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Enhancing solar mini-grid utilisation in farming communities: crop strategies to reduce costs and improve energy access

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E-mail: b.winchester20@imperial.ac.uk**Keywords:** agriculture, energy, mini-grid, photovoltaic, solar powerSupplementary material for this article is available [online](#)**Abstract**

Approximately 80% of the global population without access to electricity live in sub-Saharan Africa (SSA) with rural areas disproportionately affected. Solar-powered mini-grids are being used to increase rural electrification. However, their deployment is hindered by high costs, low electricity demand, and limited incomes in rural households. Agriculture constitutes 70% of rural incomes in SSA and faces threats due to a reliance on rainfall coupled with low irrigation levels in the context of climate change. Irrigation loads have been suggested as a strategy to enhance the economic viability of solar mini-grids by boosting electricity demand: reducing the levelised cost of used electricity (LCUE) whilst improving farmer yields and incomes. This study investigates a case study in Tanzania, selected based on the amount of population without access to electricity, the potential for irrigation, and the prevalence of photovoltaic solutions in the least-cost pathways for rural electrification. The seasonality and timing of irrigation demand, as well as crop mixes, are varied to optimise for the lowest LCUE using the open-source modelling framework continuous lifetime optimisation of variable electricity resources. Evapo-transpiration and energy-system modelling are used to estimate energy demand. We find that adding irrigation loads has the potential to increase the LCUE and lower asset utilisation (load factor) when compared to residential loads but that, by selecting crops with longer growth periods, optimising irrigation timing, and implementing multiple planting seasons, the LCUE can be up to 7% less than residential-only systems with an increase seen in asset utilisation. LCUE values of 0.54–1.30 \$/kWh were found: higher costs were associated with shorter crop-growth periods, single planting seasons, and poorly timed irrigation loads whilst lower costs were observed with bimodal cropping and solar-coordinated irrigation times. The research highlights that, when incorporating irrigation loads into rural-electrification strategies, specific factors should be considered to enhance their viability within mini-grids in SSA. We recommend to both policymakers and mini-grid developers to promote multiple planting seasons (bimodal cropping) and encourage optimal crop mixes where relevant alongside irrigation schemes and rural electrification projects as well as adopting the use of flexible tariffs for irrigation loads.

1. Introduction

Access to energy has been linked to economic growth and development [1]. Despite significant progress in

the clean energy transition worldwide, 571 million people in sub-Saharan Africa (SSA) still lacked access to electricity in 2022, representing about 80% of the global population without access [2]. Population

growth has outpaced the electrification rate in SSA, resulting in a year-on-year increase in the number of people without access [3]. This disparity is particularly pronounced in rural areas which account for 80% of the people without electricity in SSA [2]. Eastern SSA has the largest number of people without electricity access [3].

This study focuses on Tanzania, a country in Eastern Africa, as a case study. Tanzania has a population of approximately 68 million, with an annual population growth of 2.9% [4]. Out of this population, 36 million people (53% of the population) lack access to electricity [4], affecting 64% and 22% of the rural and urban populations, respectively [3]. Tanzania was selected as a case-study location based on three factors:

- the percentage of population without access to electricity [5], with 10 countries in SSA having similarly low levels of rural electrification;
- the potential for irrigation and agricultural productive uses of energy (PUEs), narrowing our scope to Nigeria, north-west Ethiopia, Madagascar, South Africa and Tanzania [6];
- and the prevalence of photovoltaic (PV) solutions (namely, PV mini-grids and stand-alone systems which usually consist of PV panels and battery storage) amongst the least-cost electrification pathways [7].

Mini-grids are decentralised systems which supply a community with electricity, have a localised means of power generation, and are usually independent of the national grid network [8]. Given the high solar irradiation potential across SSA (including Tanzania), off-grid solar solutions (both mini-grid and stand-alone-solar systems) are a promising solution. They may provide reliable electricity access at a lower cost, depending on the distance from, and reliability of, existing national grid infrastructure [7, 9] with Adamopoulou *et al* [10] highlighting that mini-grid installations in 2024 are projected to be six times higher than in 2018.

However, low energy demand and low customer ability to pay at deployment sites [11, 12], high capital costs and high discount rates in SSA [13, 14], and the need for stable policy and regulations [15–17] limit mini-grid deployment. One solution is designing mini-grids for meeting productive uses of electricity (PUEs)—energy used in income-generating activities and appliances [18, 19]. Increased electricity access for PUEs can lead to increased incomes for end users, stimulating demand for mini-grids and improving affordability for end users [6].

Agricultural PUEs are a potential solution given that agriculture accounts for one-third of the overall gross domestic product in SSA [20] and an estimated 70% of rural incomes (covering 85%–90% of the total cultivated land) in Tanzania [21]. Tanzania has two

main cropping patterns: unimodal and bimodal [22, 23]. Unimodal cropping involves planting crops during a single rainy season only. Bimodal cropping constitutes planting crops twice per year. Climate change and reduced rainfall mean that areas which typically experience bimodal seasons are now transitioning to unimodal cropping [24].

Despite the dependence of rural Tanzanian households on agriculture, land productivity remains low: growth is primarily driven by land expansion rather than improvements in yield and there exist issues surrounding food security [25]. Current farming practices use rain-fed irrigation systems which are vulnerable to climate change and drought [24]. Using energy in agriculture, particularly for irrigation and improved crop processing, positively impacts food security and farming incomes, a trend observed across SSA [26].

While Tanzania's policy landscape includes initiatives to accelerate rural electrification such as the introduction of the Rural Energy Agency (REA) and the Tanzania Rural Electrification Expansion Programme (TREEP), there remains significant gaps within the intersection of agriculture and energy. This is noted by [27] who highlights that despite the aim to promote socio-economic development in agriculture alongside rural electrification, the current policy document lacks clear guidance on addressing the interdependencies between agriculture and energy. This is corroborated by [28] who highlights that, despite the extensive development of the mini-grid tariff system and subsidies in Tanzania compared to other countries in SSA, the current structure fails to address key issues such as cost-reflective tariffs for mini-grids not connected to the grid.

A common issue when incorporating agricultural PUE into mini-grids is the lack of a consistent year-round demand due to the seasonal nature of agriculture [19, 29–31]. This can lead to a higher levelised cost of electricity (LCOE) compared to residential-only loads [18]. A 2%–4% reduction in the LCOE was reported when PUEs were deployed [19] whilst Wamalwa, Maqelepo and Williams [29] found that, in some of the cases studied, the LCOE declined, but, in others, it rose due to the seasonal nature of irrigation loads when including agricultural PUEs.

There is an understanding gap surrounding the impact of irrigation load timing (particularly seasonal variations and daytime loads) on optimal system sizing. For Tanzania specifically, the impact of bimodal cropping, and its effects on the levelised cost of used electricity (LCUE) for mini-grids, needs to be investigated; where the LCUE differs from the LCOE in that it explicitly does not include dumped or curtailed energy when levelising costs, a distinction often not made in the literature but useful when considering systems where this additional power cannot be exported to the grid.

Further, more direct policy guidance is required to integrate agricultural loads effectively and to improve investment in the sector. This study aims to address the following questions:

- (i) How do agricultural PUEs, particularly irrigation, vary across Tanzania?
- (ii) What are the potential enablers to increase the feasibility of seasonal agricultural PUEs in mini-grids? Namely, how can the seasonality of agriculture be combined with seasonal power generation, and how do crop types, regions, and patterns affect system viability?
- (iii) How should project developers, policymakers, and energy companies leverage agricultural productive uses to increase energy access across SSA?

2. Methods

The study utilised a combination of geospatial modelling tools and energy-system modelling, shown in figure 1. The scenarios considered are outlined in table 1 and consist of a *reference* scenario, constituting residential and commercial loads (i.e. without agricultural loads), along with a series of agricultural-load scenarios. All scenarios include the residential and commercial loads of the community:

- *reference*, which does not include agricultural loads;
- *irrigation*, which includes estimated irrigation loads;
- *coordinated*, where the irrigation timings are adjusted to better align with local-solar power generation;
- *coordinated-optimised*, where the coordinated loads in the *coordinated* scenario are based on a hypothetical optimised crop mix;
- and *bimodal-coordinated*, where the coordinated loads in the *coordinated* scenario are based on a bimodal (twice-yearly) cropping pattern.

In the *irrigation* scenario, irrigation takes place for 6 h daily: four hours in the morning and 2 h at night. (The irrigation load profile for the *irrigation* load is given in the supplementary methods in supplementary figures 4 and 5(b)). For the *coordinated* scenario, the irrigation load is optimised for solar generation with a characteristic solar curve and maximum load at noon. This coordinated irrigation load does not reflect typical farming practices, however, which favour irrigation in the early morning and after sundown to minimise potential evaporation losses. (The irrigation load profile for the *coordinated* load is given in supplementary methods in supplementary figures 4 and 5(c)).

2.1. Location selection

Geospatial analysis was undertaken to determine suitable locations, considering population density, areas with no electricity access, and locations of crops. Figure 2 shows the selected case study locations. The ratio of crops present in each location was assessed using the latest 26 global agro-ecological zones crop-layers dataset, available for 2015 [32]. Given 2015 is the most recent year of crop data available, we take other data and modelling inputs from the year 2015. Further detail on the crop distribution is contained in the supplementary information in supplementary table 2 and supplementary figure 1.

2.2. Community residential loads

To model the community baseline load, the National Renewable Energy Laboratory load profile explorer tool was utilised [36]. The tool can provide hourly electrical load profiles for a typical rural African household in SSA. The tool is commonly used for mini-grid modelling across SSA and was found to be relevant for this study due to lack of specific load data [18, 37]. Once the daily load profile was obtained for the community, it was used across the year and did not include variations between weekdays and weekends or seasons. However, an annual population growth rate of 2.9% was applied based on the current growth trend [4]. (More information can be found in the Supplementary Methods.)

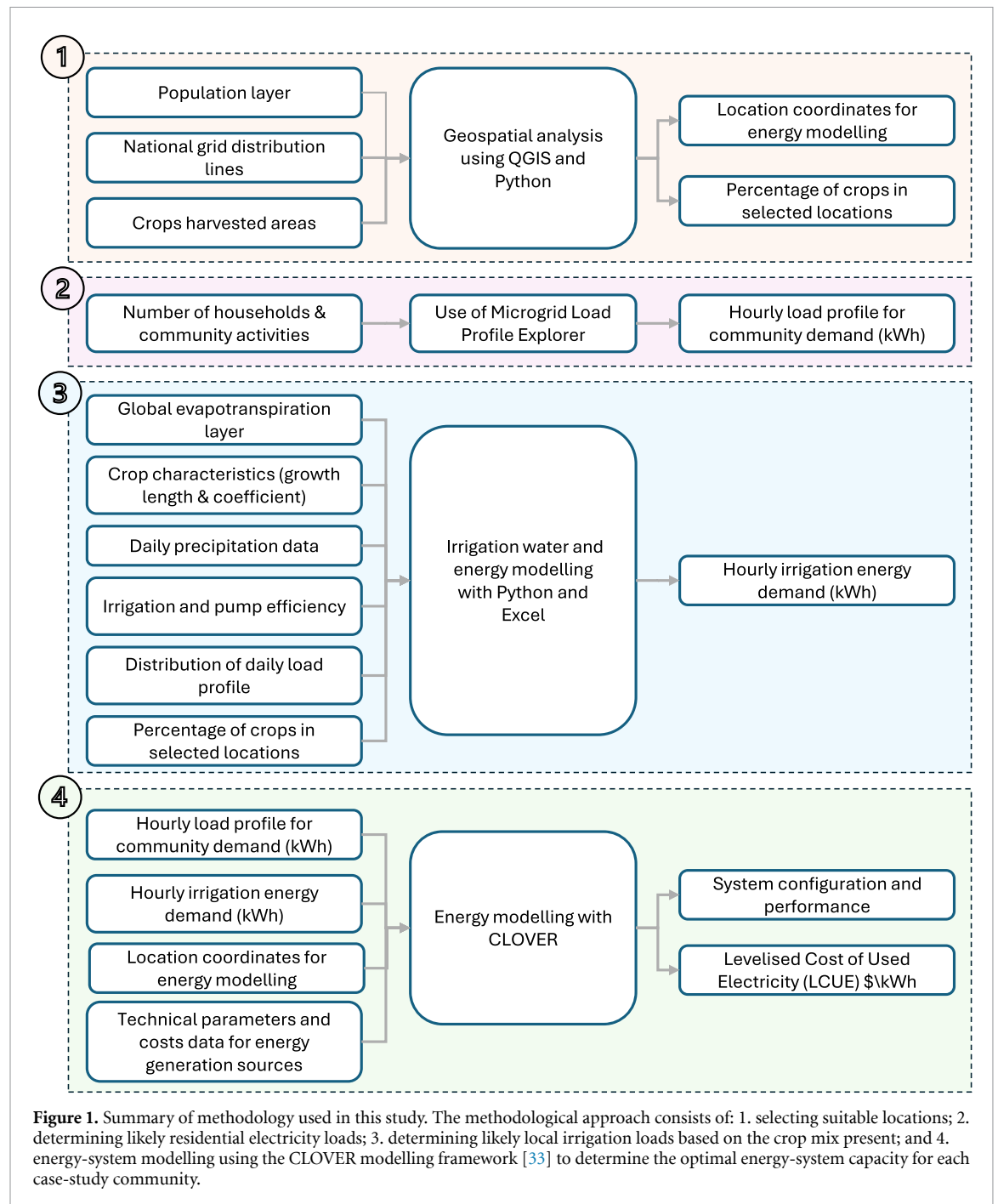
2.3. Agricultural loads

To model the irrigation load, the evapo-transpiration rate for each crop was calculated using the FAO-56 Penman–Monteith equation considering the length of crop development and planting dates for each crop [38, 39]. Crop evapo-transpiration rates (ET_c) are characterised based on K_c , a non-dimensional number which relates the ET rate to that for a reference crop, ET_o :

$$ET_c = ET_o \times K_c, \quad (1)$$

where ET_c is the crop evapo-transpiration rate in mm d^{-1} , ET_o is the reference crop evapo-transpiration rate in mm d^{-1} and K_c the crop coefficient [39]. Four growth stages are utilised in obtaining the K_c values: initial, development, mid-season and late-season stages. The variance in the K_c values is a result of changing leaf area, crop height and ground cover across these stages.

The net irrigation requirement was calculated considering the evapo-transpiration rates based on the crop mix and the effective precipitation for each location [39]. However, [40] highlights that the method used to estimate rainfall results in significantly different values for the irrigation requirement: a sensitivity analysis was undertaken to explore



the dependence of the results on this formula, methods and results of which are presented in the Supplementary Information. For this study, the dependable rain formula was used and a sensitivity analysis was performed using the USDA SC method. (See Supplementary Information for detailed formulae, with crop-specific factors in Supplementary table 4, and Supplementary table 7 for an analysis of the sensitivity of the results presented when an alternative precipitation formula is used.)

The gross irrigation water requirement involved accounting for losses during irrigation such as the irrigation efficiency and water withdrawal efficiency [29]. The equivalent daily electrical load for

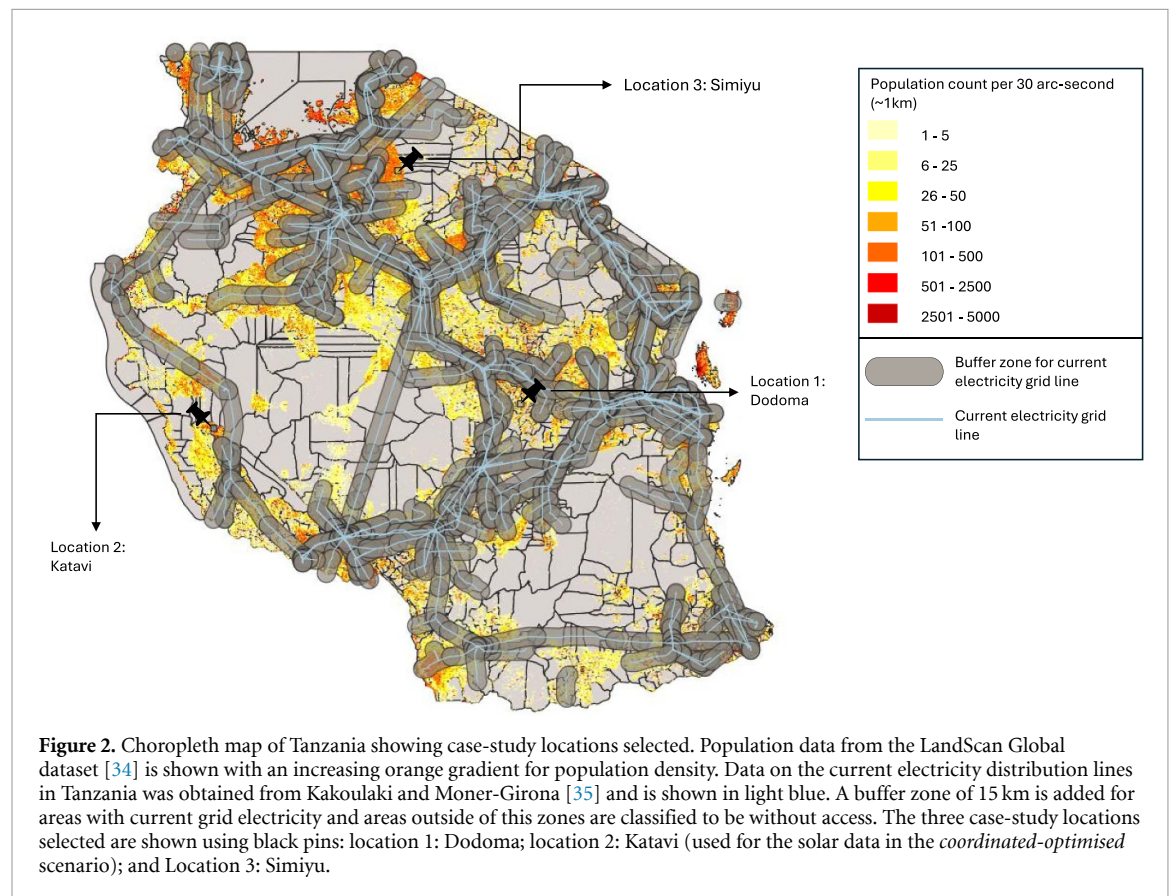
the gross irrigation requirement was dependent on the the pumping energy requirement as well as water flow rate. The output of this section was the daily irrigation energy requirement for each crop in a location in kWh ha^{-1} . More information is given in the Supplementary Methods.

2.4. Energy-system modelling

The energy systems were simulated and optimised using the energy modelling tool CLOVER continuous lifetime optimisation of variable electricity resources (CLOVERs) [33]. The optimisation process works to determine the optimal system size (installed capacity

Table 1. Summary of the scenarios used.

Scenario	Description
<i>Reference</i>	The load consists of residential loads and commercial non-agricultural loads, i.e. shops, schools and clinics.
<i>Irrigation</i>	The load is the same as the <i>reference</i> scenario with irrigation loads based on the existing crops present at the respective locations. The irrigation occurs in the mornings (5 a.m. to 9 a.m.) and the evenings (9 p.m. to 11 p.m.).
<i>Coordinated</i>	The load is the same as the <i>irrigation</i> scenario for the respective locations but the irrigation load has coordinated with the solar output in the respective locations, i.e. irrigation occurs when the Sun is up.
<i>Coordinated-optimised</i>	The load is the same as the <i>coordinated</i> scenario but the irrigation load has been calculated for a proposed optimal crop share which aims to maximise asset utilisation (load factor) and minimise the LCUE over the year.
<i>Bimodal-coordinated</i>	The load is the same as the <i>coordinated</i> scenario, but, in this scenario, three additional crops (maize, millet, and sorghum) which are modelled as unimodal in the other scenarios are here considered bimodal: they are planted twice yearly. The crop shares used reflect those in the respective locations.



of PV panels and batteries, in kW_p and kWh, respectively) to meet the electricity demand. The optimisation criterion used was the LCUE, in \$/kWh:

$$\text{LCUE} = \frac{\sum_{n=1}^N \frac{I_n + M_n}{(1+r)^n}}{\sum_{n=1}^N \frac{E_n}{(1+r)^n}}, \quad (2)$$

where I_n is the initial investment cost in year n , M_n is the maintenance and operational cost in year n , E_n

is the annual energy consumed (kWh), r is the discount rate (a discount rate of 16.7% was used for Tanzania [41]), and N is the total number of years of analysis. All costs are in USD.

The LCUE differs from the LCOE in that it explicitly does not include curtailed energy [42]. Whilst most modelling tools use a definition of the LCOE which does not include curtailed electricity in E_n , we make the distinction here for clarity as unconsumed electricity is of no value in off-grid settings. Demand

data used for the community loads are given in the supplementary methods (supplementary table 3).

3. Results

The results for the various scenarios are detailed in table 1. The irrigation load for the current crop mix farmed is presented first, along with the utilisation rates (load factors) for mini-grid assets sized to meet the load. Sensitivity analysis and scenario comparisons follow, with the crop mix, irrigation timings, and bimodal cropping all presented. Additional analyses of the results presented are given in the Supplementary Results.

3.1. Irrigation loads for existing crop regimes

The crop breakdown by area farmed, along with the agricultural irrigation load which results, are shown in figure 3, with the utilisation rates for mini-grid assets sized to meet this irrigation load shown in figure 4. Similarity is observed in the irrigation demand pattern for locations 1 and 2 (Dodoma and Katavi, respectively) where there is minimal irrigation demand from June to August, which aligns with the crop calendars. For both locations, an increasing trend in irrigation demand is observed from March through to April, as many crops are in growth stages with higher water demands (here reflected in higher K_c values), resulting in greater irrigation requirements.

For all crops in locations 1 and 3, there is no irrigation demand from mid-June through to September, as reflected by a flat line. In Katavi, banana, which is grown year-round, results in an irrigation load visible in red in June–September when other crops are not being cultivated. Gaps in demand are also observed throughout November through to May as a result of precipitation during the period. Automatic pumping regimes may result in irrigation during these downtimes (and on days where rainfall occurred) but, in reality, farmers are likely to not irrigate during or after periods of rainfall. Further, in location 2 (Katavi), the K_c values for bananas-1.1 for the initial, development, and late stages, and 1.2 for the mid-stage-result in a more consistent irrigation load requirement, with variability primarily influenced by precipitation.

Table 2 outlines the optimal (lowest-LCUE) system configuration along with the LCUE for all scenarios modelled. Optimisations were performed with a requirement that at least 95% of the demand was met and that no more than 5% of hours contained unmet energy (electricity ‘blackouts’, where not all of the demand was met). Comparing the *reference* and *irrigation* scenarios, the data show a higher LCUE for the *irrigation* than the *reference* scenario across all locations with the lowest LCUE values in location 2.

3.2. Coordinated irrigation times

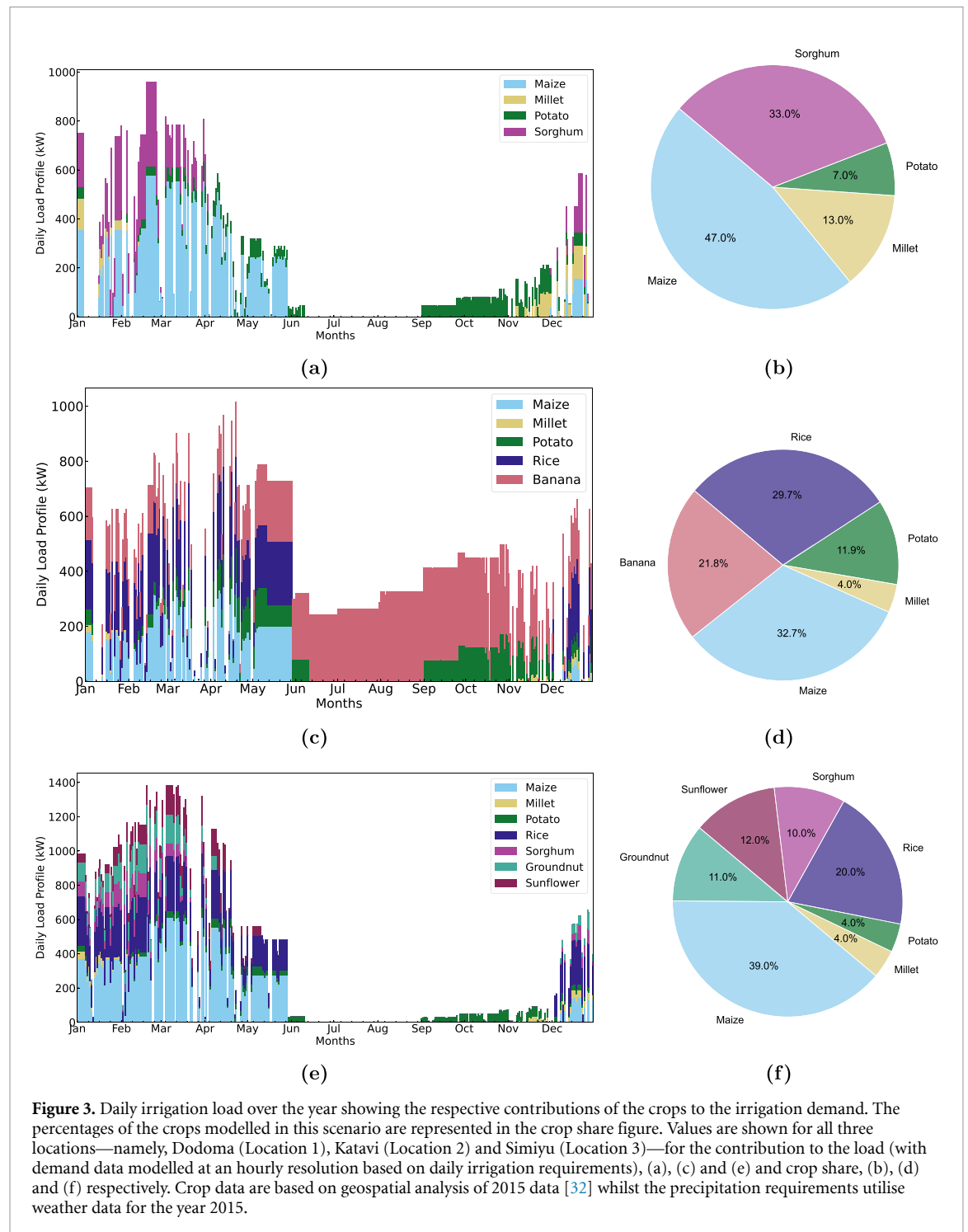
Results in table 2 show the impact of the *coordinated* scenario (where irrigation pump timings were coordinated with solar availability) on the system capacities and LCUE of the optimal system. Differences in the required storage capacity are visible: for a typical (non-coordinated) irrigation pattern, where usage occurs outside of peak solar-output hours, a higher battery capacity is needed to meet the demand. A reduction in the required battery capacity is visible when coordinating to the solar output across all locations. The largest reduction is observed in location 3, where the necessary storage capacity decreases by 85%, from 2200 kWh to 340 kWh for the *irrigation* and *coordinated* scenarios, respectively. Locations 2 and 1 also experience significant reductions in storage requirements of 77% and 69%, respectively.

This reduction in storage capacity results in a drop in the LCUE in scenarios where the load is coordinated with solar output. As shown in figure 5, the LCUE decreases by 34%, 31% and 38% for locations 1, 2 and 3 when the irrigation pump times are coordinated, respectively. Across both scenarios, the total energy demand remains the same with the coordinated load reducing battery-related costs. Despite this reduction, the LCUE remains higher than the baseline residential-only LCUE in each location; i.e. in these scenarios, the inclusion of irrigation loads does not improve the financial viability of the mini-grid, instead increasing the LCUE.

3.3. Optimised crop mix

Figure 6 shows a potential optimal load for irrigation created from the top four crops with the longest growing period with percentages assigned based on growing periods. Note, that the crop mix here has been optimised to best coincide with solar generation over the year (to improve asset utilisation and lower the LCUE of the mini-grid system) and does not include the economic profitability of crops grown. The crops in this new distribution were present in the original crop mix in location 2 but in different proportions.

Visible in figure 3(a), is an increased load demand from July through to October compared to location 2 on account of a higher percentage of banana crop in the new crop share. The system sizes and LCUE are shown in table 2 with 0.54 \$/kWh obtained for the *coordinated-optimised* scenario. This value is 7% lower than the LCUE for the optimal system in the *reference* scenario for location 2: i.e. the *coordinated-optimised* crop mix results in mini-grids which can provide electricity for agriculture and residential loads with a lower LCUE than for residential community loads only. The LCUE obtained is also 2% less than the lowest LCUE obtained for the *reference* scenarios across all three locations (achieved in location 1).



3.4. Impact of bi-modal cropping

Figure 7 displays the changes to the utilisation rates and LCUE in the *bimodal-coordinated* scenario, where the share of bimodal crops grown was increased, compared to the *coordinated* scenario across all three case-study locations. In location 1 (figure 7(a)), the utilisation rate for the first year increases from 29.8% to 40.2%. Notably, there is an increase in asset utilisation from June to October, months that previously had lower demand, driven by greater irrigation demand for bimodal crops in this period. In location 2 (figure 7(b)), although there was already a

continual demand (due to the presence of banana), bimodal maize cropping leads to increased demand from June to September, reflected in a slight increase in the utilisation rate during this period, with an increase of two percentage points on average. In location 3 (figure 7(c)), there is a noticeable increase in utilisation between the months of June to December, accompanied by an 11% increase in the utilisation rate for the first year on average.

A trend visible across all subfigures in figure 7 is that switching to bimodal cropping results in less variation in asset utilisation throughout the year. This is

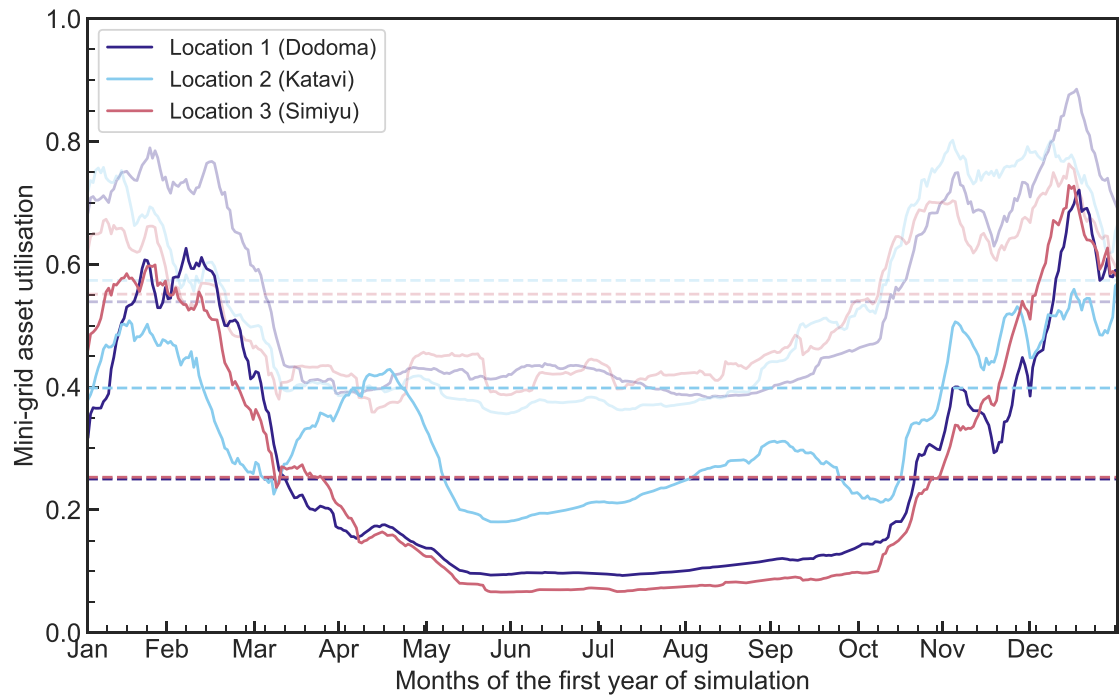


Figure 4. Mini-grid asset utilisation for the *irrigation* scenario across all three case study locations. Solid lines indicate the *irrigation* scenario whilst faded lines denote the *reference* scenario. The average utilisation rates for the *irrigation* scenario in the first year are 25%, 40% and 25% for locations 1, 2, and 3 respectively compared to 54%, 57% and 55% for the *reference* scenario for locations 1, 2 and 3 respectively.

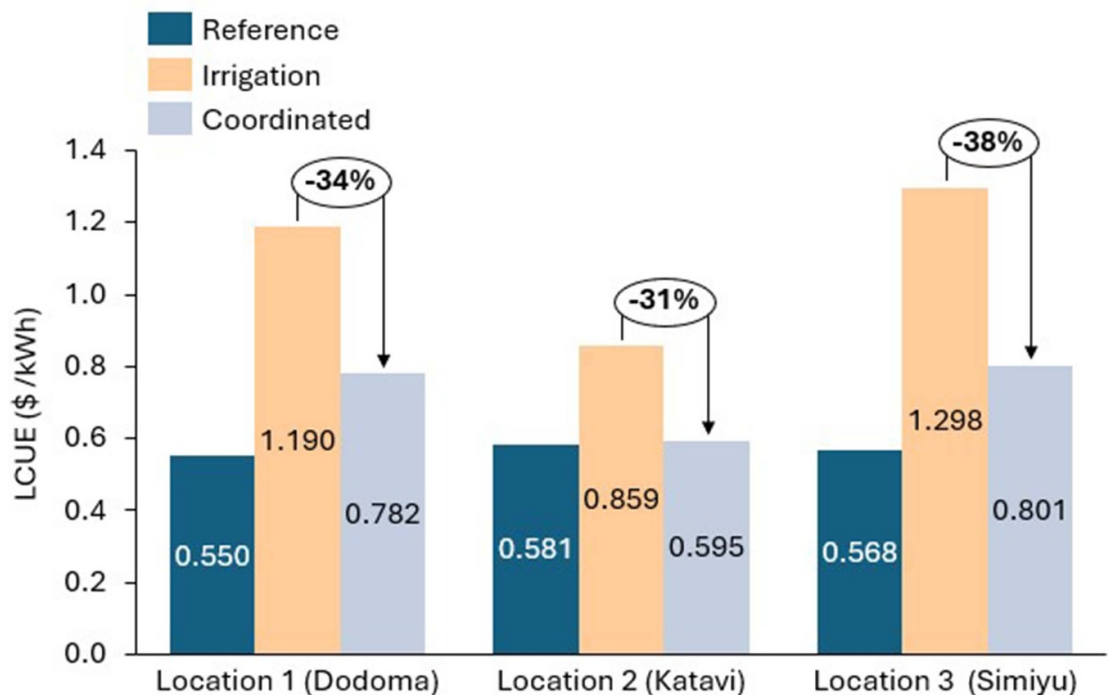


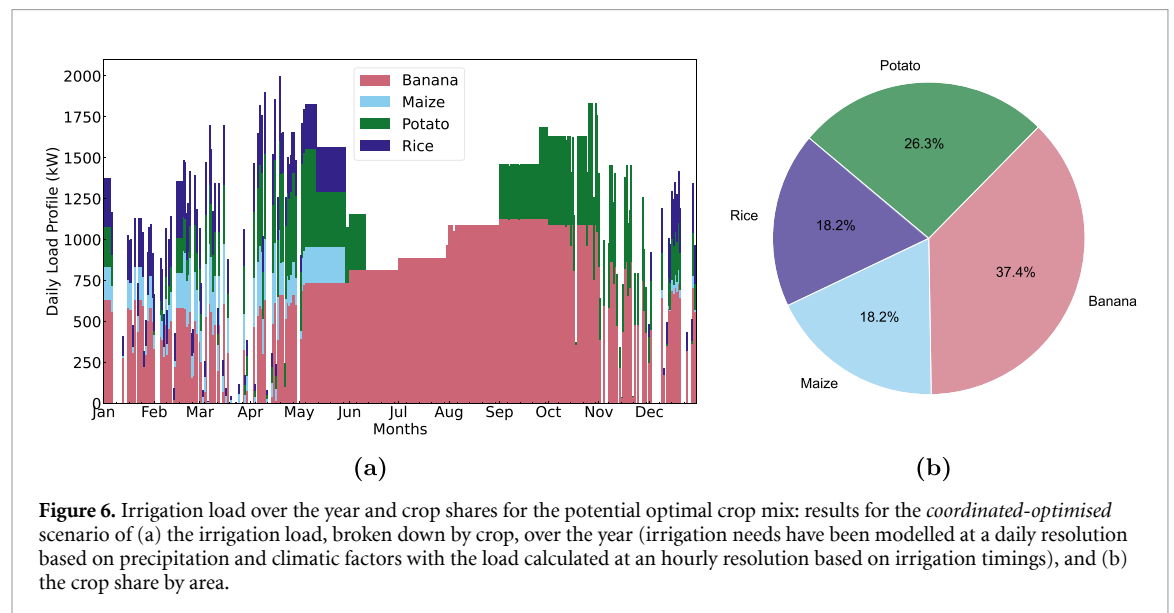
Figure 5. LCUE comparison for the optimal system sizes to meet the respective demand. Results are shown for the *reference* (dark blue), *irrigation* (yellow) and *coordinated* (light blue) scenarios across the three case study locations. The LCUE is consistently lower for the *coordinated* scenario compared to the *irrigation* scenario, with reductions of 34%, 31% and 38% when the irrigation load is coordinated with solar demand compared to being un-coordinated for locations 1, 2 and 3, respectively.

especially marked in figure 7(a). where the Winter utilisation peaks for the *coordinated* scenario (visible in blue) are no longer present (shown in red).

Figure 7(d) shows that the inclusion of bimodal irrigation in locations 1 and 2 lowers the LCUE below the baseline reference LCUE and, for location 3, results

Table 2. System sizes and LCUE for the optimal systems across all three case-study locations for all scenarios. Optimal systems are capable of providing energy at the lowest LCUE given the requirements on blackouts and unmet energy fraction (namely, a maximum of 5% of blackout hours and 5% of energy going unmet).

Location	Scenario	PV capacity (kW _p)	Storage capacity (kWh)	LCUE (\$/kWh)
1 (Dodoma)	<i>Reference</i>	105	320	0.55
	<i>Irrigation</i>	360	1450	1.19
	<i>Coordinated</i>	310	450	0.78
	<i>Bimodal-optimised</i>	360	330	0.54
2 (Katavi)	<i>Reference</i>	110	345	0.58
	<i>Irrigation</i>	350	1500	0.86
	<i>Coordinated</i>	350	350	0.60
	<i>Bimodal-optimised</i>	400	320	0.54
3 (Simiyu)	<i>Reference</i>	110	325	0.57
	<i>Irrigation</i>	500	2200	1.30
	<i>Coordinated</i>	460	340	0.80
	<i>Bimodal-optimised</i>	450	350	0.57
N/A	<i>Coordinated-optimised</i>	650	470	0.54



in a value only 5% more than the baseline reference value. This change to irrigation patterns allows the maintenance of the initial percentages of crops in the location whilst reducing the LCUE; i.e. the inclusion of irrigation loads for mini-grids, operating a bimodal cropping pattern can reduce the LCUE below sizing the mini-grid for community loads only.

3.5. Sensitivity analysis

The precipitation formula used (see section 2) determines how the irrigation loads are determined from the crop mix. A sensitivity analysis, performed with an alternate precipitation formula, shows that the change in methodology does not affect the trend in results across the examined scenarios (see supplementary information). However, a sensitivity analysis using the cost of capital reveals a notable impact on the LCUE with a clear trend of lower discount rates

resulting in reduced LCUE values. More information is given in the Supplementary Results.

4. Discussion

The discussion is structured into a discussion of the results and recommendations to policymakers. Limitations of the study, and recommendations for future work, follow.

4.1. Key findings

Irrigating crops which have a longer growth duration results in lower LCUE values because of the more consistent irrigation load required compared to crops with a shorter growth duration. This can be explained by the mini-grid asset utilisation as shown in figure 4. Sizing a mini-grid to meet these

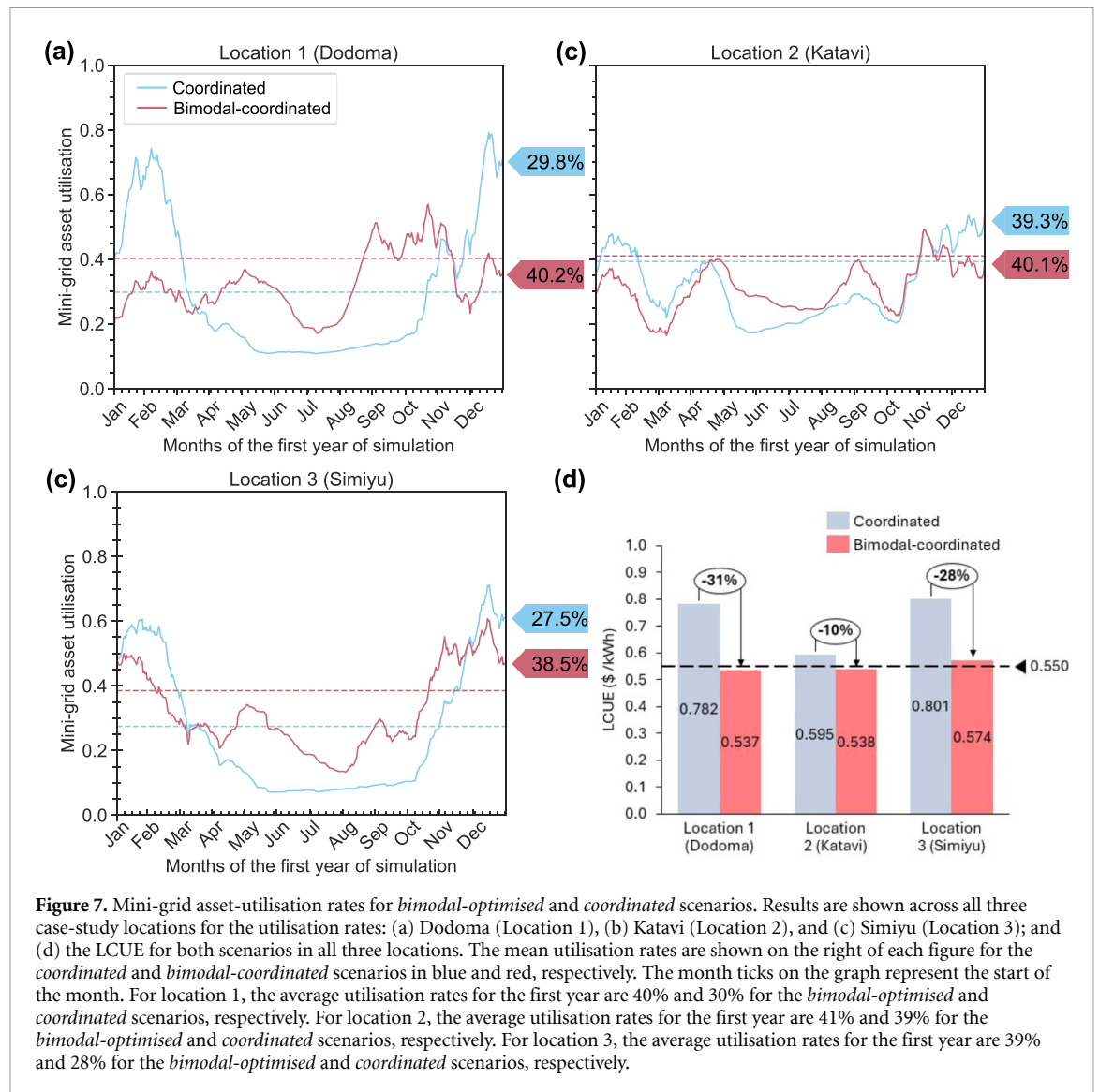


Figure 7. Mini-grid asset-utilisation rates for *bimodal-optimised* and *coordinated* scenarios. Results are shown across all three case-study locations for the utilisation rates: (a) Dodoma (Location 1), (b) Katavi (Location 2), and (c) Simiyu (Location 3); and (d) the LCUE for both scenarios in all three locations. The mean utilisation rates are shown on the right of each figure for the *coordinated* and *bimodal-coordinated* scenarios in blue and red, respectively. The month ticks on the graph represent the start of the month. For location 1, the average utilisation rates for the first year are 40% and 30% for the *bimodal-optimised* and *coordinated* scenarios, respectively. For location 2, the average utilisation rates for the first year are 41% and 39% for the *bimodal-optimised* and *coordinated* scenarios, respectively. For location 3, the average utilisation rates for the first year are 39% and 28% for the *bimodal-optimised* and *coordinated* scenarios, respectively.

loads results in higher LCUE values than community-only mini-grid systems, aligning with previous findings which noted that incorporating irrigation loads with peak demands higher than the peak loads in residential-only systems resulted in higher LCUE values. [18].

By coordinating the irrigation load with solar output, a 65%–85% reduction in battery capacity was observed, with corresponding LCUE drops between 31% and 38%. This is comparable with results from [43] who recorded a 24% reduction in the cost of electricity and a 39% decrease in storage capacity when irrigation load was coordinated with solar energy potential. However, this approach deviates from typical farming practices where irrigation is driven by the relationship between ambient temperature and evaporation losses [30] with up to a four times increase in evaporation when irrigating during the day compared to the night [44].

Early morning irrigation is crucial for water conservation, as the same amount of water applied during this time results in more efficient soil

absorption and plant growth [45]. Whilst irrigation timings may not matter for deep-rooted crops (when drip irrigation is utilised), it applies to many of the crops grown [46]. Thus, early morning and nighttime irrigation is widely used on account of its benefits in reducing evaporation and enhancing water absorption. However, the effectiveness of irrigation timing may vary depending on the irrigation method, the type of crops being cultivated, and the specific climate conditions. In this context, the potential increase in water use (along with any potential additional costs) must be carefully considered when aligning irrigation with solar output to reduce the LCUE.

By coordinating irrigation and creating optimal crop shares based on locally-grown crops, a 7% reduction in the LCUE was achieved compared to sizing for community loads only for location 2. The inclusion of irrigation loads within mini-grids can therefore result in lower LCUE values than simply sizing systems to meet community loads. However, to achieve this, consideration of crop types and growth lengths is needed such that the variation in

the utilisation of the mini-grid assets throughout the year is reduced and a lower LCUE is achieved. Further, year-round crops, in this case, bananas, can serve as a consistent load but the mix of the crops irrigated by the mini-grid should be carefully managed.

Another approach is implementing bimodal cropping. For locations 1 and 2, the LCUE values for the optimum mini-grid system with bimodal cropping were lower than those achieved when sizing the mini-grid for community loads by 2% and 7%, respectively. Hence, irrigation can lower the LCUE values for the mini-grid without altering irrigation times or significantly changing the existing crop mix. Although this improvement is marginal, it represents a significant reduction compared to the unimodal cropping strategies considered. Further, [47, 48] report that practising farming only during a specific period of the year can negatively affect farmers due to missed income opportunities and increased costs, the impact of which needs to be considered in addition to simply sizing systems for the lowest LCOE.

In Tanzania, most regions traditionally follow a unimodal cropping pattern, largely determined by the seasonal rainfall distribution [22]. However, due to climate change, already seen in a general increase in temperature across the country and more frequent dry days and episodes of heavier rainfall [49], areas which historically experienced bimodal rainfall are increasingly shifting to a unimodal pattern [22]. Introducing irrigation systems could enable a second planting season, reducing reliance on rainfall [50], and improving the resilience of Tanzania's agricultural system to climate change [51].

With recent growth in agricultural output mainly due to increasing land area rather than improved productivity [52], there exists scope for improved food security based on an improved agricultural efficiency [53]. Incorporating irrigation and including a second planting season has a three-fold effect: reduced LCUE compared to mini-grids for residential loads, increased yields due to irrigation, and enhanced use of land throughout the year.

4.2. Wider implications beyond Tanzania

Whilst these results are most applicable to communities and farms within Tanzania, implications and trends are relevant more broadly. The finding that coordinating the solar output with pumping times results in a reduction in the LCUE will be applicable to all farms using these systems as coordinating this output reduces the quantity of battery storage required to meet peaks in demand due to water pumping. The exact degree of this difference will vary from location to location depending on climatic factors and the mix of crops grown, as shown in figure 5.

The finding that a reduction in the LCUE occurs when switching to bimodal cropping, or when switching to a crop mix which can best spread agricultural

irrigation loads throughout the year, will be applicable across all regions in SSA where unimodal cropping is practised, though whether this is enough for the LCUE to fall below that of a mini-grid powering community loads only (with no agricultural loads) will depend on the crop mix and location. Further, all of our modelling tools and data are open-source and so can be used to consider similar case-study communities with agricultural loads across SSA more widely.

4.3. Recommendations to policy makers

There is a need for greater cohesiveness between the agriculture, water, and energy sectors in Tanzania. Pardoe *et al* [54] emphasise that, while the agriculture and water sectors are relatively well-integrated (with policies addressing irrigation, water management, and conservation), there remains a significant gap in aligning energy policies with these sectors, particularly when it comes to supporting agricultural demands like irrigation. Despite wide recognition of the importance of energy for agriculture, realised through Tanzania's initiatives of the REA and the TREP, clear policy guidance for the intersection of energy and agriculture is lacking [27] with guidance for grid-independent mini-grid systems for communities also inadequate [28].

Given this context, we suggest the following policy recommendations for Tanzania (relevant for SSA more widely, also):

- To effectively promote rural electrification, the deployment of mini-grids should consider irrigation schemes at the planning stage;
- Bimodal cropping should be incentivised, with subsidies building on historical policies aimed at increasing the production of specific crops [55];
- Policies should consider coordinating irrigation loads with solar generation and other community loads.

Care should be taken, however, when interpreting modelling results: simulations and optimisations should not be relied on in isolation to inform policy changes. Whilst subsidy schemes may encourage shifts towards bimodal cropping, behaviour change cannot be effected by a purely top-down approach: local needs and opinions should be properly taken into account to ensure economic improvement and community resilience are best achieved [56, 57].

4.4. Limitations

There exist several limitations in the approach taken, though addressing these would have impacts on the wider applicability of the study to various contexts:

- The modelling framework used, CLOVER, does not account for the location of loads which may be relevant when considering communities which

have widely distributed loads (e.g. disparate irrigation demands) which will result in technical distribution losses;

- Inputs, including the irrigation patterns, cropping cycles and planting seasons used, were based on published reports and so are not specific to any particular locations. On-the-ground interactions with agricultural experts, crop modellers, and farmers could improve the relevance of the study to particular communities but would need to be weighed carefully against the loss of generality to Tanzania more widely;
- Input weather data was based on satellite observations which introduces a relatively large uncertainty (18%–39%) which could be compensated for by using locally-obtained weather information recorded at the case-study site. Additionally, there will exist uncertainties in the modelling tools used—irrigation model, CLOVER, etc—which should be kept in mind when interpreting the results.

4.5. Recommendations for future work

Building upon this study, there are several areas for further research, including expanding the scope to cover a broader range of crops across SSA and investigating the impact of climate projections on irrigation demands and the knock on effect that this will have on mini-grid sizing for agricultural loads. Additionally, exploring the potential of flexible time-of-use tariffs on mini-grid revenues and farmers' incomes could provide deeper insight into the economic and technical performance of such systems.

This study has focused on the energy system, with crop modelling covered only insofar as it relates to the likely irrigation demand. Work could build on these findings to investigate the feasibility of the transitions to bimodal cropping proposed here; i.e. to determine whether the LCUE reductions justify this transition once an enhanced crop-yield modelling is undertaken.

When it comes to the modelling used to determine the likely irrigation demand, crop-specific factors and case-study precipitation data were used to determine likely electrical pumping loads. Future work could consider the groundwater resource, as well as the potential of rainwater harvesting, to determine whether the available water resource is a significant or limiting factor as to the feasibility of such agrivoltaic installations.

5. Conclusion

This research finds that including irrigation loads into mini-grids for decentralised rural electricity provision can reduce the LCUE below sizing only for community loads under specific scenarios. Without any changes to farming practices (*irrigation* scenario), incorporating irrigation demands generally increased the LCUE compared to baseline residential-only loads

(*reference* scenario). By coordinating irrigation loads with solar output and developing an optimal crop share based on the four crops with the longest growth lengths (*coordinated-optimised* scenario), a 7% reduction in the LCUE compared to sizing for only community loads was observed.

Additionally, our results indicate that by implementing bimodal cropping (*bimodal-optimised*), deploying a mini-grid in conjunction with agricultural loads can be more profitable than systems sized solely for community loads: the LCUE for bimodal cropping at locations 1 and 2 was 0.537 \$/kWh and 0.538 \$/kWh, respectively, compared to the lowest LCUE observed in the reference scenario for community loads, which was 0.550 \$/kWh. In light of the combined challenges of rural electrification, changing climate, and the need for food security and increased agricultural productivity, the joint planning of mini-grids with agricultural loads, such as irrigation, holds significant value and should be considered an important pathway to improving electrification outcomes.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.5281/zenodo.14946607> with open-source methodology available at Github via <https://github.com/CLOVER-energy/CLOVER>.

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Author contributions

A J, H B and B W conceived of the presented study. C N M was responsible for funding acquisition in securing funding for the Grantham Institute. A J undertook the research—collecting data, developing methods and running simulations—under the supervision of H B and B W. A J analysed the outputs, with contributions from H B and B W. A J wrote the original draft, with all authors providing feedback and helping to shape the manuscript.

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