Agrivoltaics in East Africa: Opportunities and Challenges

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Abstract. Agrivoltaic systems concommitently tackle food and energy security challenges on the same area of land, while also improving farmer livelihoods. Designed correctly, they can increase crop yields by reducing water and heat stresses; yield improvements depend on a range of factors including the available photosynthetically active radiation and the shade tolerance of the crop varieties. Several agrivoltaic pilot studies have been developed over the past decade, predominantly in the Global North, but there is an evidence gap in East Africa where the environmental conditions and livelihood challenges faced by agricultural communities mean there are potentially far greater benefits from agrivoltaic technology. In this paper, we discuss how the environmental conditions, electricity supply and access, farming systems, and political scenarios present opportunities and challenges for using agrivoltaic systems to address sustainable development goals in East Africa. We end by summarising what is required to support development of this technology in the region and realise the potential benefits.

INTRODUCTION

Agrivoltaic systems - agriculture combined with raised photovoltaic (PV) solar panels - offer benefits for food, energy and water security, all on the same land footprint and avoiding vegetation removal and associated land degradation. The concept itself can be simple: solar panels raised sufficiently high enough above cropland to facilitate farming activities underneath. Taking advantage of a growing global solar PV market[1], a portfolio of studies to explore the performance of agrivoltaics have been developed over the past decade, with experiments operated in France[2], Germany[3], Italy[4], the Netherlands, the USA[5], Chile[6], India[7], China, Japan, South Korea and Malaysia[8]. Evidenced impacts include greater crop yields due to shade from the panels reducing heat and water loss stress, improved PV generation efficiencies due to cooler panels, and reduced irrigation demands due to reduced evaporation and increased soil water retention, which in turn offer food, energy and water security. Reductions in yield have also been reported in cases of excessive shading (see Weselek *et al.*[9]). These findings, especially those for crop production and water use efficiencies, are inherently linked to the environmental conditions, and so simultaneously the geographic locations in which the agrivoltaic systems are situated. Just as with growing crops in a traditional open-field setting, photosynthetically active radiation (PAR), temperature, rainfall and soil conditions will all drive the crop outputs from an agrivoltaic system. To maximise socio-economic, environmental and livelihood benefits offered by agrivoltaic systems, it is imperative that experiments are conducted to test the performance of this technology in the regions where it is going to be deployed.

As well as crop production and electricity generation performance, socio-economic implications will vary by geographic location too. For example, the energy security benefits offered by agrivoltaics will be more substantial in rural, off-grid settings than peri-urban, grid-connected settings. The same applies to food and water security: the greatest benefits will be in areas facing malnourishment and drought challenges. With most agrivoltaic experiments situated in the Global North, the extent of their potential to offer socio-economic, environmental and livelihood benefits in the Global South is to date only estimated. Yet it is predominantly in parts of the Global South where such benefits are likely to be greatest - where there is ample solar radiation[10], an enormous need for decentralised energy solutions, extensive food security challenges, and frequent droughts. The growing and yet unmet energy demand, pervasive food insecurity challenges, and severe climate threats present an unparalleled opportunity for agrivoltaic systems to bring sustainable livelihood benefits along with food and energy security. In this paper we describe contexts of East Africa relevant to agrivoltaic systems: the environmental conditions; electricity access; farming systems, rural economies; and policy support. For each of those contexts we consider the opportunities and challenges they present for developing agrivoltaic systems, and the benefits that the systems could bring for communities in East Africa.

THE EAST AFRICAN CONTEXT

Environmental Conditions

Solar radiation is abundant across East Africa with 4-7 kWh/m^2/day (Fig. 1), two to seven times that of Europe[10]. The potential for photovoltaic electricity generation is therefore significant. Previously, solar panel prices were prohibitively expensive for most people and businesses in East Africa, but the rapidly decreasing costs[11] have resulted in a substantial growth in off-grid households and mini-grid solar developments[12]. Although this high solar radiation offers extensive electricity generation opportunities, the associated heat and high evaporation also contribute to challenging conditions for crop growth, particularly in terms of water stress. With 75% of the population dependent on rainfed agriculture[13], water availability is a hardship for many farmers in arid and semi-arid regions. While the total amount of precipitation is not forecast to change significantly with climate change for most of the region, it is forecast to become more erratic and less predictable, leading to lower yields for major crops (e.g. 8-45% reductions in yield by 2050)[14,15].

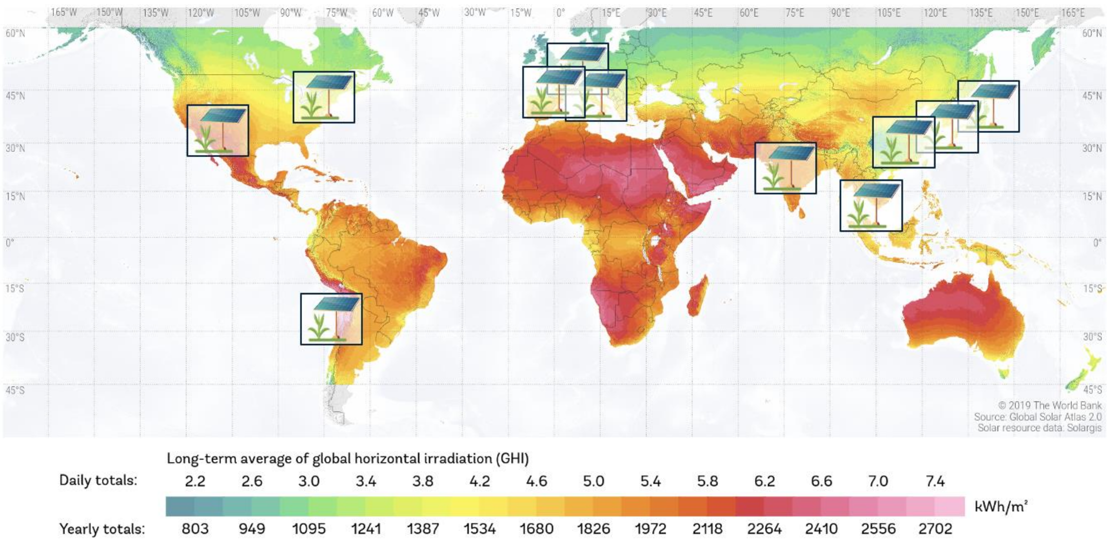


FIGURE 1. Solar radiation[10] and the locations of agrivoltaic research sites known to the authors[2,3,5–8]. The abundant solar radiation reaching East Africa (4-7 kWh/m^2/day) offers substantial potential for photovoltaic electricity generation.

Electricity Access

Two thirds of the population of East Africa do not have access to electricity (Fig. 2a). Electricity is also not evenly distributed, with almost twice as many urban communities supplied with electricity than rural communities - communities which are often geographically dispersed[16,17]. This lack of electricity means most rural households rely on biomass such as wood and charcoal for heating and cooking, which has detrimental impacts on health, deforestation, and climate change[18]. For example, 88% of Tanzania's energy consumption is derived from biomass[19]. Addressing the electrification needs of rural areas poses several challenges for the energy sector, including lack of coordinated regulation and financial investment from governments. Most money spent on the energy sector between 2000 and 2014 in low-access countries was appropriated to extending national grids[20], yet this is costly, resource inefficient and time intensive. Off-grid solutions are therefore the only option to bring power to unconnected communities in the short-term. The International Energy Agency reports that 71% of investment to achieve universal electricity access around the world by 2030 needs to be spent on off-grid and mini-grid infrastructure, and 95% of that directed at sub-Saharan Africa[21].

Unfortunately, most rural households cannot afford off-grid solutions, leaving much of the rural population in the dark without electricity. However, new policies (e.g. Public Private Partnerships, cost reflective tariffs, and connection subsidies) and international donor support are now expediting electrification initiatives - including off-grid and mini-grid infrastructure. Electricity demand across Africa is predicted to triple between 2015-2030[22], and access rates are currently growing 4% annually in East Africa[23], the region with the greatest potential for solar photovoltaic growth on the continent[24]. With the decreasing price of PV panels, solar infrastructure is more cost-, resource- and time-efficient for rural communities than grid expansion.

Farming Systems

Agriculture dominates labour in East Africa, employing 70% of the population[25], and the proportion of land devoted to arable farming is increasing (Fig. 2b). Smallholder farmers account for 75% of productivity, which is mostly for subsistence or for sale at local and regional markets; commercial productivity and access to international markets are not available to most farmers. With so much reliance on small scale, rainfed food production, climate change and water scarcity are prominent challenges facing both livelihoods and food security for most East African communities.

The impact of electrification for off-grid farmers and agricultural communities can be enormous[26]. On the farm, electricity from an agrivoltaic system can improve yields and reduce yield losses to drought, pests and diseases by powering irrigation systems and better post-harvest storage, e.g. though refrigeration for preservation, or heat treatments to kill pests. Further, farmers could transition to higher value commercial crop production, and power post-harvest processing machinery to add value to products e.g. pulping to produce juices. The electricity generated also reduces farm operation costs and purchase price instabilities, such as for diesel to powering generators[26]. Beyond the farm, the electricity could power lighting, low-emission cooking, educational activities, charging for mobile phones, refrigeration for medicine, and digital entertainment services. Agrivoltaic systems in the Global North deliver low-carbon electricity directly to end users and national grids, but the livelihood benefits derived from these systems will be even greater in rural East Africa.

The benefits of agrivoltaics to agricultural communities extend beyond food security and value addition - they also present opportunities for equitable social inclusion. Women play significant roles in the community, and they are known to be the driving force of change to society when given an opportunity[27]. They contribute to ~50% of the agricultural workforce[28] - in addition to handling household activities such as cleaning, cooking, food preparation, firewood collections, and fetching water[29] - yet the solar energy sector is dominated by men. Integrating the agriculture sector into energy developments through agrivoltaics presents an opportunity for women to become involved in the energy sector and energy decision making. Women and children are also disproportionately affected by harmful particulate emissions from cookstoves fires, as they spend more time in the home[30]. Electrification to power e-cookstoves will reduce these emissions and improve the health and wellbeing of the household.

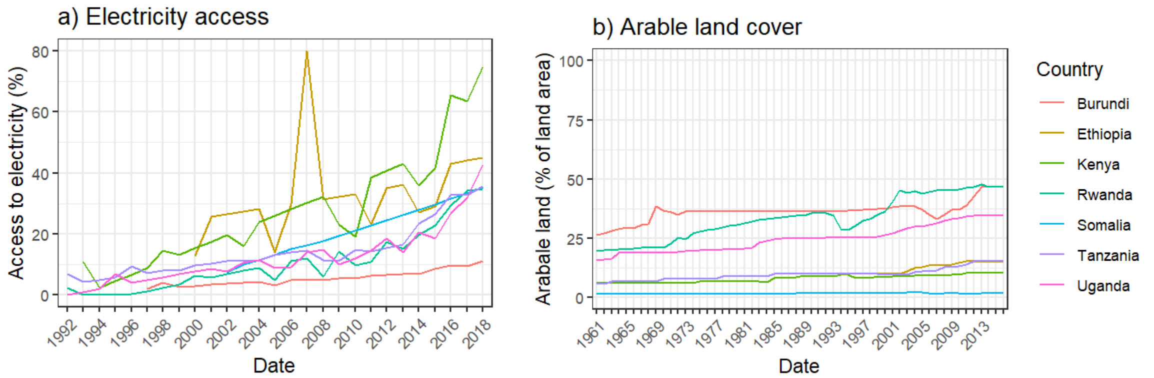


FIGURE 2. (a) Access to electricity (% of population) in East Africa 1992 and 2018. Agrivoltaic systems are not yet operational in East Africa, where they could provide electricity to rural and remote communities not connected to the national grid, and contribute low carbon electricity to the energy grid when grid-tied. (b) Arable land as a percentage of total land area in East Africa between 1961 and 2016[31]. With arable land cover doubling for many nations over the past 55 years, land use conflicts are likely to arise between arable land use and solar energy developments.

Economic Context

The agriculture sector accounts for 24-44% of GDP in East African nations, contributing to the livelihoods of 80% of the population. The solar energy sector is expanding to tackle electrification challenges and already employs over 100,000 people in sub-Saharan Africa, and this expansion requires innovative business strategies to enter nascent markets. There are three broad business models currently used to operate mini-grids: utility owned, community owned, and privately owned, each with various advantages and disadvantages. The model that has achieved the greatest success has been the Anchor Business Customer (ABC) model, which supplies power to three different groups of targeted customers: 1) an anchor client, who is ensuring a steady revenue for the developer; 2) small village businesses or institutions with a greater load demand than regular households; and 3) rural household customers. Both the community model and the ABC model could be applied to agrivoltaics, as such systems offer several improvements in community livelihoods. While mini-grids offer a more cost-effective solution to increase energy access than grid expansion, they do not solve the plethora of issues plaguing electrification for low-income rural communities, such as not having the financial means to realise the livelihood opportunities offered by electrification.

Mini-grid systems that offer financial benefits beyond those associated solely with electricity access will broaden the livelihood benefits attainable by the community and increase the likelihood of securing finance to cover initial costs. Agrivoltaics do just this, adding an income source from mini-grid infrastructure via the sale of crops. The sale of higher-value crops in marginalised zones further improves livelihood gains, while the mitigation of environmental challenges reduces risks to farmers' incomes. Agrivoltaics will promote agricultural trade to enhance rural livelihoods. For example, rural households generate much of their income from the production and sale of agricultural goods to non-local markets, and agrivoltaics will extend this by improving both crop production and post-harvest processing to create higher value products, including goods such as juices which can be transported more easily and sold to national and international companies. Agrivoltaics will also generate new, skilled employment opportunities for agrivoltaic construction, operation and maintenance, especially in rural locations currently lacking modern infrastructure. These jobs will tackle rural unemployment and boost incomes as well as food security.

Policy Support

There is growing attention on developing agricultural systems in East Africa through trade policies[32]. The role of agriculture in the economic development and welfare improvement of the region is substantial: agricultural trade accounts for approximately 40% of inter-regional trade[33]. Despite this, inadequate national policies accompanied by poor market systems supporting food production, marketing and distribution results in higher food costs for the local population compared with imported food. This is exacerbated by underdeveloped infrastructure supporting efficient logistics and supply chains. The challenges for food systems has been linked to the failures in policy systems that can support regional trade and infrastructure development. Concurrently, with the expanding renewable energy sector, there has been a substantial reduction in the cost of solar PV systems that can provide utility-scale electricity services to millions of East Africans who lack on-grid electricity access. This adds to the pressure on land resources available for farming, for which demand is also increasing (Fig. 3). Rising land use competition will cause social, political, ecological, and economic conflicts. One approach to addressing this land use challenge is adopting integrated food and energy systems, like agrivoltaic systems, which support simultaneous growth of crops and energy production on the same plot of land. As most governments are pushing to promote sustainable land and natural resource management, policy reform supporting dual use of land for agriculture and energy will be desirable.

Various financial instruments have been used to promote investment in the energy sector. Government bodies have the mandate to pool resources from various sources, such as government funds, investors, and development partners, towards renewable energy projects. These government bodies also offer tools to attract investments from the private sector, including partial risk guarantees during the early phase of projects, and credit enhancement instruments directed at reducing the risks faced by commercial lenders and other financial institutions. This financial mobilisation for renewable energy initiatives could be used to support agrivoltaic development. However, there are currently no mandates spanning co-use of land for energy and agriculture, so new supporting policy briefs need to be produced.

Optimising the Design of Agrivoltaic Systems

Local environmental conditions, farming systems and socio-economic contexts will all influence the design of an agrivoltaic system. Physically, the layout of the PV panels will need to be optimised to allow sufficient sunlight to reach the underlying crops. This will depend on both the amount of solar radiation at the location and the shade-tolerance of the target crops, for example an agrivoltaic system in an area receiving ample PAR (such as East Africa) and growing shade-tolerant crops will be able to comprise a denser PV panel layout than an agrivoltaic system at higher latitudes and with less shade-tolerant crops underneath. The elevation of the panels to facilitate farming underneath will also depend on the planned activities; taller crops or mechanised farming will need a taller panel mounting structure than shorter, hand-picked crops. Tool use must also be considered, with panels high enough to avoid damage. Taller systems will be more expensive to construct and laborious to maintain, and may be unnecessary if the farming system solely comprises short, hand-picked crops. The orientation of agrivoltaic systems also needs to consider diurnal solar radiation patterns. Many conventional ground-mounted solar parks comprise arrays (rows) of PV panels on an East-West axis, with the panels either statically tilted at an optimal angle for maximum solar radiation, or mechanically tracking the sun to further improve energy conversion; however, this orientation would mean some crops receive mainly direct PAR during the day, while those in the shade receive mainly diffused PAR. Agrivoltaic systems designed with North-South oriented arrays (with panels still optimally tilted), especially near the equator, would ensure a more even distribution of direct/diffuse sunlight throughout the day for the underlying crops.

Incorporating a rainwater harvesting feature into an agrivoltaic system will offer further benefits for crop production and water conservation. Such a system could comprise guttering at the lower edges of the solar panels that channel water into a large water tank feeding a drip irrigation system to the roots. Raised on a plinth, this system could be entirely gravity fed, thus avoiding the need for additional mechanics and electronics that could fail. Rainwater harvesting would maximise the amount of rainwater reaching to the crop roots, rather than evaporating from above-ground plant biomass and the soil surface, or running off into drainage ditches. Further, controlled irrigation, rather than relying on rainfall, would enable farmers to store water from rainfall events to be used for irrigation at a later date during periods of drought.

Knowledge exchange and co-design is essential to appropriately designing and implementing agrivoltaic systems. The first key driver in implementing agrivoltaics successfully is capacity building. It is important that the end-users, ranging from multinational agribusinesses to smallholder farmers, have access to information on how agrivoltaic systems work, how they are competitive with alternative solutions, and what benefits they can bring. Cross-sectoral dissemination and engagement strategies are also key to realising the benefits of agrivoltaics, which span both the energy and agricultural sectors. The private sector plays a key role in sustainability innovation[34], and policy makers should explore ways to improve interactions between the private sector and governments' climate smart agriculture programmes. To support investment, it will be necessary to demonstrate the economic competitiveness of agrivoltaic systems compared to conventional ground-mounted PV systems, which are slightly cheaper due to the smaller mounting structures. Metrics such as land equivalent ratio (LER)[2] and levelised cost of energy (LCOE)[35] can be used to compare the values of agrivoltaic systems with alternatives, informing policy reform to support dual use of land for energy and agriculture. To overcome initial implementation barriers, governments could provide incentives to farmers that co-use their land for food and energy production, such as by subsidising development costs. Government- and NGO- backed training and knowledge exchange programmes will also support the expansion of agrivoltaics effectively. Two-way knowledge exchange between the local farmers, who are experts in growing their crops in their environment, and international agrivoltaic researchers, who are experts in agrivoltaic design and implementation, is essential for effective co-design of these systems. A platform for smallholders to engage with regional and international markets would also strengthen the livelihood benefits, as would networks for continued knowledge exchange with other farmers.

TESTING AGRIVOLTAICS IN EAST AFRICA

There is a growing portfolio of evidence demonstrating the performance of agrivoltaic systems in the Global North, which provides a valuable evidence base for developing agrivoltaics elsewhere. Similar evidence now needs to be generated from pilot projects in East Africa, where environmental and socio-economic conditions mean the sustainable development and livelihood benefits are even greater. Such systems needs to reflect the different agro-ecological zones where agrivoltaics are likely to be developed (e.g. semi-arid and humid), test a range of suitable crops (e.g. tomatoes, cabbages, kales, coffee, and shade-tolerant fruits), and study relevant application models (e.g. community owned and privately owned).

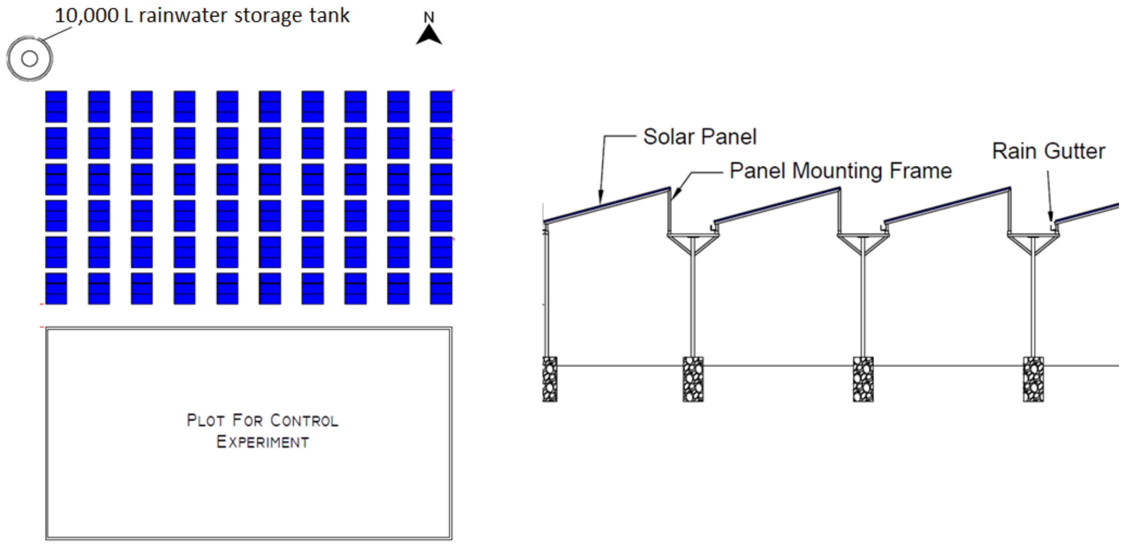
To evaluate the livelihood impacts of agrivoltaic systems on agricultural communities in East Africa, we are conducting a multidisciplinary research programme that addresses the intersections between modern energy technologies, land governance, agronomy, and community perspectives. Our project comprises three interlinked work packages that:

1. Evaluate land governance, evaluates stakeholder perspectives over the course of agrivoltaic development, and generates empirical crop production data from three pilot systems in Kenya, Uganda and Tanzania to inform a financial cost-benefit analysis of agrivoltaic systems.
2. Spatially map gradients of suitability for agrivoltaic deployment based on a range of social, technical and environmental factors.
3. Create policy briefs and business strategy guidance to support the uptake of agrivoltaic systems across East Africa.

Our three pilot systems, currently under development, will test the impacts of three agrivoltaic structures on crop yields and financial added value for farmers. Local stakeholders will be surveyed to gain insight into their individual challenges and expectations from agrivoltaic systems, aiming to inform effective implementation strategies to ensure maximum livelihood benefits for end users and local communities. Each system has a different design to reflect the site owners' requirements (Table 1, Fig 3.).

TABLE 1. The locations, hosts, agro-ecological zones, capacities, and additional features of the three pilot agrivoltaic systems being deployed in Kenya, Uganda and Tanzania.

Country and region	End user	Agro-ecological zone	Agrivoltaic system
Kenya (Kajiado County)	Latia Resource Centre, agribusiness for farmer capacity building	Semi-arid	56 kWp with rainwater harvesting
Uganda (Lamwo District)	3 x neighbouring villages	Humid	3 x 60 kWp
Tanzania (Morogoro)	Sustainable Agriculture Tanzania, non-profit agricultural training centre	Semi-arid	35 kWp with rainwater harvesting and battery storage



(a) (b)

FIGURE 3. Diagrams of the agrivoltaic system at Latia Farm, Kenya. (a) Layout of agrivoltaic plot and the open-field control plot. (b) Side profile of a section system. The rows of solar panels are on a North-South axis to increase direct PAR reaching the crops throughout the day. The structure includes a rainwater harvesting system to maximise rainwater use efficiency.

SUMMARY

East African communities face concomitant food and energy security challenges. The current expansion in off-grid electrification in the region is aimed at delivering increased access to electricity for rural communities, but does not address their insecure food supplies, limited opportunities to enhance livelihoods through higher value agricultural products and increasing pressure on land resources. Technologies which integrate crop production and clean energy supplies could deliver multiple sustainable development goals in a resource-efficient manner. Agrivoltaic systems do just this by presenting an opportunity for farmers to improve their crop production and develop higher value agricultural crops and commodities and powering post-harvest processing equipment. Shade from PV panels reduces evapotranspiration - alleviating water stresses limiting crop growth - while powered equipment such as refrigeration can reduce post-harvest yield loss. The benefits of electrification can be extended to the broader community too, to power household appliances and charge mobile phones for example. Despite the benefits of agrivoltaic systems being demonstrated by research in the Global North, there is as yet no empirical evidence of the potential benefits of agrivoltaic systems in East Africa, and awareness of such alternatives to conventional solar parks by development decision makers is lacking. Further, the absence of cross-sectoral policy support remains an uncertainty and a challenge for farmers and agribusinesses seeking electrification infrastructure that offers benefits beyond electricity provision. Empirical research generating locally relevant evidence and demonstrating the benefits of such systems given the local environmental conditions and target crop varieties is required to gain political, business and community support for agrivoltaic systems in East Africa.

ACKNOWLEDGEMENTS

This work was funded by the Global Challenges Research Fund, through a project awarded to SH by the UK Research and Innovation’s Economic and Social Research Council entitled “Harvesting the sun twice: Enhancing livelihoods in East African agricultural communities through innovations in solar energy” (project reference ES/T006293/1).

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