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Evaluation of Solar Powered Agricultural Technologies for Productive-Use Applications: A Modeling Approach

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IKEA Foundation
STICHTING DOEN NATIONALE POSTCODE LOTERIJ
FMO Entrepreneurial Development Bank
Good Energies POWER FOR A BETTER WORLD

Authors and Acknowledgements

The Access to Energy Institute strives to be the world's first charitable and collaborative research and development platform for the off-grid industry. Launched in 2019, the A2EI works with entrepreneurs, inventors, and organizations to support the development and research around appliances and energy related services.

The research was supported by Imara Tech, a Tanzania-based start-up that manufactures productive-use technology for rural smallholder farming communities.

A special thank you goes out to Jesse Oljange of Avomeru for his willingness to share data and be a thought partner throughout the writing process.

This research would not have been possible without the support of our generous donors: IKEA Foundation, Stichting DOEN, FMO, and Good Energies Foundation.

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PREAMBLE

I could not tell you how many meetings I have sat through where we sat around a table and brainstormed a list of agricultural machines that we thought could potentially be solar-powered. Or conversations where someone asked me, 'So, exactly which agricultural technologies can be solar powered then?'

Those conversations always left me with mixed feelings. The idea of productive-use agricultural technology is such an enticing idea for so many of us, for so many good reasons: the job creation, the value addition, the environmental impact, the strengthening of rural communities. But often it felt like we had more questions than answers.

Over the years, advances have been made. Solar water pumps and cold chain technologies continue to be at the forefront of productive-use off-grid technology. Although still a maturing sub-sector, the conversations around these products have shifted to be less about whether they work and more about how to scale them.

For other products, there is still uncertainty. The verdict is still out on solar mills, egg incubators, and the rest of the laundry list. The occasional success stories that trickle in often feel like hard won exceptions to the rule.

Eventually I got tired of the questions. 'Wouldn't it be nice if someone just put this topic to rest?' I thought. 'Wouldn't it be great if we had a list of what products are productive-use and which ones are not?'

That desire for conclusive answers, whether they be good or bad, spurred this research. In May 2019, A2EI surveyed stakeholders from a cross-section of the off-grid energy sector working and asked them what products they wanted answers on. We took that list, cut it down, added some of our own favorites, and got to work.

The result of that endeavor is this paper. Ten products were selected for study, of which two are presented here. The remaining eight will be released in the coming months.

In writing this research, I felt it was very important to put forward a concrete conclusion on each of the technologies studied. Of the ten products researched, only one was deemed to have inconclusive results.

Just as importantly, I knew there needed to be nuance. The off-grid landscape is diverse and dynamic. For those reasons, the modeling approach is laid out so that anyone reading this can input their own data and arrive at their own conclusions. Even where the assumptions might break down, I believe the approach to be sound.

In addition to the upcoming release of the full report, we are beginning work on a new project that builds on these results. Products identified as a "Go" in this research will undergo a more extensive research and product development process over the next two years. I hope that work will validate this research and enable us to bring forward a second wave of productive-use agricultural appliances to the off-grid market.

Until next time,

Elliot Avila
Lead Author

EXECUTIVE SUMMARY

Two agricultural processing technologies are considered in this research:

- A small-scale oil extraction machine
- A small-scale coffee pulping machine

A business model was developed for the application of each technology for income generating activity in off-grid areas. The primary power source for each technology was modeled as solar energy, which was considered under two different cost schemes: a grid-tied tariff and a stand-alone tariff. The business models used data collected from interviews conducted in Tanzania with operators of similar technologies and end-users such as farmers.

Each business was evaluated by its unit economics and other simple financial metrics. Businesses were further evaluated by considering the product's desirability to customers and end-users and the viability of the product to scale.

The oil extraction machine was found likely to be viable on solar power if using a hydraulic system, but not if using an expeller. The coffee pulping business was found to have positive unit economics but still likely non-viable due to how transport of coffee restricted the business model.

Spreadsheets containing all assumptions and calculations used in this research are available on the A2EI website so that readers can input their own data.

METHODOLOGY

Modeling Small Businesses: Income as a Value Proposition

Why would a customer buy a solar-powered, productive-use technology? For entertainment? For environmental reasons? Because it makes them feel good?

We posit that the most important value proposition that productive-use technologies deliver to customers is their ability to earn income from the technology. Therefore, we can evaluate different technologies simply by assessing a potential customer's business model.

This conclusion forms the basis for this paper. For each technology, a business model was developed and evaluated. Conclusions were then made based on the potential risks and returns of the modeled business.

Desirability, Feasibility, and Viability: Customers, Technologies, and Businesses

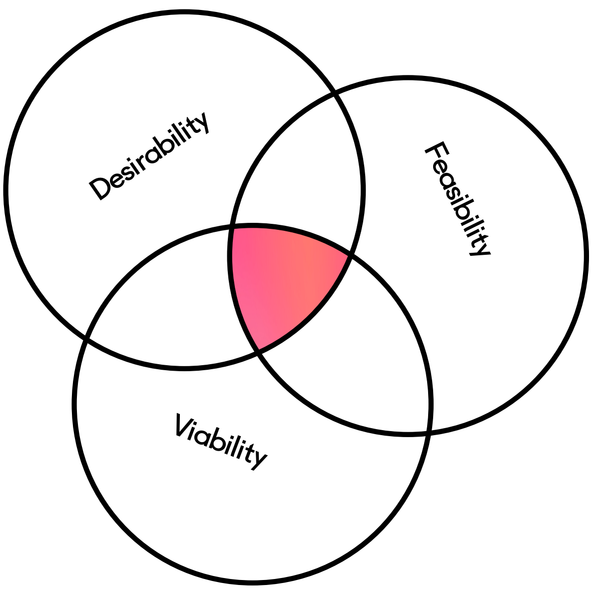
We framed our research and its conclusions loosely along the lines of a Desirability-Feasibility-Viability (DFV) framework. In a DFV approach, we must satisfy customer, technical, and business requirements to successfully scale a product concept. A breakdown on any axis results in a failed product.

- Desirability: Does the product deliver an attractive value proposition to our users and to their customers?
- Feasibility: Does the technology work?
- Viability: Can a business successfully bring this product to market?

This approach loosely manifested itself in the development of the business models for each product. Each model began with addressing the Feasibility of the product. Our modeled businesses were based on operation of existing technologies that we believed had high potential to scale based on research. For this reason all products modeled in this paper are Feasible.

The Desirability of each product was evaluated through the business models and their profitability. Consideration was also made for the Desirability of the services that end-users received from the productive-use technologies.

Lastly, the Viability of each product was considered through discussion of potential challenges that are associated with scaling of the product. Customer education, financing, and logistics are examples of Viability factors that were considered.



Modeling the Costs of Solar Energy

A key parameter in each of our models was the cost of solar energy. We modeled two cost structures that we believe are reflective of the current off-grid pricing models: grid-tied and stand-alone.

Grid-Tied System Modeling

Grid-tied refers to systems such as pico-grids, mini-grids, and other grids where a user pays based on quantity of energy consumed. Under these conditions, users consume electricity without consideration for system dimensioning, which is handled by the utility provider.

For grid-tied systems, we modeled a tariff of $1.00 USD per kilowatt-hour, based on a 2018 paper by Rocky Mountain Institute found that mini-grid prices ranged from $0.60 to $1.00 per kilowatt-hour[1]. We chose to model the upper bound to be conservative, and because our experience indicates this is lower than tariffs on many of the remote and decentralized mini-grids in Tanzania.

Stand-Alone System Modeling

Stand-alone systems refer to solar systems dimensioned specifically for a given purpose, in this case powering a productive-use technology. Doing this gives more control over energy costs and can bring down prices, however the usage of the system is constrained by the sizing. Over-sized systems result in extraneous costs whereas under-sized systems result in power outages.

For stand-alone systems, we modeled a cost of $0.40 USD per kilowatt-hour, based on a model developed and described in a paper by Lee and Callaway, 2018, which found that most regions in Africa can achieve 95% energy reliability using solar at a cost of $0.40 per kilowatt-hour[2]. We assumed that an ideal, cost-effectively dimensioned system would result in the average cost of energy at this price point over the lifetime of the system.

We then applied a scaling factor we termed Utilization Rate to the stand-alone tariff to account for the seasonal usage of agricultural technologies: systems that are unused for periods of the year result in less energy consumed for a fixed cost, resulting in higher unit energy costs.

Painting in Broad Brush Strokes

In planning this research, we wanted our results to be useful to the off-grid industry at large. To achieve this breadth, it was necessary to sacrifice depth. Model variables were reduced to what we deemed essential and complex topics were simplified wherever possible.

Assumptions used in our modeling, such as technology specifications or cost data, were selected to be representative but do not capture nuances, outliers, or a complete picture.

How to Interpret and Use Results

To put it informally, the results of our analyses are rough estimates. Our conclusions should be treated as a guide, but not as an exacting one.

We encourage readers to consider the assumptions made in each model and how plausible they are in their own operating environment, and then to input their own data and assumptions into each model. To support readers in forming their own conclusions, we tried to be transparent about our methodology and assumptions, as well as call out important variables for extra consideration.

Geographic Focus: Tanzania

This research was conducted in Tanzania, with the majority of local data collected in the north of Tanzania. The further away from Tanzania you go, the more discrepancies we would expect between our assumptions and what might be find on the ground. Consequently, our conclusions become less relevant the further one is from Tanzania.

Despite this, we believe the results and our conclusions are of practical use to practitioners all over the world. However, to make full use of this report, readers may need to invest time to gather their own data and apply it to the models.

DIY Modeling: Using Your Own Local Data

All spreadsheets used in calculations for this research are available for download on the A2EI website. Users can download these and input their own data and see how this affects the results. Users can also easily edit these to include their own variables.

Feeding Back: Improving the Models

Come up with your own model? Know of contexts where the data is totally different? Have a new technology that out-performs anything here? Got an axe to grind?

We would love to hear from you.

We hope that this paper forms the basis of a conversation that continues far beyond the reaches of our lab. As technology evolves, as businesses innovate, and as we collect data from more parts of the world, we hope to continue to collect and share these new insights so that others may learn.

Comments, questions, and more can be directed to *info@A2EI.org*.

OIL EXTRACTION

Introduction

Oil-bearing crops such as sunflower, avocado, moringa, and sesame are commonly grown across Tanzania. Oil extraction machines are used to extract oil from crops for applications such as cooking and cosmetics.

Overview of Technology

Oil extraction machines function by exerting high amounts of pressure on oil-bearing crops until the oil is separated from the rest of the biomass. Heat is sometimes added or passively generated, which can affect the quality of the oil. Raw oil often undergoes separate refinement and filtration processes to remove impurities.

Oil presses are one of the simplest forms of oil extraction machines. Crops can be placed within a container of the press that is held under pressure until the oil passes through small outlets in the press. Presses often use hydraulic systems to generate pressure, but non-hydraulic designs such as ram presses and screw presses are also used in small-scale manual presses as they are easier to manufacture. Presses cannot be continuously operated, as the biomass must be removed after each pressing action and the pressed material is often held under pressure for some time. This results in periods of each pressing cycle wherein the machine is not actually powered.

Oil expellers are the most common extraction machine used by SME's in Tanzania. Expellers have a screw that turns in a sleeve that continuously moves material forward as it rotates, resulting in increased pressure at the end and heat from friction. Larger machines ranging from 15kW and above are often used for sunflower, but small-scale hand-operated expellers can be found in use with moringa.

Overview of Oil Extraction Technologies

Model	Small-Scale Hydraulic Press	Small-Scale Expeller	Large-Scale Expeller
Typical Power	1 - 5 kW	1.5 - 3 kW	15 - 20 kW
Throughput	15 - 75 kg/hr	5 - 35 kg/hr	~ 200 kg/hr
Advantages	Powered for only brief periods Simple fabrication Cold-pressed	Continuous extraction	High throughput
Disadvantages	Batch processing	High energy consumption Requires precise fabrication	Energy Intensive Generates heat

The table above shows only a small cross-section of technology architectures. Other oil extraction methods such as centrifuges and the use of solvents are used in industrial processes, but are beyond the scale of processing done in SMEs.

Productive-Use Case Analysis: Small-Scale Expeller and Hydraulic Press

In the following section, we model two hypothetical businesses providing oil pressing services. One business uses a small-scale expeller, and another uses a hydraulic press.

Limitations of Modeling

Oil extraction is affected by numerous variables, some of which are not explicitly included in our model.

Looking at the input materials, the crop type (e.g. sunflower vs. sesame), crop strain, moisture content, and pre-extraction processing (e.g. hulled vs. dehulled sunflower) can each influence the performance.

Further, the specifics of the extraction technology are also important. The motor selection, hydraulic pump selection, hydraulic system configuration, machine dimensions, operating parameters (e.g. holding time and holding pressure), and the addition or removal of heat can all affect performance.

Our market and business assumptions will also affect results, such as the local price of animal feed, crop prevalence, local connections to market, presence of other competing extraction units, and other factors.

Variables that were determined to likely influence results in a significant way were either included in our analysis or else noted in the discussion of results.

Model: Oil Extraction Business Using Small-Scale Expeller

Technology Inputs and Assumptions

For our technology, we modeled a press based off of specifications of a small-scale expeller presented in Callahan et al in Small-Scale Oil Oilseed Presses[3]. The throughput is measured by the amount of input that can be processed per hour, rather than the output.

TECHNOLOGY ASSUMPTIONS		
Specification	Unit	Value
Power	kW	2.2
Throughput	kg/h	28

Business Inputs and Assumptions

To model our business, we interviewed operators of large-scale sunflower oil expellers operating in the Meru region of Kilimanjaro. Many operators offer oil pressing services for free but keep the seed cake (reported to be roughly 70% of the mass of the seed), which can be used in animal feed mixes or sold raw for animal feed. If the customer chooses to keep their seed cake, most operators charge them 150 TZS ($0.065 USD) per kg of seed.

BUSINESS INPUTS AND ASSUMPTIONS		
Specification	Unit	Value
Price per Seed	$/kg	$0.065
Seasonal Utilization Factor	%	50%
Daily Usage	h/day	8

The utilization of the press is expected to be seasonal and interviewees reported their businesses were active roughly 50% of the year. During the peak season, presses were operated for the entire day, which we modeled as 8 hours.

TARIFF ASSUMPTIONS		
Specification	Unit	Value
Grid-Tied Tariff	$/kWh	$1.00
Stand-Alone Cost	$/kWh	$0.40

Calculations

HOURLY INCOME FOR SMALL-SCALE EXPELLER BUSINESS			
Calculations	Unit	Value on Grid-Tied Tariff	Value on Stand-Alone
Hourly Revenue	$/h	$1.82	$1.82
Hourly Operating Expenses	$/h	$2.20	$1.76
Hourly Gross Profit	$/h	($0.38)	$0.06
Daily Gross Profit	$/day	($3.04)	$0.48

Model: Oil Extraction Business Using Small-Scale Hydraulic Press

Technology Inputs and Assumptions

To model our hydraulic press, we collected information from a hydraulic press being used to press dried avocado for oil in western Tanzania.

The press holds 5 kg of dried avocado and can press a batch in four minutes. Most of this is holding time and loading time, during which the motor is not on. Of the four minute cycle, one minute is used to extend and retract the 3.75kW motor, representing a duty cycle of 25%.

TECHNOLOGY ASSUMPTIONS		
Specification	Unit	Value
Power	kW	3.75
Loading Capacity	kg/batch	5
Batch Cycle Time	s/batch	240
Batch Hold and Release Time	s/batch	60
Batches per Hour	batch/h	15
Duty Cycle	%	25%

Business Inputs and Assumptions

For our business, we assume similar service charges as with sunflower. Although, the market price for pressed avocado cake is higher than for sunflower seed cake, we chose to keep the per kilogram rates equivalent so as to focus on the technology.

BUSINESS INPUTS AND ASSUMPTIONS		
Specification	Unit	Value
Price per Dried Avocado	$/kg	$0.065
Seasonal Utilization Factor	%	50%
Daily Usage	h/day	8

For our utilization rate, we again assumed a 50% utilization factor due to seasonality of raw material and an 8 hour work day.

TARIFF ASSUMPTIONS		
Specification	Unit	Value
Grid-Tied Tariff	$/kWh	$1.00
Stand-Alone Cost	$/kWh	$0.40

Calculations

HOURLY INCOME FOR SMALL-SCALE HYDRAULIC PRESS BUSINESS			
Calculations	Unit	Value on Grid-Tied Tariff	Value on Stand-Alone
Hourly Revenue	$/h	$4.88	$4.88
Hourly Operating Expenses	$/h	$0.94	$0.38
Hourly Gross Profit	$/h	$3.94	$4.50
Daily Gross Profit	$/day	$31.50	$36.00

Discussion of Modeling Results

Under the given assumptions, the hydraulic oil press outperforms the expeller when powered by solar.

Due to its high loading capacity, the hydraulic press is capable of processing larger volumes per hour and thus generates higher revenue. Despite having a higher power motor, the hydraulic press uses less energy and therefore has lower operating costs than the expeller due to its non-continuous operating cycle. Although our model used a 3.75kW motor, smaller motors could likely be used. In ideal systems, the rated power of a motor does not influence the energy used to complete a pressing cycle but does influence the speed at which a cycle is completed. This implies that gross profit margin as a percentage of revenue remains constant regardless of motor size.

Given the number of variables excluded from our analysis, we would expect that the business case for the hydraulic press is dependent on the conditions under which is it operated.

Aside: Scaling Input Power of Hydraulic Systems

Consider our same modeled hydraulic press business, but this time with our input power reduced from 3.75kW to 1.25kW. Assuming an identical hydraulic pump and no transmission losses, our new press system will consume the same amount of energy to complete a press cycle as the old system, but now takes three times longer to complete the press and release actions.

Even though we scaled down our motor size by a factor of 3 in our model, our new production rate (and consequently our resulting profit) is only reduced by a factor of 1.5 due to the holding time remaining constant in both systems.

This is good news for systems constrained by power output limitations: as input power is reduced, profit is also reduced but at a lower rate.

Or to put it another way: increasing the input power results in diminishing returns for the operator, so it's okay to keep things small.

Modeled calculations demonstrating the above are included in the Excel sheets available on the A2EI website.

Conclusions

Our research found potential for hydraulic presses to be used in profitable productive-use businesses when solar-powered.

The operating cycle of the hydraulic press reduces the energy consumption in comparison with other mechanized extraction methods. Because hydraulic systems are able to efficiently create leverage, press systems could be scaled up or down to meet technical or market requirements without compromising unit economics.

More research on individual use-cases needs to be done to accurately size the market potential of this kind of technology and understand how competitive it is with alternatives. However, given that a press is versatile enough to work with different crops and power levels, we believe there would be demand in rural and off-grid areas. We see potential for business models where oil is pressed for household consumption and for models where oil is pressed at a light industrial scale, such as in the case of the business pressing dried avocados.

As noted, a large number of factors influence the outcome of an oil-pressing business. More precise and detailed analysis should be completed before considering implementation of an oil extraction machine.

COFFEE PULPING

Introduction

Coffee is one of East Africa's most lucrative cash crop for farmers and requires many steps of production before it can be cupped. Coffee pulping is one of the more laborious steps of the production process, when the coffee bean is removed from the cherry so that it can be dried and further processed for brewing.

Overview of Technology

MODEL	MANUAL PULPING MACHINE	BICYCLE DRIVEN MACHINE	SMALL MOTOR DRIVEN MACHINE	LARGE MOTOR DRIVEN PULPING MACHINE
Power	Hand	Bicycle	.375 - 2.25 kW	4+ kW
Throughput	90 kg/hr	450 kg/hr	200 - 5000 kg/hr	3000+ kg/hr

Most farms in northern Tanzania use manual pulping machines similar to the one shown in the picture above. In manual machines, coffee cherries and water are poured into an inlet at the top. A hand crank feeds the cherries into the machine where a rotating drum splits the cherries and expels the beans at the front of the machine.

Most of these manual coffee pulping machines in northern Tanzania are decades old. Not every coffee grower owns a pulping machine, and neighboring farms often share access. Laborers also bring machines directly to farms to provide pulping services.

Because of their design, the coffee pulping machines can be retrofitted to be powered by an alternate source. One local innovator built stands that allowed the pulping machines to be bicycle-driven, which increased the throughput dramatically. Small motor driven units are also possible.

In Northern Tanzania, larger coffee pulping machines are sometimes owned and operated by cooperatives. Like the manual pulping machines, most of these machines are decades old but still in regular use.

Productive-Use Analysis: Coffee Pulping Service Business

For our business case analysis, we model a small motor-driven coffee pulping machine powered by solar that is operated as a service for neighboring farms.

Limitations

Our model excludes considerations for transport in the calculations, however these are discussed at length in the results.

Technology Inputs and Assumptions

For the technology, we model our technology based on a CAPE Estrella No. 5 coffee pulping machine, which is powered by a 1HP motor and achieves 1200 kg/h throughput[4]. Two channel pulping machines are commonly used in northern Tanzania, although they are usually smaller and lighter than the modeled machine.

TECHNOLOGY ASSUMPTIONS		
Specification	Unit	Value
Power	kW	0.75
Throughput	kg/h	1200

Business Inputs and Assumptions

To calculate the business case, we surveyed coffee-growing households. Farmers reported paying 100 TZS ($0.043 USD) per 15kg bucket of cherries to be peeled. We estimated a utilization factor of 40%, as farmers reported the harvest season and pulping process spanned five months.

BUSINESS INPUTS AND ASSUMPTIONS		
Specification	Unit	Value
Cherries per Bucket	kg/bucket	15
Price per Bucket	$/bucket	$0.043
Utilization Factor	%	40%
Daily Usage	h/day	8

Because the utilization rate is 40%, our effective Stand-Alone energy cost is equivalent to our grid-tied tariff.

TARIFF ASSUMPTIONS		
Specification	Unit	Value
Grid-Tied Tariff/Stand-Alone Cost	$/kWh	$1.00

Calculations

INCOME FOR SMALL-SCALE COFFEE PULPING BUSINESS		
Calculations	Unit	Value on Grid-Tied/Stand-Alone
Hourly Revenue	$/h	$3.44
Hourly Operating Expenses	$/h	$0.75
Hourly Gross Profit	$/h	$2.69
Daily Gross Profit	$/day	$21.52

Discussion of Modeling Results

The unit economics of a small-scale solar-powered coffee pulping machine suggest it is viable. However, we must consider how transportation and portability impact the business model.

Without a portable power source, farmers must bring their coffee directly to the machine for processing. Logistics such as these present a challenge to the successful operation of our modeled business. Transport introduces additional costs and pain points for end-users and consequently reduces the desirability of the offered services.

Despite coffee's high market value, the pulping process is not valued particularly high: based on our data, the local market rate to pulp coffee is just $2.87 per 1000 kg. This indicates that the value addition of the pulping process as perceived by farmers is low.

Faced with the cost and inconvenience of transporting large amounts of coffee cherries for a benefit of little value, we find it likely that the services of our modeled business are less desirable than alternatives, such as paying day laborers to pulp coffee directly on the farm.

ABOVE: An engine-driven pulping machine at an off-grid coffee cooperative.

Mini-Case Study:
Coffee Cooperatives and Alternative Business Models

Many small-scale coffee farmers are organized into cooperatives through which they sell their coffee. Some of the larger cooperatives offer processing services: farmers deliver their coffee cherries and the cooperative will pulp, dry, sort, and grade it before bringing it to market.

Because all processing is centralized at the cooperative site, the issue of portability is lessened: customers receive more value for the cost of transport. This makes our model more viable.

However, coffee cooperatives also have higher quality standards and often must be pulped immediately after harvest. In the Kilimanjaro region, coffee is harvested during the day, resulting in large batches being processed at night. Under these conditions, we would expect the operating cost of solar to be much higher, and might not be competitive with engine-driven models.

Conclusions

Despite favorable unit economics and relatively simple technical challenges, the transportation and portability requirements of our business model hinder the ability for solar-powered coffee pulpers to be operated productively.

This is an example of a product where the technology is productive-use on paper, but is difficult to use in an actual business. If there were a cheap portable power source available or a solar grid connecting numerous coffee farms, a different conclusion might be reached.

Those interested in boosting incomes of coffee-growing communities might have better luck with non-technical interventions, such as securing better markets.

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