



Identifying high-priority impact areas for electricity service to farmlands in Uganda through geospatial mapping

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ABSTRACT

This article explores the food-energy nexus in sub-Saharan Africa by studying opportunities for improved agricultural productivity through electricity access. The study fills an acknowledged data gap by using geospatial analysis to identify priority areas for serving on- and near-farm electricity demand, using maize and coffee farming in Uganda as a case study. We use publicly available data on electrification infrastructure and crop statistics along with a select portfolio of variables, to identify areas where least-cost electricity delivery models intersect with agricultural needs, thereby highlighting target areas for further investigation. These findings are validated by community surveys in a key farming district. The analysis finds significant areas of underserved staple and cash crop farmlands can be served through grid and mini-grid electricity access within the next ten years. Such framing provides a useful lens for informing near-term interventions, and the paper concludes with practical recommendations.

1. Introduction

1.1. Agricultural productivity and the need for energy infrastructure

Given that a significant share of sub Saharan Africa's gross domestic product comes from agriculture and that food systems account for over two-thirds of the continent's labor force [1,2], much focus is being placed on the potential of the agriculture sector to deliver economic and livelihood relief across Africa, in light of the Covid-19 pandemic and unprecedented unemployment rates. Regional urban markets for agricultural goods are growing rapidly. In 2016 food and beverage accounted for US \$850 million, or two-thirds of retail spending on the continent [3], and estimates suggest African agribusiness could be a trillion dollar market by 2030 [4], mostly driven by demand in cities.

However the agriculture sector is challenged by productivity and profitability [5,6]. According to the OECD-FAO Agricultural Outlook, small-scale farmers constitute approximately 80% of all farms in sub Saharan Africa, with more than 75% of farmers preparing their lands using only hand tools. Only 5% of cultivated land is under irrigation, with most farmers depending entirely on rainfall [1,6,7]. Yields from maize, the continent's most important crop, remain low, currently average 2 tons ha⁻¹yr⁻¹ compared to 8 tons ha⁻¹yr⁻¹ in the Americas

[8]. Moreover, post-harvest value addition, including activities such as milling, canning or oil pressing, which are usually major employment and revenue sources in developed agrarian economies, are largely absent in Africa. Whereas processing adds about US\$180 of value per ton to agricultural produce, that value is US\$40 of value per ton in sub Saharan Africa [8]. Currently, the percentage of crop production processed through electrified value chains in sub Saharan Africa is quite low, estimated at 10% conservatively [8].

As regional urban demand for food goods rapidly increases, and as the recent continental free trade agreement opens new markets, agricultural energy needs are likely to expand. By 2030, the percentage of crop production processed with electricity is expected to grow to 15% because of the increased participation of small-scale farmers in formal value chains. The agriculture sector currently accounts for 2% of total energy consumption across the continent but the World Bank estimates demand from agricultural activities could double by 2030, reaching about 9 GW [8], with irrigation and primary processing for three crops - maize, rice and cassava - representing 83% of this demand [8]. Post-harvest handling and processing could greatly improve the revenue economics of both on-grid and off-grid technologies, by acting as anchor customers and high-energy consumers, representing added incentive for electricity service providers.

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According to the FAO, the potential of this agriculture and energy nexus is well-recognized, but under-supported with data for policy-making [9]. To date, the nexus discussion has been largely supply-side driven, a stronger understanding of the demand-side is needed [10]. One specific research gap that has been articulated in the literature is on which types of electricity delivery models are most economically viable for serving different farm needs [11]. This study was designed to address that gap through the identification of priority areas for least-cost electricity delivery models at the sub-national level. The study uses readily available data on (i) existing and projected electrification infrastructure, (ii) crop statistics, and (iii) a select portfolio of variables including climate, population density, road networks and distance to markets, in an overly analysis which identifies priority areas for serving farmlands through different delivery models. Replicability and implications are demonstrated using maize and coffee farming in Uganda as a case study.

These data sources have not been combined in this way to date, so this exercise demonstrates a simple, replicable method for rapidly identifying specific geographic areas of opportunity which can be used by practitioners and policy makers for targeting zones of interest. Identified priority areas and their respective output statistics can be used to further investigate farming needs and for energy demand estimation. The model, output shapefiles, and all input data have been made available via QGIS cloud at: <https://qgiscloud.com/yifeiliu/PowerAgriResearchMapOnline/>

The key research questions governing this study are:

- Which electrification technologies provide the least-cost delivery path to serving farmlands in Uganda?
- Which geographic areas can be identified as high-priority opportunities to support expanded access to agro-processing activities such as maize milling?
- What policy interventions does such analysis suggest for improving agricultural productivity through electricity?

1.2. Literature review

A review of the available literature shows that most agricultural research in Africa focuses on inputs at the farming level or agricultural product value chains and markets. Research on agro-processing and the value-addition value chain is fragmented or non-existent, and represents an important research need [12]. The slim literature which does explore post-harvest and primary processing shows that there are a number of critical enabling factors: access to land and the challenges of land fragmentation, access to water, access to markets, trade barriers and competitiveness, access to financial services and micro-credit, access to farm technology inputs and quality machinery, and access to infrastructure including electricity [13–15].

Geospatial methods are widely adopted in studying agricultural planning, electrification planning, and the agriculture-water-energy nexus [16]. [17] emphasizes evolving remote sensing technologies as a promising opportunity to manage the agriculture-water-energy nexus through cheaper, automated, and high spatiotemporal resolution data [18]. argue that environmental integration such as GIS and LCA provide a methodology capable of giving information to determine energy crops implementation strategies. Further [19–21], use spatial analysis to provide insights in improving agricultural productivity and [22] use similar tools to identify land suitable for agricultural land reform [23, 24]. focus on general electrification planning while [25] considers the proximity to agriculture communities as one of the electrification planning criteria [26]. develop a GIS-model to estimate water and electricity consumptions from groundwater irrigation and to suggest least-cost solutions, with a focus on location and extent of irrigated croplands (dates, vegetable, and olives).

Few of these methods have been applied to the sub Saharan Africa context. There are few direct, quantitative assessments of the linkage between electricity access and agricultural value addition for the

continent, and findings are mixed. Most studies obtain results through local survey and household data [27]. [28] integrates GIS approaches into the planning process for grid-based and off-grid rural electrification in Uganda, but does not consider agricultural productivity or yield in the model [29]. uses an approach which involves a geospatial analysis to examine Uganda's Water Land Energy resource constraints and inform food security policy with regard to 2012 and 2050 agricultural resource demand at national, district, and local scales. These are important studies that focus on local context, however there remains a gap in efforts to spatially identify priority regions for intervention. This is the focus of the present study.

2. A case study of mapping priority areas in Uganda

2.1. The status of maize and coffee primary processing in Uganda

Uganda is an example of a predominantly agrarian African society. Agriculture accounts for 70% of employment. Most farming is small-scale, low-input, and non-irrigated. Maize is the most widespread cereal crop, grown in all parts of the country. More than 2.1 million farmers – or roughly 60% of maize farmers – farm on less than 2ha of land and operate with zero cash inputs for yield improvement. Their yields average 1100–2100 kg/ha compared to yields of over 3500 kg/ha from commercial farmers [30]. Because of smallholder farmer's limited ability to invest in post-harvest handling or agro-processing, there are very few hubs for maize processing at the village level in Uganda [5,31].

A recent USAID millers survey finds most districts have limited milling capacity. The survey found 780 electric and diesel mills are present across 62 districts. The central region has the highest percentage of maize millers (38%), followed by the eastern region (22%). The northern region (22%) and western region (18%) have the lowest number of maize millers (18%), and a heavier reliance on diesel mills (see Map 2a) [30]. Most maize millers (46%) have a low production capacity, of less than 5 metric tons (MTs) per day. Uganda's entire western region, for instance, had only 173 active maize mills, with a total of 55 metric tons daily processing capacity.

Higher capacity mills are mostly found in urban, electrified areas. However across all regions unreliability of power supply and high tariffs are consistently the biggest challenges reported by millers [30,32,33]. Farmers dependent on diesel mills also reported frequent mechanical breakdown and equipment which does not meet commercial maize flour quality standards. Together this leaves large farmland areas and entire districts without access to high-quality milling [30]. As electrification rates across Uganda are low, and as stand-alone solar mills are not yet commercially viable [34], expanded on-grid access and mini-grids represent important near-term opportunities to serve the needs of thousands of communities without high-quality, reliable grid access, while also displacing diesel-powered mills.

Similarly, Uganda's exports are dominated by traditional cash crops such as coffee, cotton, tea, and tobacco, with coffee being the principal cash crop and leading foreign exchange earner. While other cash crops are largely grown on plantations - such as a sugarcane, tea, and palms - only a small portion of coffee comes from plantations. Most coffee is farmed by smallholders, also limited by processing capacity. The Ministry of Agriculture, Animal Industry and Fisheries is implementing initiatives to improve mechanization. Efforts currently focus on yield improvement interventions, with less attention to primary processing. As such this study identifies farmland areas best served by grid extension and mini-grid expansion for primary processing with a focus on maize and coffee, Uganda's most widespread staple and cash crop, respectively.

2.2. Data and methods

The method described herein leverages readily available crop statistics and the analytical outputs of an open-access electricity

optimization platform commonly used by energy planners in sub-Saharan Africa. The Global Electrification Platform (GEP), developed by the World Bank ESMAP, is an open-access tool for determining least-cost pathways to deliver partial or 100% electricity access for a given country by 2030, based on a standard set of optimization variables. It is a tool used regularly by international institutions, such as the International Energy Agency (IEA), as well as local planning institutions in East Africa [35]. By leveraging these key data sources, the inputs to the mapping model are thus transparent, familiar to likely end-users, and easily adaptable. For instance, the criteria which determine the least-cost delivery models can be adjusted by the end-user in GEP, to explore different technology cost scenarios for mapping. Likewise, the particular crop(s) of interest can be easily substituted.

The mapping model is based on geospatial overlay analysis tools, which allows a user to quickly integrate spatial data and attribute data in a highly adaptable way. For instance, as we demonstrate for Uganda, additional data, such as milling access by district, can be layered in to explore specific agricultural activities more narrowly. Likewise, the attribute filters used to constrain the search space can be easily adjusted by the end-user. Thus, the method presented here is a simple, easily adaptable, replicable way of pairing farmlands with their respective projected least-cost electrification delivery model that is accessible to local practitioners and policy makers. The following sections details the data sets and analysis method.

2.3. Data sets and sources

Croplands and yield statistics: crop yield statistics data were obtained from the IFPRI Global Spatially-Disaggregated Crop Production Statistics Database [36]. This database provides crop yield estimates for five classes of cropland by country for the year 2010. The data have a resolution of $1 \text{ km} \times 1 \text{ km}$ and report annual yield in kg/ha. For this study, the maize, coffee robusta, and coffee arabica crop yield statistics are used. Farmlands are classified based on the type of agricultural activity. The five classes include: marginal or unsuitable croplands; fully or partially irrigated croplands; rain-fed croplands; rainfed croplands with low-inputs; and rainfed croplands with high-inputs. Inputs include high-yield crop or seed varieties, fertilizer, chemical pest, disease or weed controls, animal traction and/or mechanization. Irrigated and rain-fed high-input croplands indicate production for commercial markets, while rain-fed low-input croplands or marginal croplands indicate subsistence level farming.

Least-cost electrification projections: Least-cost electrification pathways for 100% electricity access in Uganda are taken from GEP [35]. GEP includes seven electrification technologies: grid, stand-alone diesel, stand-alone PV, diesel mini-grid, PV mini-grid, wind mini-grid, and hydro mini-grid. The projected population growth, the projected grid tariff and cost of solar, and the demand targets can be varied to demonstrate least-cost electrification pathways under different scenarios. Solutions are provided at a $1 \text{ km} \times 1 \text{ km}$ resolution. The solution set for Uganda was obtained from the IEA's application of GEP, published in the Africa Energy Outlook [37]. The Africa Energy Outlook is a highly cited energy projection for the continent, used by donors and policy makers. The scenario selected for this study assumes high population growth (2.3%), a high top-down demand target (U4R3), high on-grid costs (0.131\$/kWh), low PV cost (-25%), and a non-linear electrification growth rate subject to a maximum rate of grid connection (2.5% of population per year). Under this scenario grid, standalone PV and PV mini-grid are projected to be the most prevalent technologies in Uganda by 2030.

Road networks and distribution infrastructure: A 2018 Africa road inventory data, including Uganda, were used to identify primary road networks [38]. This is the most recent road network data set currently available and is assumed to reflect current road networks. Data on existing, developing and proposed electricity distribution lines, distribution substations, and distribution transformers as of 2018 were

obtained from Energy Sector GIS Working Group Uganda [39]. Though these two data sets represent the latest available data, road networks and distribution infrastructure are currently evolving, so this is a limitation to consider in projecting out to 2030. Estimates of maize milling density and capacity at the district level for Uganda were obtained from the USAID Maize Milling survey [30].

Additional variables: Travel hours to nearest towns (>50k ppl) and the corresponding high-population growth projections were also obtained from the GEP [35]. Historic precipitation data for 1970–2000 was obtained from WorldClim [40]. Monthly spatial precipitation data in millimeters with a resolution of 30 s (approximately $1 \text{ km} \times 1 \text{ km}$) were used. Regions with precipitation lower than 350 mm were considered as dry regions. In this study precipitation data were used mainly as a filter to reflect spatial trends and to help provide insights in which regions may need more electrification to support irrigation. However, across Uganda, precipitation is high so precipitation levels did not affect the analysis, though this may not be the case for other countries. One limitation is that precipitation trends have likely varied in the past twenty years. All data sources can be found in Table 1 below.

2.4. Analysis method

The data analysis process followed the steps below. A visual process flow diagram is seen in Fig. 1 below.

- The electrification projection outputs for Uganda were obtained and were spatially joined to a $0.083^\circ \times 0.083^\circ$ grid ($10 \text{ km} \times 10 \text{ km}$) in WGS 84 geographic coordinate system in ArcGIS.
- A frequency count was applied, such that the dominant electrification technology projected to serve each cell could be identified. Grid extension, stand-alone solar and PV mini-grid had the highest frequency counts. Wind and hydro mini-grid were largely absent, and not identified as the least-cost electrification technology in any cells for Uganda.
- The grid cells were divided into classes based on frequency counts for each technology using the Jenks natural break optimization system which identifies real classes within the data by minimizing differences between data values in the same class but maximize the differences between classes [41]. In this way, cells choropleth maps for each technology can be easily used in overlay analysis.
- Maize, coffee robusta, and coffee arabica data for Uganda were downloaded as raster layers. For each crop, there were five layers representing: subsistence, rainfed high-input, rainfed low-input, irrigated, and aggregate (called completed) croplands. In ArcGIS the Raster Calculator tool, the Int tool, and the Conversion tool were used jointly to convert the floating raster layers into polygon features and each layer was spatially joined to a $0.083^\circ \times 0.083^\circ$ grid ($10 \text{ km} \times 10 \text{ km}$) in WGS 84 geographic coordinate system.
- The rule of mean was used, such that if a data point had a spatial relationship with multiple grid cells, it was counted as many times as it was matched with the grid cells. This approach ensured each grid cell captures all relevant information on cropland and yields. Average crop yields for each cell were extracted.
- Similarly, for each crop and cropland layer grid cells were classified based on average crop yield across the cell. Cells can thus be easily selected based on yield thresholds during the overlay analysis. The thresholds of choice are determined by the end-user. This study, for instance, used quintiles (i.e., >20%, >40%, >60%, >80%) as first set of thresholds (Threshold I). Given the distribution, in this study grid cells with average yields greater than the second quintile (>40%) were considered as "high yield". A secondary threshold (Threshold II) of 100 kg/ha was set to filter out extremely low yields and zero values regions (i.e., $\geq 100 \text{ kg/ha}$, <100 kg/ha). Cells with average crop yields <100 kg/ha were mostly zero values and thus were excluded from analysis.

Table 1

Data sources, type, region, and publication year.

Name	Type	Region	Country	Year (of the dataset)	Source
MAPSPAM IFPRI's data product of global crop geography	Raster	SSA	All	SPAM 2010 v1.1 (Updated 2019-10-09)	IFPRI
Global Electrification Platform	CSV	Global	except Cote d'Ivoire	2019	WorldBank
Global climate and weather data	Raster	Global	All	updated in 2020	WorldClim
Uganda Electrification data	Raster	Uganda	Uganda	received in 2020	IEA
Uganda Administration Layer	Shapefile	Uganda	Uganda	2015, updated in 2018	ESRI
Uganda District 2016	Shapefile	Uganda	Uganda	2016	Energy Sector GIS Working Group Uganda
Uganda Road Network	Shapefile	Uganda	Uganda	2017	Open Street Map
Uganda - Lake	Shapefile	Uganda	Uganda	2014	Energy Sector GIS Working Group Uganda
Uganda_Distribution_Lines_2018	Shapefile	Uganda	Uganda	2018	Energy Sector GIS Working Group Uganda
Uganda_Distribution_SubStations_2017	Shapefile	Uganda	Uganda	2017	Energy Sector GIS Working Group Uganda
Uganda_Distribution_Transformers_2017	Shapefile	Uganda	Uganda	2017	Energy Sector GIS Working Group Uganda
Uganda Maize Millers	CSV	Uganda	Uganda	2017	SPRING

- All data layers for other variables, such as precipitation, travel times, and population density were spatially joined to a $0.083^\circ \times 0.083^\circ$ grid cells for Uganda using the same spatial join method. Annual precipitation levels were grouped into five classes following the same Jenks optimization, with lower classes meaning a greater need for irrigation in agriculture. Travel hours to the nearest town with a population higher than 50,000 persons were also classified into five classes using the Jenks optimization, with lower classes meaning better accessibility to the market. Thresholds and classifications can be modified by the end user.
- Each cropland cover was overlain with the choropleth maps for each electrification technology (grid, PV mini-grid, standalone PV), as well as the precipitation and proximity to market layers. Thus for each cropland type, and for various thresholds of yield, the least-cost electrification pathway for that region or cell can be identified. Again, the filter set-points and yield thresholds for analysis can be determined and modified by the end user as needed.
- Finally, the district level maize mill count data was layered into the analysis. was also set as a filter in Uganda, specifically for maize yield. By overlaying mill capacity data and the maize yield data, farmlands with milling capacity in their respective district could be identified. Likewise, croplands without maize milling in their respective district can be identified. These areas were intersected in ArcGIS with the electrification data to demarcate areas where grid extension and/or PV mini-grid services can support farmland areas underserved by existing milling capacity.
- A series of statistical analyses were conducted with ArcGIS's tabular tools to determine percentages of croplands that satisfied various criteria. For instance, the percentage of maize and coffee croplands of different yield thresholds currently underserved by milling capacity, that are projected to be served at least-cost by grid extension or PV mini-grids.

2.5. Survey method

A survey to maize millers and farmers was conducted as a bottom-up approach to validate findings from the mapping analysis. In August 2020 the team conducted surveys in Mukono District, in the central region of Uganda. Mukono district is about 27 km east of the capital Kampala with roughly half a million people distributed across almost 600 villages and 15 sub-counties. There is one town council. Over 80% of Mukono district is agricultural, characterized by low acreage subsistence production, with maize being the most widely grown crop (Ntambirweki-Karugonjo et al., 2012). Despite this, Mukono District is currently served by only 13 maize mills (SPRING, 2017). As such, surveys were issued to both millers

and farmers to ascertain milling capacity and challenges to access. Millers and farmers from eight villages in Mukono District were surveyed through one-on-one interviews, totalling 115 farmers and millers.

3. Results

Virtually all maize croplands in Uganda are rain-fed low-input. Yields average 2344 kg/ha, which is relatively high for low input maize, though yields are significantly lower in the Northern and Central regions (see [Map 2a](#)). As such, rainfed low-input croplands are the focus for this study. Across the country precipitation is high, so applying precipitation levels as a filter in the overlay analysis had no effect. Likewise, given the country's density, applying travel time to nearest town as a filter had limited effect.

According to the GEP 2030 projections for Uganda, standalone PV, PV mini-grids and grid extension are the primary models for delivering electricity at least cost (see [Map 2a](#)). Over 90% of maize croplands will be within proximity to extended grid infrastructure. There are some key maize growing areas where the grid is not likely to reach, such as the Northern region (where yields are lower) and many of the lake regions (where yields are higher). Coincidentally, these are also the areas with least milling capacity. PV mini-grids will be the least-cost electrification technology for such areas according to the overlay analysis, and in this way PV mini-grids would serve to complement grid extension by reaching cropland areas that are underserved by grid and milling capacity. More specifically, such districts include Kibale, Kamuli, Lira, Pader and Arua.

For maize croplands with averages yields above the 40% percentile, the overlay analysis finds that 40% of this low-input, high-yielding maize intersects with – and thus could be served by PV mini-grids - and almost 20% of those are cropland in districts with no milling capacity at present (see [Table 2](#)). By 2030 a third of cropland areas currently without grid access would be served at least-cost by PV mini-grids (see [Map 2b](#)). Thus, this overlay analysis can help identify areas managing to produce high maize yields on rain-fed low input croplands that are currently without grid access or milling capacity, and can project the least-cost service delivery model for these areas. Note that these are very conservative estimates as milling activity can only be identified at the district-level. The percentage of farmers or croplands not near mills is likely much higher, as even in districts with milling the mills are not likely accessible by all smallholder farmers. Further work can then be done to identify specific electricity needs, understand local supply chains and identify viable markets.

For a cash crop like coffee that is less for local consumption in communities, access to local processing activities such as pulping or

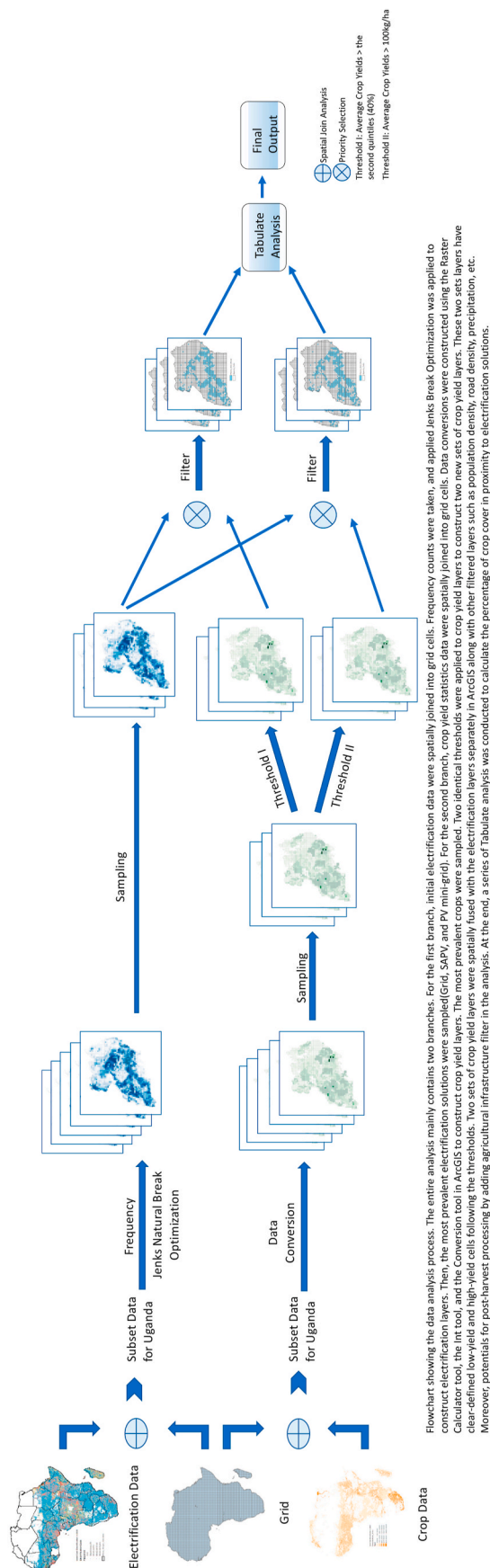


Fig. 1. Flowchart showing the data analysis process.

grinding could allow for value-addition revenues to circulate in the community. The overlay analysis finds that there are many coffee producing areas in Uganda currently without grid access. While there is some overlap with PV mini-grid, most of these areas would be served at least-cost by grid extension (see Map 2c). Table 2 depicts the area of maize and coffee croplands at various yield thresholds overlapping with grid, mini-grid and standalone PV technologies a least-cost delivery methods and shows the intersect with key variables including population density and milling capacity.

This process can be replicated for any number of crop types. Overlay analysis must be interpreted in context of the particular crop value-chain. While some crops, such as maize and coffee are mostly processed in a decentralized fashion, they same does not apply for all crops. With sugar cane for instance, another popular cash crop grown in Uganda, while there is widespread sugar cane farming across the country there are a few large sugar processing factories, in well-established, electrified areas like in Jinja, where all sugar cane harvest is directed. Thus, for many cash crops, the farming and the post-harvest processing are physically decoupled activities. Thus assessing the impact opportunity of electricity access requires a thorough understanding of the value-chain. This aligns with the literature, which suggests that impact of off-grid electricity access and off-grid processing technologies can vary widely between cash crops and staple crops.

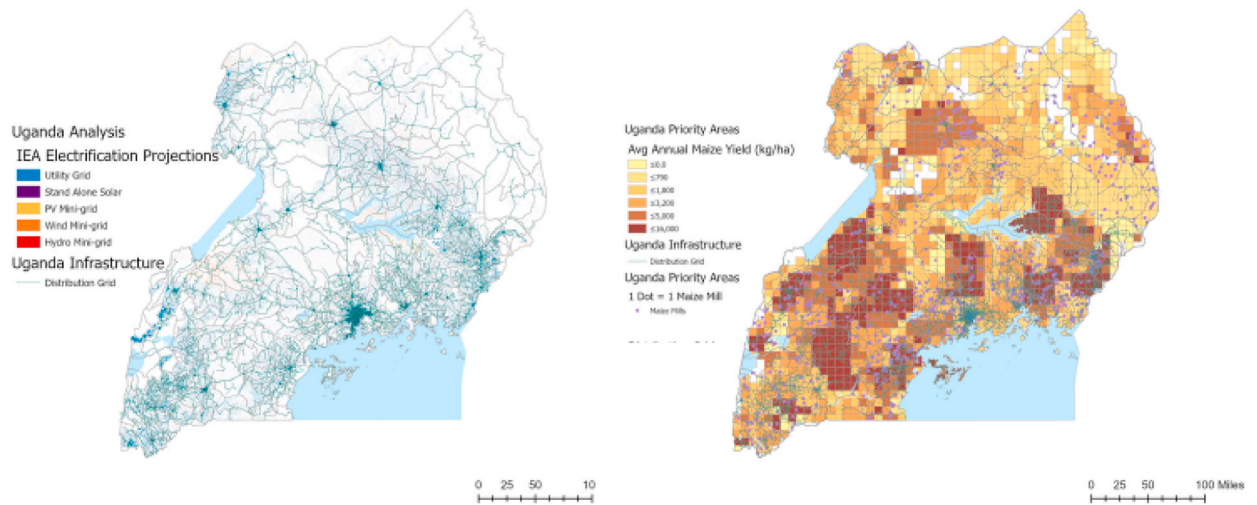
3.1. Surveying miller and farmer communities in Uganda

Mukono District represents a maize farming community with very little access to milling capacity. Millers and farmers from eight villages in Mukono District were surveyed in one-on-one interviews. A total of 115 farmers from eight villages within the Kyampisi sub-county were interviewed: Nakasajja, Nakumbo, Mulungi Omu, Kwaba, Nateete, Kiwumu, Kasanga and Kalagi. Farmers were identified by area local leaders and were randomly selected. Kyampisi sub-county is one of the two sub-counties in Mukono North Constituency. Maize, beans, and sweet potatoes are the most common food crops grown (Uganda Bureau of Statistics, 2017). Mill owners and/or operators from five (5) mills, two in Nakasajja and three in Kalagi were interviewed.

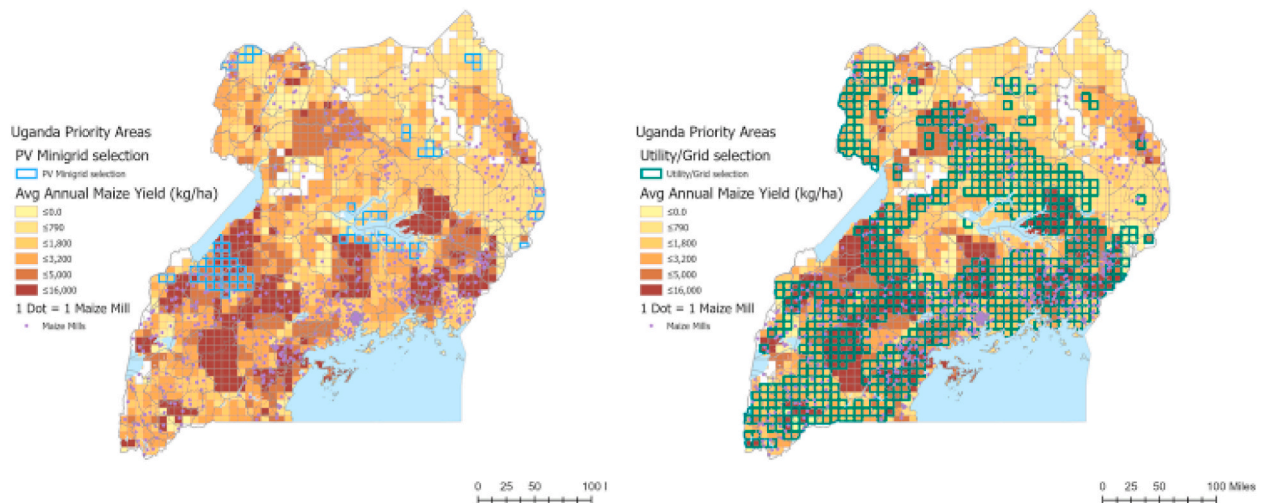
The survey shows that over 60 % of the interviewed farmers in this sub-county farm on less than 2 acres of land and 83% harvest maize twice a year. At least 60% of the farmers reported an average production of at least 1 ton per season, or 2 tons per year, consistent with the figures in Section 2.3 of this paper. Regarding yield improvements, 45% of the farmers expressed a desire to implement better agricultural practices, including crop rotation and intercropping, mechanization, irrigation and use of inputs such as fertilizer, pesticides, and better-quality seeds. The main hindrances to applying the above interventions included: a lack of extension services; high costs of inputs like fertilizers and high yield seeds; land fragmentation which limits mechanization; erratic rainfall patterns and prolonged droughts; poor transport facilities and infrastructure and thus high transport costs; price fluctuations for produce, and an inability to access agricultural credit.

Regarding post-harvest processing, farmers mostly pre-dry their maize on the stalk in the garden before it is harvested for further sun-drying. 60% of farmers then further dry on tarpaulin. This thus makes the quality of drying inconsistent, reduces grain viability for milling, and in some cases attracts a lower purchase price from middlemen. None of the farmers surveyed use commercial, solar, or electric dryers. The high purchase costs of electric dryers; lack of electricity in some villages, as well as a lack of exposure to other drying options were cited as the major hindrances to using drying methods other than sun drying.

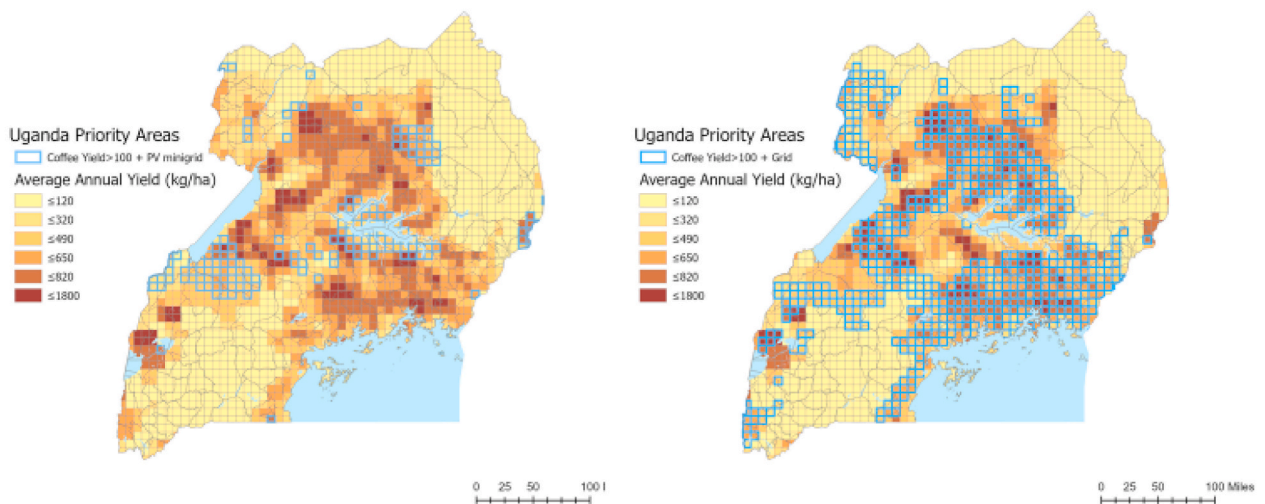
The miller responses showed that maize grain is obtained either by direct purchase from farmers, through delivery by middlemen, or by farmers delivering the maize directly to the mills. The middlemen mostly buy the maize from farmers in bulk and sometimes provide storage and further drying for the maize before reselling it to the millers and other organizations. During a good harvest season, each of the 5



Maps showing IEA projections for Uganda electricity expansion and average low-input, rainfed maize yields for Uganda with maize mills by district



Maps showing average low-input, rainfed maize yields for Uganda, maize mills by district and highlighted areas of intersection with above average mini-grid and grid projections (frequency count)



Maps showing average coffee yields (robusta and arabica) for Uganda, maize mills by district and highlighted areas of intersection with above average PV-mini-grid and grid extension

Map 2. Maps Showing overlay results for rain-fed low-input maize and coffee croplands with PV- mini-grid and grid extension. Yields less than 100 kg/ha are filtered to exclude extremely low yields and zero values.

Table 2
Percentage intersects of different yield levels with least-cost electricity technology, population density, and milling activity.

	Grid										
	% of area intersect with crop cover	% in districts with mid population density (>300pppl/km ² , <1500pppl/km ²)	% in districts with high population density (>1500pppl/km ²)	% of area intersect with crop yield>20%	% of intersect areas without mills	% of area intersect with crop yield>40%	% of intersect areas without mills	% of area intersect with crop yield>60%	% of intersect areas without mills	% of area intersect with crop yield>80%	% of intersect areas without mills
Low Input Maize	97.65	34.02	1.41	76.91	26.19	76.91	19.56	41.16	10.36	25.70	6.74
Irrigated Maize	1.78	83.16	0.25	1.78	71.42	1.19	0.12	0.71	0.12	0.47	0.00
Total Maize	97.77	34.11	1.42	94.68	26.31	78.10	20.04	53.09	13.29	28.67	7.69
Coffee Robusta	56.74	33.52	1.98	56.74		51.08		38.54		20.64	
Coffee Arabica	19.57	44.89	1.40	19.57		19.09		9.01		3.61	
Total Coffee	70.98	33.52	1.98	70.98		70.50		41.54		23.13	
PV Mini-Grid											
	% of area intersect with crop cover	% in districts with mid population density (>300pppl/km ² , <1500pppl/km ²)	% in districts with high population density (>1500pppl/km ²)	% of area intersect with crop yield>20%	% of intersect areas without mills	% of area intersect with crop yield>40%	% of intersect areas without mills	% of area intersect with crop yield>60%	% of intersect areas without mills	% of area intersect with crop yield>80%	% of intersect areas without mills
Low Input Maize	80.49	22.90	0.11	63.32	32.67	41.12	17.77	24.57	12.96	14.85	7.29
Irrigated Maize	0.81	89.62	0.00	0.81	50.13	0.81	0.00	0.81	0.00	0.00	0.00
Total Maize	80.49	22.90	0.11	63.32	32.67	41.12	17.77	30.64	14.58	18.09	8.91
Coffee Robusta	48.07	15.12	0.00	48.07		30.65		17.69		6.08	
Coffee Arabica	24.73	27.23	0.20	24.73		20.68		16.42		8.88	
Total Coffee	69.24	15.12	0.00	69.24		50.46		24.63		10.37	
Stand Alone PV											
	% of area intersect with crop cover	% in districts with mid population density (>300pppl/km ² , <1500pppl/km ²)	% in districts with high population density (>1500pppl/km ²)	% of area intersect with crop yield>20%	% of intersect areas without mills	% of area intersect with crop yield>40%	% of intersect areas without mills	% of area intersect with crop yield>60%	% of intersect areas without mills	% of area intersect with crop yield>80%	% of intersect areas without mills
Low Input Maize	96.40	17.35	0.29	91.15	7.90	71.72	22.15	39.06	13.16	22.39	8.00
Irrigated Maize	3.95	69.18	0.00	1.10	89.39	0.55	0.11	0.44	0.11	0.00	0.00
Total Maize	96.40	17.39	0.29	91.26	7.90	72.69	22.59	49.03	15.45	25.90	9.21
Coffee Robusta	56.05	10.60	0.43	56.05		49.52		33.73		6.08	
Coffee Arabica	17.86	31.63	0.02	17.86		14.92		15.67		4.32	
Total Coffee	70.49	10.60	0.43	70.49		58.94		39.20		19.99	

mills surveyed processes over 3 tons of maize grain per day. All millers surveyed suggested that there is capacity for additional milling to fully serve their communities, whether through extended hours or new units.

All the millers cited the high cost of electricity as their main challenge, as well as poor quality, aged and faulty equipment, further exacerbated by lack of quality spare parts. The quality of the grain (including dryness and presence of stones) greatly affects the grade of the final product, normally classified as grades 1, 1.5, and 2 in decreasing order of quality. Most mills report that they charge the same price range irrespective of the grade of the flour, given that the power consumption is the same. Milling is done predominantly and preferably during the night to take advantage of the lower off-peak electricity rates, with some of the larger mills citing monthly electricity costs of over US\$ 1300 during the busy season. The single diesel mill located in an off-grid area requires about USD 200 per month for fuel.

Millers all noted that there is a lack of miller cooperatives which could bargain for incentives, such as lower power tariffs and government support for better quality machinery. This, together with previously mentioned challenges, has led to limited expansion into additional services such as packaging, sale, and exportation of the value-added product (milled grain). In the off-grid areas, lack of electricity is the major deterrent to development of the milling sector. This aligns with the challenges identified in literature and findings on the opportunity for grid or mini-grid access to expand agro-processing activity.

Electricity access is not a solution in itself but serves to complement other enabling factors. For instance, farmers noted that better access to extension services like training on good farming practices such crop rotation, intercropping, fertilizer application, mechanization would create incentive towards improved productivity and better crop yields. Having sizeable grain storage facilities as well as employing better drying methods would enable both millers and farmers to enjoy better prices and price stability. This is of added importance currently given the adverse impact of the pandemic on demand from institutions which are usually the larger customers by volume of product.

4. Discussion

4.1. Study limitations and future work

There are several important limitations to consider in this analysis. First, is that the key input on electricity delivery models comes from the GEP and is thus subject to the limitations of the GEP model (such as the limited number of factors considered in the optimization; the approximation of relationships between factors such as population growth, demand, and technology costs; the limited number of electrification technologies included in the model; and limited scenario options). Further, depending on the selected assumptions, outputs will differ. For instance, the assumptions selected for the purpose of this study (high on-grid costs, low PV costs) may yield a higher frequency of distributed energy technologies as least-cost than other selected scenarios.

Likewise, thresholds for each attribute can be set by the user. This study explores maize and coffee yields using a quintile distribution, in the absence of literature that clearly defines standard values for high and low yield for maize and coffee. Again, different thresholds may produce different outputs. Future work could involve correlation studies to determine whether there are yield thresholds for various crops best suited to electricity needs analysis.

USAID survey data is used to identify districts with milling capacity. The survey conducted to produce this data set has its own limitations, and the survey does not provide precise mill locations. This limits the results of this study to district-level, despite having higher resolution data on croplands and electricity technology projections. This may also overestimate the accessibility of croplands to milling, because even in districts with mills, the mills may be too distant from croplands for viable access. Further, the crop yield statistics and climate data are based on historic data, which does not capture current changes and

possible future changes, though being used to project need to 2030. The same applies to road network and existing grid infrastructure data. As more recent data becomes available these can be substituted into the modeling framework, for more refined analysis on projections.

Finally, while this model provides a convenient way to combine existing data sets on agriculture and electricity infrastructure, it does not integrate water resources. Data sets on ground water resource for Uganda were not able to be sourced for this study, so a deeper exploration into irrigation potential was not possible. There are studies currently attempting detailed agricultural demand estimation from irrigation. As future work, these outputs can be incorporated into this study's framework. Moreover, given that agro-processing activities do not necessarily co-locate with farmlands, to have a clearer picture of agricultural value-chain impacts electricity access, future work may consider integrating value-chain models or business model analysis with geospatial modeling, as well as exploring the role of transportation in agriculture value-chains, and opportunities for electrified mobility.

Together these limitations affirm that the results of the mapping analysis should be used to understand areas of need and the set of possible solutions, rather than to prescribe a course of action.

4.2. Recommendations

This study demonstrates a simple method to combine publicly available data and tools to quickly identify the most economical electricity delivery models for croplands at the sub-national scale, focusing on particular cropland attributes or activities are needed by the end user.

In this example, the least-cost electricity technologies to serve rain-fed low-input maize and coffee croplands across Uganda are explored, particularly in relation to milling access. Layering district-level mill count data with least-cost electrification projections for the country, and maize crop statistics, shows that more than 70% of rain-fed low-input croplands overlap with areas where grid extension is projected as the least-cost delivery model. More than 26% of these are croplands in districts currently without mill presence.

Furthermore, there are particular areas – such as the Northern region and the lake regions - where milling access is low, and grid extension is not likely by 2030. The overlay analysis identifies these as areas that would be served at least cost by PV mini-grids. Over 32% of croplands best served by mini-grids also do not have milling access. Particular districts of interest can then be identified for the end-user for deeper investigation. These results demonstrate the immediate potential of grid extension and mini-grid technology to support low-input agriculture.

The need for increased milling capacity in maize farming areas, and the primary challenge of electricity access is affirmed by the literature and the farmer survey conducted in Mukono district, an important maize growing district in Uganda. Given the lack of supply chain linkages that connect smallholder farmers to commercial maize buyers or aggregators, localized milling access near to farmlands is important.

This study focuses on milling as an example, but the analysis can be replicated for other crops and processing activities. For instance, while oil seeds are major cash crops in Uganda, vegetable oils are still mostly imported due to limited processing capacity [42]. In fact oil seed and oil palm are part of a suite of strategic commodities the Ugandan government is targeting for smallholder intervention [43], demonstrating the broad opportunities for domestic processing activities across multiple crops.

Even interpreting results conservatively, there is a significant opportunity to improve electricity access in underserved cropland areas. Given the lack of market structures that connect smallholder farmers to commercial buyers, localized processing activity is important. However, as the results of the survey show, given the lack of milling capacity, and equipment challenges, as well as lack of standards around post-harvest handling and drying, maize milled locally is often not of high enough quality for commercial off takers. This presents a challenge for smallholder farmers move up the product value-chain.

Policymakers can encourage further exploration into the on-farm and processing electricity demand for different cash and staple crops by region and district. Likewise, further research is needed into the serviceable nature of these local processing markets. The literature suggests that several micro-enterprises, from fruit drying, to refrigeration, milling, egg incubation, and oil pressing are being piloted. However, except for solar irrigation, most technologies require more scale, and currently favor commercial farmers because of smallholder farmer inability to pay. Thus, even where demand hotspots are identified, understanding the financial capacities of farmers and the opportunities for cooperatives or other organizing structures to support collectives of farmers is needed.

5. Conclusions

The available literature on energy access and agriculture linkages is small but growing. It calls for better understanding of the most economical electricity service delivery models for agriculture needs. This analysis explores the spatial linkage between energy access and opportunities for advancing on-farm access to electricity for post-harvest and primary processing activities. The study uses publicly available data on electrification infrastructure, crop statistics, and other variables to identify priority impact areas where different electricity technologies could support agricultural productivity, highlighting these as target areas for further investigation. The study demonstrates replicability using maize and coffee farming in Uganda as a case study.

The analysis highlights the limited availability of milling capacity. Large swathes of maize croplands are in districts without milling capacity. This analysis identifies specific areas where mini-grids may be particularly helpful in reaching districts where grid extension is unlikely. Conversely, coffee farming overlaps strongly with current or projected grid extension, so on-grid processing options may be more feasible. The general findings are confirmed by farmer and miller perspectives, captured through survey. The survey results also show that given the many competing barriers to agricultural development, the provision of electricity infrastructure, is complementary to a host of other necessary enabling factors, requiring holistic policy action.

While many African countries, including Uganda, have implemented government initiatives to improve mechanization, these efforts often focus on yield improvement interventions, largely neglecting value-addition. These results indicate the clear need for further investigation into the linkages between energy access availability and post-harvest processing opportunities, and the need for deeper analysis to understand integration of small-holder farming into commercial supply chains.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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