The UJM interviewees were recruited as key informants from the case study sites. In addition to the UJM process, intercept surveys were undertaken with farmers adjacent to Latia and SAT (with more details below). The breakdown of interviewees can be seen below in Table 1.

Using qualitative data analysis, the theme and volume of mentions of codes at different time steps were used to identify the importance of issues by country and stakeholders. This data has been used to track the UJM experience (positive, negative, mixed or neutral) across the different timesteps. From this a single UJM visualization that integrates the specific experiences from our two case study sites was developed. Based on participants perceptions a second visualization highlights the critical agencies that were involved in the installations of the AV systems but also the agencies that potentially need to be involved to optimize the upscaling and wider adoption of this technology for different stakeholders.

2.3. Neighbouring farmer interviews

Additional semi-structured interviews were undertaken to supplement the UJM and contextualize the case study sites in relation to adjacent farmer perceptions and farming practices. In Tanzania, interviews were undertaken with 30 farmers from villages surrounding SAT in an opportunity sample. The farmers were asked about their livelihood strategies and food insecurity issues and their knowledge of the SAT AVS. Their opinions of building community solar mini-grids, linked to AV expansion on larger farms, or expansion of local energy access through wider uptake of AVS by smaller farmers or cooperatives that could benefit their livelihoods and the community were then explored. They were also asked if they could identify any disbenefits from the expansion of solar including AV systems.

To investigate the impact that the installation of the AVS at Latia Farm had on neighbouring farmers who had recently installed solar panels we undertook intercept interviews. In total fourteen farmers who had solar panel installations raised on stilts were spoken with to identify their motivations and intentions for these investments. Using an opportunity sample, a semi-structured interview procedure was undertaken to investigate the motivations, benefits and origins of the elevated installations.

2.4. End of project workshops

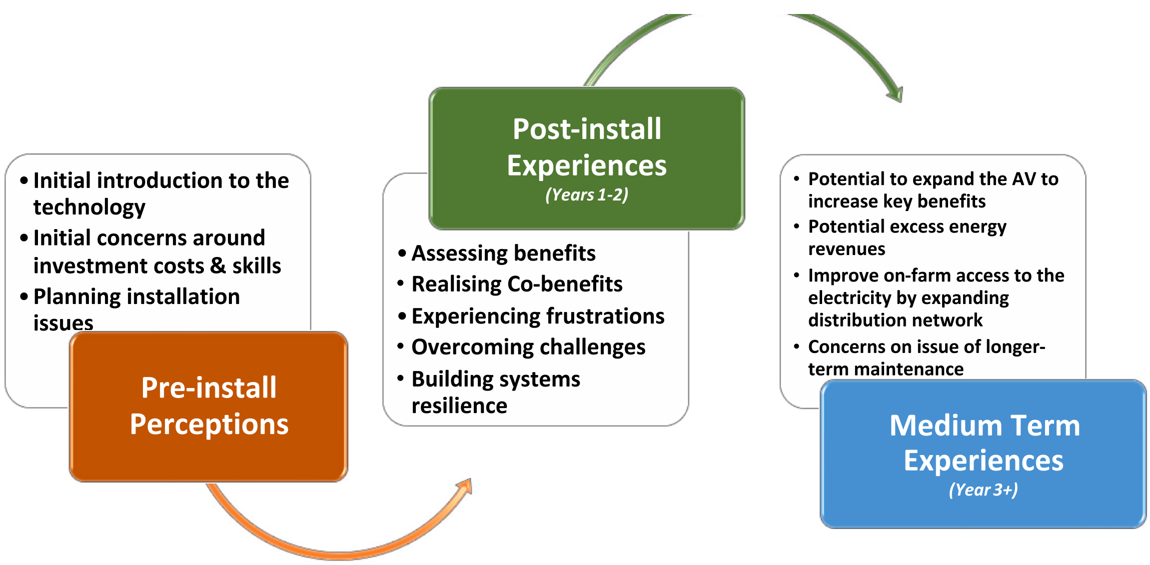
The emerging themes were further explored, tested and developed during two end-of-project stakeholder conferences in July 2023, one in Nairobi and the other in Dar es Salaam. Stakeholder groups recruited by the Kenyan World Agroforestry Centre (ICRAF) project partner used ten different use cases of how agrivoltaics could be deployed at different scales, in different settings and by individuals, communities and corporations. These stakeholders were drawn from a wide range of participants including government representatives, NGO's, civil society organisations, private sector companies and researchers. They discussed and analysed the potential of AV systems in East Africa. In total 38 people participated in Kenya and 22 in Tanzania.

3. Results

3.1. User journey mapping findings

The findings from the UJM indicate a generally upward trajectory in experiences from initial concerns pre-installation and issues of planning and preparing the construction site; through beginning to recognize the key benefits of the system after one year whilst experiencing frustrations on the initial technical challenges; to maximizing the benefits in year three onwards by integrating the power, water and production into the farm systems (see Fig. 3). These experiences indicate the key "touch-points" occur mainly in the pre-install and immediate post-install phases when the farms need most support: Firstly, to convince them of the system opportunities, to help ensure a successful installation of the technology (during pre-install); and secondly, to overcome teething technical difficulties as they acclimatize to using the systems (during post-install). Our data indicated that after a few years of the systems embedding into the farm operation the "touch-points" are mainly positive meaning less support would be required after the initial set-up unless major unexpected high-impact technical breakdowns were experienced.

When investigating the key concepts coded from the interviews that represent the motivations and concerns of the case study participants; there is a consistent interest amongst the interviewees in the energy (*prioritised energy* (energy prioritised above/at the expense of farming



Code	Pre
Prioritised Energy	4.3
Grid System	3.7
Barriers - Fabrication	3.3
Barriers - Bespoke or Emergent	3.3
Risk - Negative	1.7
Benefits - Improve Livelihoods	1.7
Benefits - Water Harvesting	1.3
Barriers - Economic	1.3
Barriers - Technical	1.2
Benefits - Green Economy	1.0
Securitisation - SDG goals Met	1.0

Code	Post
Grid System	5.2
Prioritised Energy	4.8
Benefits - Crops & Livestock	4.6
Barriers - Technical	3.8
Barriers - Fabrication	2.6
Benefits - Water Harvesting	2.6
Barriers - Bespoke or Emergent	2.4
Risk - Positive	2.4
Benefits - Resilience	2
Barriers - Economic	1.8
Risk - Negative	1.6
Benefits - Scaling Up	1.4
Benefits - Improve Livelihoods	1.2
Policies	1.2

Code	Medium Term
Grid System	4.4
Benefits - Crops & Livestock	3.8
Barriers - Economic	3.4
Prioritised Energy	3.4
Barriers - Fabrication	3
Benefits - Scaling Up	1.8
Barriers - Bespoke or Emergent	1.6
Benefits - Improve Livelihoods	1.6
Benefits - Resilience	1.6
Policies	1.4
Risk - Negative	1.4
Barriers - Technical	1.2
Benefits - Green Economy	1.2
Barriers - Policy or Regulation	1
Benefits - Water Harvesting	1

Fig. 3. Overview of UJM key emergent themes (Green: Neutral; Blue: Positive; Red: Negative). The detailed issues at the different timesteps and their relative weights (in terms of mentions by interviewees) are highlighted in the data tables. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(agricultural or pastoral or water provision) and the energy generation potential of the system; and *grid system* (mention of the type of electricity system (e.g.: on grid, off grid or smart) which identify the practical and financial opportunities difficulties or downsides of different setups and or the potential to be independent of or connected to a wider/national grid).

Initially there was little understanding about AV. *"When first of all, Kenya Climate and Innovation Center approached us we were not so keen on all. So we were not so much convinced. We had a meeting whereby the whole concept could be actually explained to us that we really understand it, because at that point I would say that it was the first time I was hearing about Agrivoltaics and I was thinking are Agrivoltaics and agriculture related?"*

Then there were concerns about the perceived risks and barriers (*fabrication*[2], *bespoke or emergent,*[3] *economic,*[4] *technical*[5]) linked to the installation. By the post-install stage these have to some extent been replaced by appreciation of the benefits (w*ater harvesting, resilience, crop & livestock)*. At the medium-term stage the interviewees included consideration of the opportunities and barriers to scale up AV systems to other stakeholders (*improve livelihoods, scaling up, green economy*[6]). These points will be expanded upon below.

Investigating these experiences in more detail (see Table 2) reveals additional granularity to these key aspects of the technology adoption process. This detail reveals that the immediate post-installation phase could be the most crucial touch-point in the User Journey in terms of the successful upscaling and long-term adoption of this technology. Years one and two were where technical issues with the operation of the AV systems became apparent. In our case study farms these were caused by misunderstandings from farm workers and managers about the operation of the inverters alongside issues with the integration of the technology with the national energy grid. Inverters convert the solar power from direct current (DC) to alternating current (AC) which is equivalent to the feed supplied by the national energy agencies. In the former case, workers tried to use direct current (DC) appliances with the alternating voltage (AV) power supplied by the system which resulted in damage to the inverter. In the latter, power surges from the national grid damaged the inverter. In both cases this resulted in significant damage to the systems leading to downtime until replacement parts were sought and installed. Costs for these expensive replacement parts and repairs were covered by the solar installer under the warranty and as part of the research. However, it is unclear whether this would be the case in purely commercial installations. *"OK, now, once we had.. yes once there was a serious power surge in the line and then it damaged the inverters many manufacturers will not cover such a warranty because it's an external cause and not a manufacturing defect"*. Additionally on Latia farm, due to the way the panels were integrated with the national grid, the AV system could not supply electricity directly to the farm during power cuts. This was a particularly frustrating "touch-point" as the farm managers had identified this aspect of resilience as a key benefit. This could be overcome with a battery installation or alternative approaches to temporarily decouple the system from the grid to become independent. However, both of these solutions have costs and implementation drawbacks.

3.2. Neighbouring farmer interview findings

The perceptions of farmers neighbouring the case study sites reveal useful observations about the opportunities for AV in the water-energy-food nexus as well as the challenges of introducing these systems. *"One of the things that we want to address is food security, and we believe that the system will improve security. We will improve productivity. Will lower the cost of production. That's one. Secondly, we are saying that we will we want to have a neighbourhood that benefits generally from our activities"*. *"For butternut squash the ones grown under the panels tended to be very big in size, the crop was very healthy even the physical appearance of the crop was very good…. tomatoes the fruits were fewer, but they were bigger and of high quality compared to the control plot"*. Similarly, In Tanzania, the farmers identified several co-benefits from increased access to reliable electricity that would begin to address food insecurity and improve livelihood opportunities. For agriculture, reliable electricity was seen as enabling wider uptake of irrigation that would facilitate multiple cropping cycles rather than relying on rainfed production with typically two crop seasons. For those already irrigating using diesel, this transition of power source would reduce the costs of production, again boosting incomes.

Improved water access allows the wider growing of horticultural crops of higher value that could improve farmer incomes. *"So at Latia farm the benefits I'd say we are seeing, firstly, there is a direct performance benefit in terms of reduced energy bills and that is something the farm is especially interested in as well as the money that are saving from the bills then there's also irrigation"*. In addition, this greater intensity of cropping was seen as beneficial as it would require higher levels of labour, increasing local employment opportunities. The availability of power could facilitate improved post-crop processing, such as maize milling, thereby improving incomes and reducing the currently incurred transport costs to access these services. For livestock keepers the identified benefits included boosting the productivity of poultry through the adoption of incubators and reducing the risks of animal attacks on livestock through the introduction of security lights.

More broadly, the availability of power was anticipated to be beneficial for health, education and livelihoods. All the participants already used small-scale household solar for lighting, mobile phone charging and some for entertainment (radio or TV power). However, they identified that larger solar systems could generate electricity for refrigeration that would enable the local pharmacy to store vaccines and medicines alongside facilitating later opening hours from utilizing lighting. In addition, households could install better electric lighting to enable improved student learning at home boosting education. All participants identified the benefits of improved business opportunities utilizing power boosting community vibrancy and local incomes. These opportunities were as diverse as hairdressers, cold drinks vending, entertainment facilities, mobile phone charging and welding businesses. This improves food security because greater incomes allow for the supplementing of local or household crop production with purchased foods. A final co-benefit identified was that of installing PV powered street lighting to improve personal safety and enable these businesses to operate later in the evenings. Overall, none of the participants identified any dis-benefits from the increase of solar energy production in the community. Obviously, many of these benefits rely on being able store solar electricity for use after dark which requires additional investment in batteries. Although these opportunities could be delivered through PV as well as AV systems, a pure PV mini-grid development would require the release of land from food production or other uses.

In Kenya, the motivations and experiences of farmers neighbouring Latia farm, who had installed elevated solar panels on their land, revealed additional opportunities and barriers to the expansion of AV systems. The initial recommendation to raise these panels had primarily come from local solar installers (50 %); whilst 29 % decided to elevate the array as their own idea. The motivation for raising the panels was linked to reducing the potential damage to the panels from strong winds in the Machakos region (36 %, $n = 5$). Additional factors were improving

[2] Fabrication, building or maintaining repairing AV systems. Maintenance of the physical components of the AV.

[3] AV is too new and needs development, or there is no generic design and each system needs to be bespoke.

[4] AV discussed using economic reasons for or against the development. E.g.: funding, investment potential, profit margins, cost benefit analysis of the technology compared to other solar technologies.

[5] Issues about efficacy, need for storage, types of crops, quality of crops produced, agronomic requirements of crops such as water requirements or soil characteristics etc.

[6] The potential of AV to develop new sustainable economic opportunities.

Table 2
Key findings at each UJM stage (Green: Neutral; Blue: Positive; Red: Negative. Key themes in bold; sub-themes as bullets; KE = Kenya, TZ = Tanzania).

• Questions on whether system will meet expectations (KE & TZ) **Initial concerns around investment costs & skills (KE & TZ)** **Planning installation issues** • Financing of installation (-ve) (KE & TZ) • Considering additional security needs (-ve) (KE & TZ) • Organising installation groundworks (KE & TZ) • Identifying optimal site location for AV install (KE & TZ)	• Power production meet expectations and exceed farm needs (+ve) (KE & TZ) • Increased access to water (both rain-water harvested; increased borehole pumping (KE)) (+ve) • Crop production improvement in yields and quality under panels for specific crops (+ve) (KE & TZ) **Co-benefits** • Power available for other purposes (+ve) (TZ) **Experiencing frustrations (-ve)** • Power outages from system (-ve) (KE) • System not working as initially expected (-ve) (KE & TZ) • Power surges from national grid overload inverter (KE) • Connection of DC equipment damages system (TZ) • Delays in system repair due to parts availability (–ve) (TZ) • Panels dictate the size/height of rainwater storage tanks influencing gravity fed drip irrigation (TZ)(-ve) **Overcoming challenges** • Need support from Solar Installers to overcome technical challenges (-ve) (KE & TZ) • Downtime in system (-ve) (KE & TZ) **Building Resilience** • Routine local maintenance of panels straightforward (+ve) (KE & TZ) • Security concerns overcome with additional security guards (+ve) (KE & TZ) • Battery system added to store excess power (+ve) (TZ) • More resilient system developed (+ve) (KE & TZ)	**Potential excess energy revenues (+ve) (KE & TZ)** • Ambition to export excess power to neighbouring farms (+ve) (KE) • Feed-in-tariff for excess energy returned to the grid would increase revenues (KE & TZ) **Continue to expand on-farm access to the electrical energy by expanding distribution network (+ve) (TZ)** • Widen range of equipment and processes accessing power (+ve) (TZ) • Diversify range of on-farm business activities (KE & TZ) • Increase water pumping capacity using electricity (+ve) (TZ) **Issue of longer-term maintenance (KE & TZ)** • Remaining concerns over the costs of long-term system warranties (-ve) TZ • Need to increase capacity of local solar installers to maintain and install these systems (KE & TZ) • Improve the availability of maintenance and parts (KE & TZ)

the security from theft (29 %, $n = 4$) and to maximise the panels exposure to the sun (29 %). The panels, unlike the case study where they were supported by bespoke steel supports, were all supported by scaffolding rather which reduced the initial installation costs. The solar panel energy was universally being used to pump water for irrigation and had often been linked to investments in increased water storage to ensure supply in seasons when the panel energy generation was insufficient to meet demand. The farmers had been worried about the initial investment costs of the installations, but felt the benefits from water security as well as the low running and maintenance requirements of the system, had outweighed these initial concerns. Only one of the farmers interviewed intended growing crops under the panels as an AV system. The remainder were using the land as a storage area (benefiting from the shade) including housing the irrigation water storage tanks. Most however, felt that they had enough land to not require cultivation under the panels. This was partly because these neighbouring farms installations were considerably smaller with fewer panels than the experimental array at Latia farm resulting in a much lower land footprint. None of the systems were providing power beyond the farm.

3.3. Expansion of AV findings

When considering the expansion of AV systems to other farms and farming systems the user journey interviews, supported by data from the end-of project workshop events, revealed the participants perceptions of who would most likely benefit from adopting the technology (see Fig. 4). Medium scale farms and larger commercial crop producing farms were considered to have the ability to invest and benefit the most from adopting the technology. The scale of these farms, their financial and human resources, secure tenure and the range of crops they grow were seen as the key factors making these the groups most likely to be beneficiaries from adopting the technology. Coffee producers were seen as particularly suitable (in both the Kenyan and Tanzanian workshops) due to their production method and the potential to utilise AV power to undertake coffee processes of drying, roasting and grinding.

For small-holder farmers there was a perception that they faced too many barriers to adopt the systems. These barriers included tenure insecurity, investment costs and lack of uses for the excess power. *"I can say one barrier is the capital because you find the majority of farmers are small scale farmers in Kenya and some of them cannot find that investment to implement and install AV projects on their farms. That's why I'm advocating the government should come in and help farmers and because we are having the devolved government now the county government, they should be the one playing the major role in ensuring that farmers are getting the investment support to install solar panels"*. However, uptake by cooperative community groups was considered a viable option. The communal sharing of the risks and benefits, as well as distributing the investment costs across multiple farmers, made these types of groups potentially suitable for AV systems use in lower income settings. A key factor was seen to be the ability of a cooperative to distribute the risks. For example, if one harvest under the panels was a failure, other crops grown in the collective may do well and compensate for the shortfall in income. This perception was partly based upon the case study farmer's experiences during the project crop trials where successes varied between seasons and crops and were influenced by the specific agricultural practices employed. Salad and market garden crops, typically grown by women in rural East Africa, were seen as particularly suited to cultivation under the panels. As a result adoption by women's farming cooperatives may be particularly beneficial [29]. However, there were specific gendered barriers that could prevent adoption including lack of land tenure for women and difficulty in accessing loans to invest in the technology [30]. Overcoming these barriers would need specific and targeted interventions. In addition, it was felt that cooperatives would be able to facilitate more effective sharing of the electrical power across a wider community.

This would be a particularly beneficial outcome from the adoption of the technology where many rural villages still have limited access to electricity. Sharing the power of the system widely was seen as the most effective way of benefiting from the electricity supply. This was connected to the belief that rural youth entrepreneurs upon recognising the availability of electricity in their communities would establish new business benefiting from the energy opportunities. *"The rural youth, there I see apart from the production of crops but also the energy and the possibility of some youth entrepreneurs utilizing the energy to provide other services in the community and there will be a potential beyond just their own use of the land for cultivating crops and the energy for household use and maybe processing. You know the youth are always very innovative with all sorts of ideas. So that will be a potential as well for some youth for some additional income if they have such systems in the rural areas."*

Finally, it was recognised that livestock keepers could also incorporate the systems into their production practices, harnessing the panel benefits to grow fodder crops, pump water for livestock and crop watering, especially during dry seasons and droughts. The livestock systems considered suitable included poultry production, where the power could be used to heat hatcheries, improving production efficiency. It should be noted that these livelihoods exclude traditional pastoralist practices with communities, who due to their migratory lifestyles, were

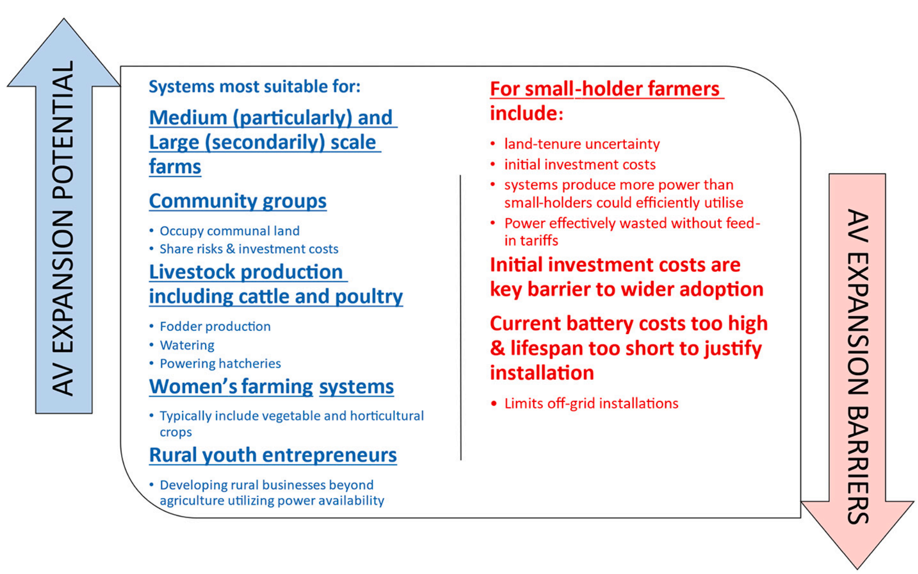


Fig. 4. Interview participants perceptions of potential AV expansion opportunities and barriers [UJM and end-of-project event findings combined].

not considered viable for the adoption of a fixed-place technology such as AV systems. Indeed, interactions between pastoralists and AV systems was seen as a potential threat or source of conflict if the installations interfered with livestock movement or access to grazing and became a focus of contestation for land access. This touches upon global concerns of PV installation in terms of land use conflict. *"I will say that choosing the right site is very important when you select the site for this unit it's very…very important that you select a site that is suitable and are aware of potential land use conflicts"*.

Considering the issues of scaling out AVs (defined here as widening the adoption across a broader range of farms and farming systems) reveals those organisations with the most potential to facilitate access to this technology and encourage and support successful future development and deployment (see Fig. 5). Reviewing UJM participants experiences of the agencies responsible for the installation of the AV systems at their farms reveals the existing actual organisations critical to implementation of the technology. The end-of-project workshops used case scenarios to highlight potential gaps that would require other agencies to come onboard to widen AV expansion. For the case study sites the critical organisational stakeholders were identified unsurprisingly as the farm operators and solar developers. This was partly due to the research team operating as an intermediary that dealt with some of these 'required' agencies during the project process and shielding the farms managers themselves from directly requiring their inputs. However, to widen the uptake of AVs the interviewee's identified gatekeeper organisations able to address the issues of finance (both obtaining and benefiting directly from the solar system); exploiting commercial benefits; and reducing risks, as critical interventions where other agencies would be required to expand the use of AV by a range of other farms and farming systems.

4. Discussion

This research aimed to explore two research questions; firstly, what are the critical enabling factors, institutions and support that would be required to successfully widen the adoption of this technology across the East African region. Secondly, could this wider adoption help address the climate-energy-food production-population growth challenges forecast as increasing in the coming decades.

In relation to the first question overall, the consensus view from our cross-section of participants was that AV technology could be beneficial to a range of East African agricultural systems but innovations in the financing, regulatory and policy landscape would be needed to enable this wider uptake of AV systems rather than overcoming any specific technological issues. Addressing these areas explored below would enable the widest range of stakeholders to adopt the technology and could be particularly beneficial for those currently most vulnerable to food insecurity and energy poverty issues.

The first major finding was that government interventions are required to deal with land tenure uncertainties to facilitate the upscaling of this AV technology across the region particularly for small-holders and cooperative farms (see Fig. 4). Our study indicated that without security of land access or ownership farmers, financiers of development funders are unlikely to invest in such static fixed location technology.

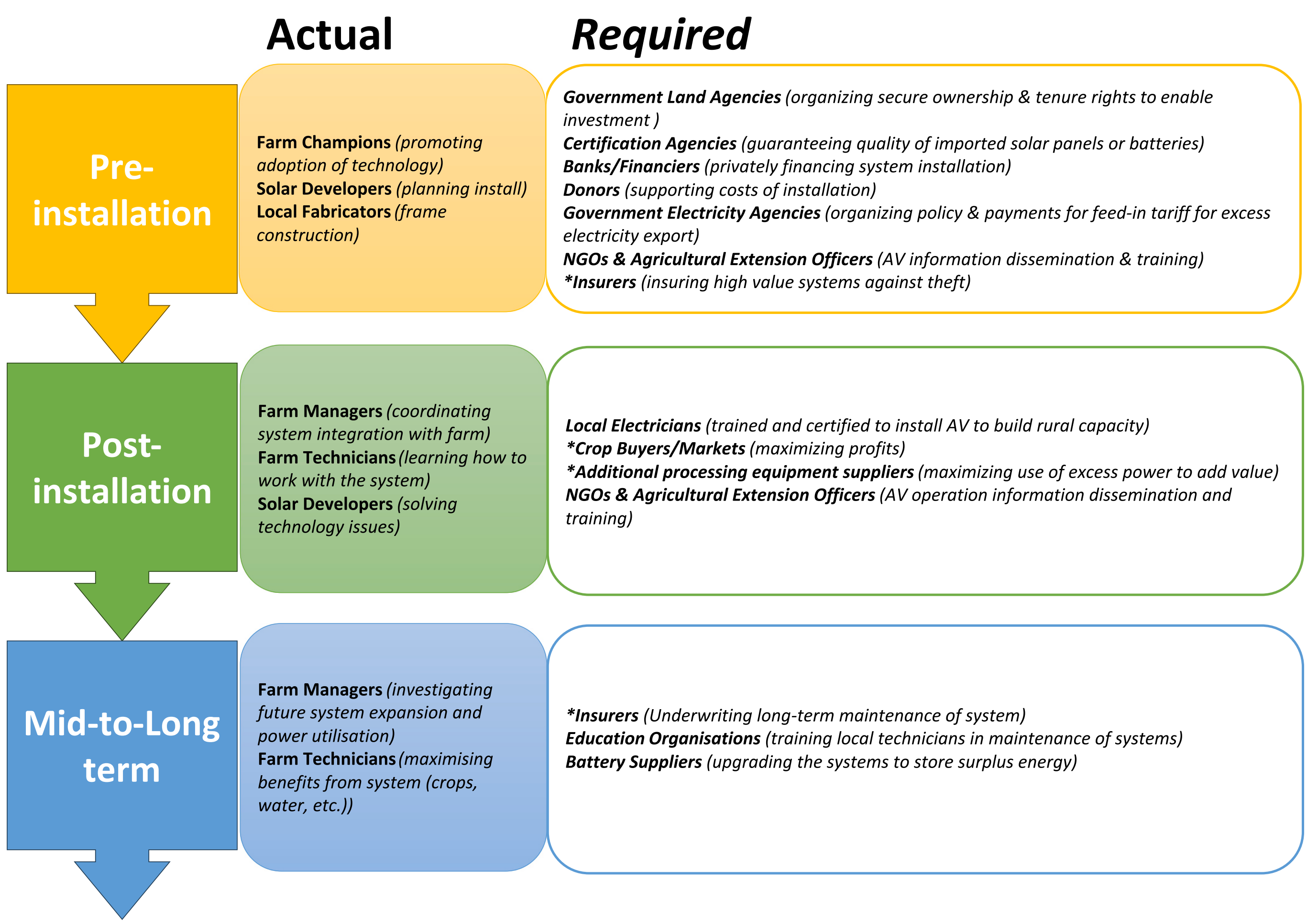


Fig. 5. Actual and required key gatekeeper organisations needed in the up-scaling of AV systems. The exact gate-keepers may vary by type of farm (this was not investigated in this project and remains a research gap to be filled). [Note: *Potential organisations were generated from the user journey interviews; all remaining potential organisation suggestions came from the end-of-project workshops].

Our workshop participants highlighted that these land reforms make investments in agriculture more appealing to both local and global agencies which could facilitate expansion of AV systems. Our participants highlighted that this issue requires interventions from government land agencies to resolve [33]. Existing reviews of the issues of land tenure on investments present a mixed picture. Singirankabo and Ertsen [28] argue that data on existing land tenure reforms should not be generalised between countries and data on the impacts on small-holders in particular are lacking. Chimhowu [32] identifies how changing tenure effects power dynamics in rural communities; some of which could benefit small-holder and women farmers. However, whilst many papers highlight the potential that reforms consolidating customary and statutory land rights can have on food security and investment [29,30] they also raise the need for more research to evaluate the wider equity implications of these significant changes [28,29].

The second critical finding emanating from the UJM and workshop was the need to provide appropriate finance mechanisms for different types of potential beneficiaries. This finding is supported by similar studies looking at widening PV access in East Africa [31,34]. For larger commercial farms evidence of the return on investment [35] from these systems would be required. For small-scale or community organisations alternative financing options, such as micro-finance solutions, could be critical [36]. However a review of these approaches indicated that the current interest rates on these loans may prohibit this broader inclusive uptake of AV [37].

Related to financial mechanisms the third critical aspect needing consideration to enable the wider adoption of AV technology was in the current regulatory framework for energy investments and payments for surplus distribution of electricity from AV systems could affect the expansion of these technologies. Gordon [38] highlights how differences between Ethiopia and Kenya influence the location of renewable energy investments with Ethiopia's more conservative and bureaucratic system favouring large scale on-grid developments. This would inhibit the deployment of smaller distributed AV systems. Meanwhile, in Kenya the opportunities favour smaller off-grid investments linked to mobile phone pay-as-you-go services. This approach could better support distributed micro-grids linked to AV in off-grid rural locations. However, for on-grid connections, such as Latia farm, the current application of the feed-in-tariff (FIT) policy for AV in Kenya means that producers would be charged for excess power they fed back into the national distribution network. This is due to the nature of the metered connections measuring the excess power fed into the grid as consumption rather than generation. In Tanzania, the current low-costs of electricity for on-grid farms also mean that the economic savings from reduced energy costs would be less important to farmers in these locations reducing the attractiveness of the investments. These differences highlight how local contexts, national policies, and their implementation will be critical factors in the potential investment and uptake in this technology through impacts financial returns and improved livelihood opportunities for AV. The issue of FIT and alternative mechanisms for paying renewable energy producers for their excess power has been explored by Ndiritu and Engola [39] who highlight that these payments may only be appropriate for larger producers (greater than 10 MW) with an alternative energy auction system proposed for larger generators. In studies from Tanzania issues with FIT are also identified with recommendations that tariffs are tailored to different technologies and types of installation (whether on-grid or off-grid) to promote appropriate and tailored investments [37]. These types of innovations in subsidies could be beneficial for encouraging expansion of AV and could target such developments for specific locations or types of farming.

Another major consideration in widening the expansion of AV is that additional supporting agencies would be required to become involved at key touch-points in user journey adoption process. These can be classified into three groups: Administrative (government departments, donors, financiers and insurers); agricultural support (extension officers and markets); and technical (installers, local electricians and supporting educational institutions). The relevance of these agencies changes through the adoption process with administrative requirements dominating the pre-installation process shifting to agricultural and technical support post-installation. Administrative advice and support can make the AV adoption processes clear and straightforward allowing farmers to assess the cost-benefits easily and smooth the investment pathway. Absence of this support will typically mean that at present it is likely only larger organisations (such as commercial farms) or innovators (early adopters, similar to our case study farms who were initially selected for this trial due to their history of independently testing new production approaches such as hydroponics) who are likely to be able to overcome the financial and bureaucratic challenges required to install an AV system. Post-installation the requirements shift towards agencies that support successful AV agricultural production. These include NGOs and extension services who could help ensure that farmers optimize the system to their local conditions by sharing learning and knowledge between AV adopters. This would help maximise the food security benefits from improved yields or income from diversification of cropping systems that work best under the panels. In the mid-term (4–5 years) having a greater number of trained specialists able to support AV installations distributed across the region could become critical. This requires changes to education curricula so that skills training is available across the region rather than expertise being concentrated around the larger cities. AV in off-grid rural areas offers potentially the largest benefits, with improved food security and reduced energy poverty, but may need the greatest support for adoption.

More minor aspects requiring government intervention to enable the uptake of the technology is for nationally legislated certification of the quality of panels would help build trust from investors in AV that they were purchasing reputable reliable products [41]. Without certification our findings indicate that uncertainties in the returns on investments from poor quality solar products could deter farmers. This finding is supported in the literature looking at the mis-selling of domestic solar products in Africa [38].

In relation to the second research question on the energy-water-food-climate nexus the first major finding from this study from the neighbouring farmer interviews and was that access to power was a critical limitation for agriculture and rural development more broadly in and around our case study sites in Kenya and Tanzania. This restricted farmers development options and was contributing to food insecurity through both production shortfalls and reduced livelihood incomes. The benefits that increased solar power access could bring were numerous and would deliver a wide range of outcomes to support improved rural sustainability and increase food security for the region. The interviews with farmers in Kenya, who have already adopted PV systems, demonstrate some of these benefits in relation to improved irrigation systems supporting better yields particularly in dry seasons.

Compared to other regions, this East African study demonstrates some similarities, but also unique challenges for AV adoption. Other rapidly developing regions are experiencing similar pressures across the food-water-energy nexus with demand for land presenting challenges for meeting potentially conflicting needs [42–44]. Similar pilot studies have revealed the land remediation benefits from installing AV [45] and identified issues with selecting specific crops that perform well under the panels [44]. A study from India is one of the few to also consider the socio-economic challenges of expanding AV which also highlights key threats and weaknesses in terms of the investment costs, risk of theft and lack of awareness amongst farmers [46].

The challenges with subsidies for renewable energy producers such as FIT across East Africa [39,40,47,48] highlight that innovations in these mechanisms are required to stimulate their adoption and maximise the water-food-energy nexus benefits. This could include targeting payments towards regions and farms that are currently increasingly marginal due to water or energy scarcity in East Africa but which could be brought back to productivity and profitability through improved access to water from irrigation generated from the AV systems and economically supported through revenues generated by selling excess electricity. These types of innovations could stimulate the adoption of AV helping to address water-food-energy nexus issues and help deliver the wider economic and social benefits for East Africa described by Chisika and Yeom [49].

Limitations of this study

A major caveat to our findings is related to the nature of the case study sites. Both farms could be considered innovators and entrepreneurial in their willingness to test and evaluate new approaches or technologies as these experiences could provide a competitive advantage for training (part of their core business). These factors make the case study farms different from most commercial and small-holder enterprises who may typically be more conservative in their investments and reticent to try 'unproven' technology. Despite this bias in our farm participants the findings from the user journey indicate that they were critical of the technology especially in post-install when problems were experienced. This means that the UJM results are still indicative of the wider challenges that upscaling the technology will need to address.

Another criticism of the data is that not all farming systems that could benefit from the installations took part in the interviews or workshops. This was particularly the case for small-holder subsistence farmers and cooperative groups including women focussed organisations. This means that assumptions of the challenges these groups could face in adapting the technology were based upon the views of other stakeholders who may have biases in their viewpoints or knowledge. Testing AV across a larger sample of case studies with a broader range of types of farmers, environmental conditions and farming systems is required to fully explore the potential implications of and the conditions required to successfully adopt these approaches more widely.

5. Conclusion

5.1. Theoretical implications

This studies results highlight that our AV adopters experienced upward trajectories in terms of their experience with the technology as they maximised the benefits for production and overcame initial challenges with the systems. The mapping also revealed key touch-points in their experiences that could affect successful adoption for other users. The User Journey Mapping methodological approach proved useful for capturing the evolution of different groups experiences with the adoption of the agrivoltaic system in a structured framework. This enables the comparison of views between participants, countries and roles. A similar approach could be useful for assessing other technological innovations designed to address challenges of net zero or climate change implementation and adoption enablers and barriers.

5.2. Managerial implications

At present, our findings highlight that the opinion of our participants is that the agencies and institutions who would be required to assist farmers at the negative touch-points are currently not well positioned to provide this support at these critical stages. This could undermine any attempts to upscale the technology across the region. The systems were perceived as most appropriate for medium and large-scale commercial farms with access to capital and who can best utilise the AV power for crop processing. However, these AV systems could potentially be suitable for a range of farming scales, systems and practices, including community cooperatives and livestock keepers. Land tenure insecurity and finance restrictions are perceived to be the largest threats to the wider upscaling of AV, particularly for small-holders.

5.3. Ideas for future research

Our findings on the expansion potential for AV across different East African farming systems requires further research and validation. Engagement with small-holder and cooperative farmers to determine if the barriers identified in this study can be overcome would be particularly pertinent. This could be used to determine if wider AV adoption would address food-water-energy nexus issues particularly for these vulnerable groups alongside addressing poverty alleviation.

CRediT authorship contribution statement

Steve Cinderby: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Karen A. Parkhill:** Writing – review & editing, Writing – original draft, Funding acquisition. **Stephen Langford:** Writing – review & editing, Formal analysis. **Cassilde Muhoza:** Writing – review & editing, Methodology, Investigation.

Declaration of competing interest

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Data availability

Data will be made available on request.

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