EFFICIENCY FOR ACCESS

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MILLING

Solar Appliance Technology Brief

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EFFICIENCY FOR ACCESS COALITION

Photo Credit: Agsol

CONTEXT

This technology brief is one in a series of insight briefs developed to synthesise the latest market intelligence and chart the pathway to commercialisation for some of the off- and weak-grid appropriate technologies most relevant to catalysing energy access and achieving the Sustainable Development Goals.

The first iteration of the LEIA Technology Summaries was published in 2017 to help the newly established Efficiency for Access Coalition navigate a nascent market. At the time there was limited data and reliable research available on market trends and performance of appliances suitable for resource-constrained settings. This brief updates and expands on these summaries, bringing together the latest insights on market and technology trends, consumer impacts and pathways to scale for solar mills intended for use by small holder farmers. You can access briefs on all technologies that are a part of this series here.

This brief was developed by CLASP and Energy Saving Trust as part of the Low Energy Inclusive Appliances programme, a flagship programme of the Efficiency for Access Coalition. The Coalition is a catalyst for change, accelerating the growth of off-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life and support sustainable development.

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SDG INTERLINKAGES

SOLAR MILLING

SDG 1: No Poverty
SDG 2: Zero Hunger
SDG 3: Good Health & Wellbeing
SDG 5: Gender Equality
SDG 4: Quality Education
SDG 7: Affordable & Clean Energy
SDG 8: Decent Work & Economic Growth
SDG 9: Industry, Innovation & Infrastructure
SDG 10: Reduced Inequalities
SDG 13: Climate Action

Solar milling can improve the income and quality of life for farmers, especially women, by lowering operating costs, reducing drudgery, increasing farm productivity and improving food security. A transition from diesel to solar mills also produces many health and environmental benefits in the form of better air quality and lowered emissions.

Introduction

Grains are the most commonly produced and consumed food crop in the Global South, and milling is critical to processing these grains for sale and consumption. Over time, technological advances that evolved in response to available power sources have allowed for improvements to the quality and quantity of the end product and have reduced labour inputs. Early mill houses were powered by water or animals to turn a grinding stone. Over the past century, small diesel engines have increasingly replaced reliance on manual mills. In countries with high electrification rates, mills have evolved again to exploit the availability of electricity. In Sub-Saharan Africa and South Asia, however, the low rate of electrification and lack of reliable electricity access have led to the continued widespread use of diesel engines for milling.[1] A relatively low-speed, water-cooled diesel engine can, for example, power a hammer mill.[2]

The main objective of grain milling is to improve the digestibility of grain for human or animal consumption. Milling is often, though not always, preceded by other agricultural processes, such as drying, sorting, hulling, grating and polishing. All mechanical mills consist of a power source that drives a particle reduction mechanism. This can be through high-speed impact, such as hammer mills, or low-speed shearing forces, such as stone or plate grinding mills. It is generally the concept of 'fineness' that determines the flour quality. The desired fineness can be controlled through a number of methods, such as screens and hammer tip speed for impact mills, or size, spacing and pressure of grinding stones or plates.

Unlike other appliances, such as lamps (lumen) or pumps (litre/hr), there is no uniformly accepted taxonomy on the metrics used to evaluate a mill's final service or product (e.g., flour quality). Because preferences differ by culture and because the product going into the mill (feedstock) can influence the mill's function, there are no common standards to define an acceptable end-product.

There is also no uniformly accepted taxonomy for defining or classifying mills. They can be defined by a variety of parameters, including:

- **Grinding mechanism** (e.g., hammer mills, plate mills, etc.): This classification is commonly used in the agricultural sector.
- **Power source and motor configurations** (Table 1): These attributes are commonly used to classify mills in the energy sector.

Table 1. Mills Defined by Power Source

Category	Diesel Mill	Standard Electric Mill	Solar Mill
Details	Diesel by a diesel-powered engine that is coupled to the mill.	Driven by an AC induction motor that is coupled to the mill via a belt and typically operated on the grid or mini-grids.	A subset of electricity mills, driven by a motor powered by a standalone solar PV system, with batteries as optional.[3]
Motors		Typically AC induction, but can be DC or PM motor.	Typically DC motor or PM motors, but can be AC motor (with an inverter).
Typical Power Ratings (kW)	7.5 - 17.5	7.5 - 15	1.5 - 2.2
Average Throughput (kg/hr)[4]	120 - 150[5]	120 - 150	32[6] - 60[7]
Pro	Most common due to low (upfront) cost, high throughput and relative availability.	Similar (high) throughput to diesel mills with lower operational cost.	Typically the most efficient using advanced motors, with additional controls and features. They have almost no operational costs.
Con	Typically inefficient and have health, safety and environmental concerns associated with widespread use. High operational cost due to fuel purchase with fluctuating prices and frequent repair and maintenance.	Are more expensive to acquire than diesel mills and operational costs can vary depending on electricity tariffs.	Most expensive and have the lowest throughput.

1. Brian Clarke and A. Rottger, Small mills in Africa: Selection, installation and operation of equipment, Food and Agriculture Organization of the United Nations (2006): http://www.fao.org/sustainable-agricultural-mechanization/resources/publications/details/en/c/1118167/.
2. Id.
3. Where batteries are not included, they are referred to as direct-drive applications.
4. These throughputs are for maize. Note that throughput will vary significantly by grain. For example, rice is very soft and milled into flour easily.
5. Samuel Booth et al., Productive Use of Energy in African Micro-Grids: Technical and Business Considerations, USAID-NREL Partnership (2018): https://www.nrel.gov/usaid-partnership/microgrids-energy-africa.html.
6. Based on results from the functional tests conducted by Agsol.
7. CrossBoundary and Energy4Impact, Appliance Financing 1.0 Innovation Insight: Offering household appliances on credit did not significantly increase mini-grid revenues (2021): https://www.crossboundary.com/wp-content/uploads/2021/04/CrossBoundary-Innovation-Lab-Appliance-Financing-1.0-Innovation-Insight-29-Apr-2021.pdf.

- **Relative size as defined by throughput**: This classification is useful in context to determine relative scale; however, there are limits, as categories are set arbitrarily.
- **End-use function** (e.g., spice grinder, rice mill, community mill): These definitions are helpful to contextualise the mills and in consumer-facing applications.

The various ways of classifying mills are not mutually exclusive and present a challenge for discussion and comparison. This technology brief focuses on small and medium electric grain mills (including solar mills), with throughputs of < 200kg/hour.

State of Play

The primary performance metric for mills is throughput, typically measured in kg/hour. Throughput is directly proportional to power (kW) and energy (kWh). Where power is sufficient and affordable, it is easy to oversize mills to ensure high throughput, which leads to shorter customer waiting times. However, this can lead to high energy consumption and expensive underutilised mills, especially where there are high operational costs and an insufficient customer base.

A mill's energy efficiency metrics can compare the performance of mills that differ in size, motor type, grinding mechanisms and configuration. Mill efficiency is measured by amount of product milled per unit of energy (kg/kWh). A variety of factors, including motor type, grain/produce moisture content and sieve hole diameter, influence the mill's efficiency. Permanent magnet (PM) motors demonstrate the most energy-efficient motor type. For the sieve hole, the smaller the diameter, the greater the energy used. All factors must be standardised for comparable efficiency figures. Where power supply is limited (i.e., standalone solar) or unsubsidised (i.e., mini-grids, which are also somewhat limited), efficiency is crucial, as efficiency gains directly translate to improved unit economics.[8]

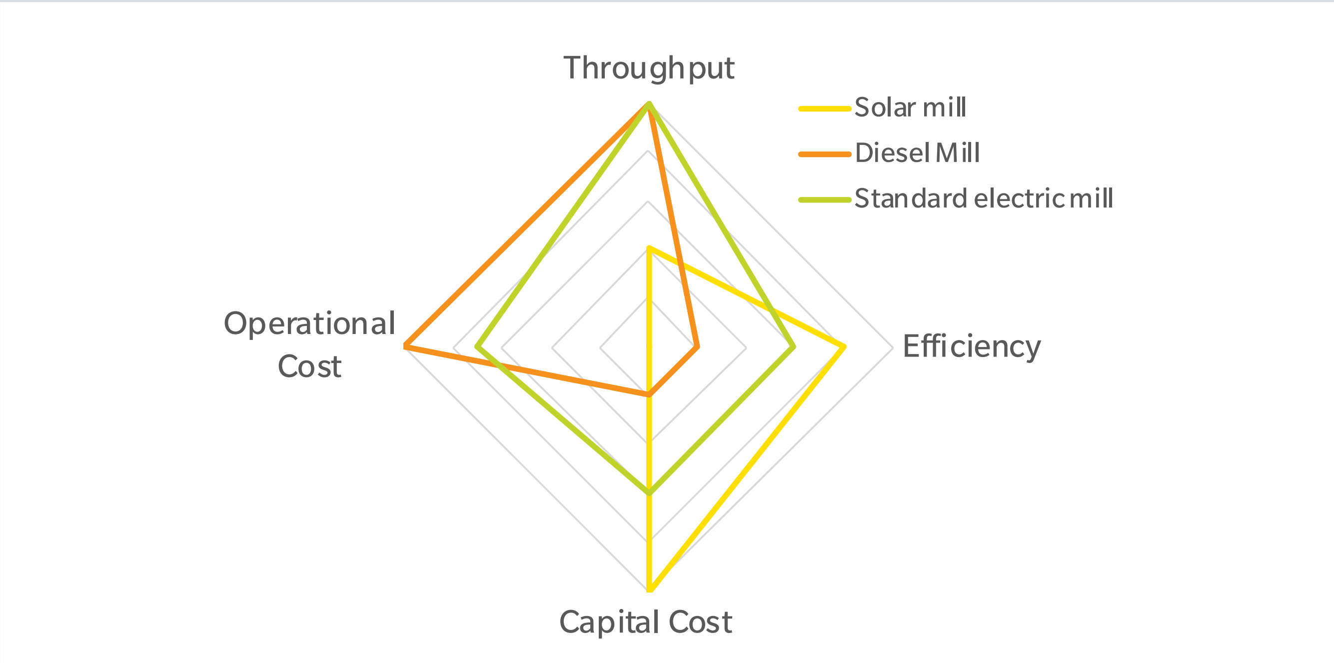
The ideal scenario optimises efficiency and user-acceptable throughput for an accurately sized and affordable mill. An ideal scenario must balance three parameters: efficiency, throughput and cost. Cost can be further subdivided into capital and operational costs, or viewed over the mill lifetime using lifetime cost analysis.[9] Capital cost includes the cost of any standalone PV system needed to power the mill.

The appropriate balance is typically different for each location and context, making a universal ideal impossible (Figure 1).

Since the launch of the [Low-Energy Inclusive Appliances (LEIA) programme in 2017](), technology and business model innovations have emerged to develop the optimum milling configuration for different contexts. The major energy efficiency technology innovations relevant to mills are:

- **Direct-drive applications with variable speed inverters:** In order to lower the capital cost of solar mills, battery exclusion and increased energy efficiency are being explored in direct-drive applications. However, it is challenging to vary throughput to match the energy available at a given instance. Without the appropriate feed control, low solar irradiance may halt the mill due to the mill's minimum energy threshold requirement.

Figure 1. Relative Performance Polygon of Mills by Type[10]



8. Elliot Avila, Productive Use Report: Evaluation of Solar Powered Agricultural Technologies for Productive-Use Applications , A2EI: https://a2ei.org/news.
9. Few comparative llifetime cost analysis have been conducted, thus this report will use capital and operational costs in making comparative cost statements.
10. This graph gives relative comparisons based on literature review and programme experience and has been submitted for review. There are insufficient studies of the various technology, mill characteristics and context to provide definitive throughput, cost or efficiency figures for each class of mills. The ranges vary widely and it is difficult to establish robust averages.

- **PM Motor Integration:** Some solar mills have integrated PM motors, resulting in energy efficiency gains. For smaller mills (mixer/grinders), lower peak power, rather than reduced energy consumption, will drive PM motor adoption. PM motors offer greater control of acceleration and deceleration since the motor is electronically controlled. This provides better control on product quality and better control interfaces.

Other technology innovations that are improving the economics for solar mills in off-grid areas include multi-functional designs and increased ease of serviceability for consumable parts. For example, the ability to mill multiple grain types increases the value proposition for a larger customer base.

Current solutions also face the challenge of achieving necessary utilisation rates in remote rural areas with low population densities.[11] Examples of business models that can maximise utilisation are:

- **Provision of ancillary services**, such as hair cutting or selling cold drinks, as a way of leveraging idle energy from the solar PV or battery system.
- **Demand side management** to ensure maximum operation at peak sun-hours through aggregated milling. Pick and drop models require significant customer behaviour change and trust, which is difficult given existing mill competition. Solar mill operators will need to explore more innovative business models or incentives to align milling time and customer behaviour to a planned schedule for maximum production.[12]

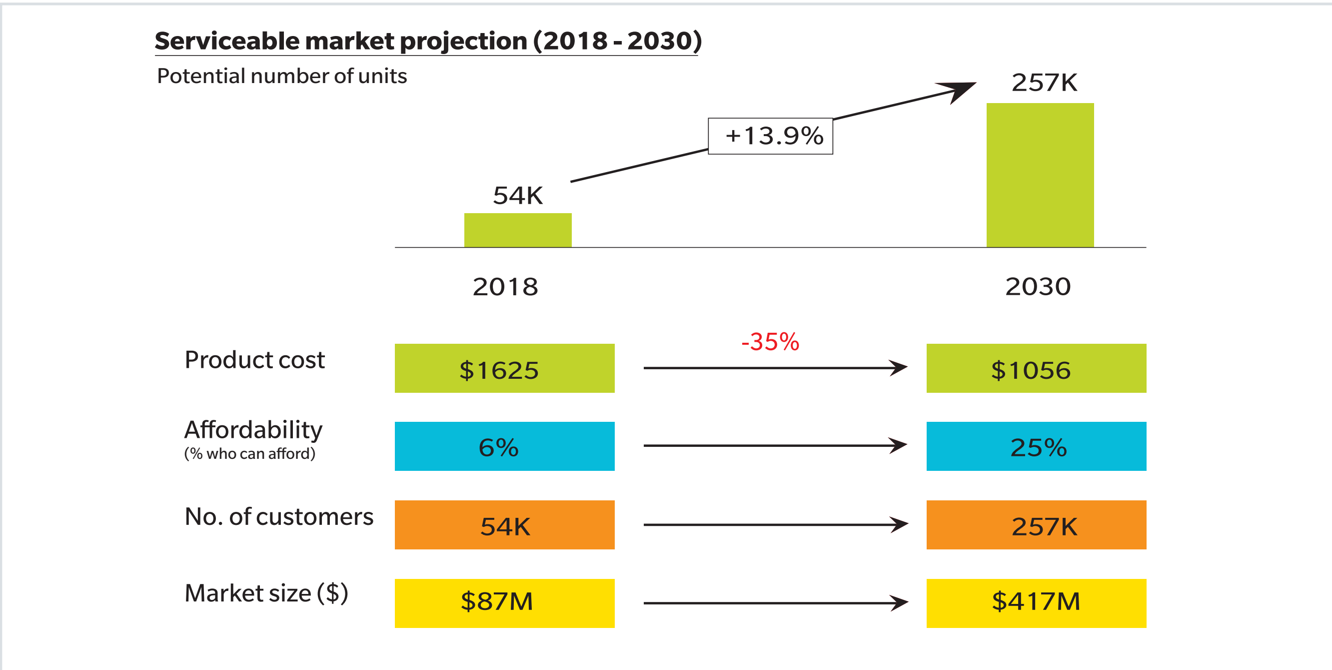
Market Insights

Standard on-grid solar mills are slowly replacing the large-scale diesel mills that dominate the off-grid market. The economics of small-scale agricultural processing (including milling) do not always make sense, whether they are solar-based or otherwise.[13] Additionally, large-scale milling is currently limited only to a few value chains that can supply the quantity of grain required for commercial viability. Aggregation provides much needed economies of scale, which brings down the unit cost of processing.

The market for small-scale milling (at the household or small community[14] level) remains nascent. In 2018, the Sub-Saharan Africa addressable market value for all small-scale (<1kW) agro-processing was estimated at USD 1.5 billion. The serviceable market, accounting for affordability and access to financing constraints, however, was estimated at USD 87 million.[15] The serviceable market is projected to grow to USD 417 million by 2030 if product costs are reduced and the proportion of people who can afford the agro-processing units increases (Figure 2).

The value proposition for solar milling is highest in remote areas where the distance to travel to existing mills is a greater challenge; however, the trade-off is that population density is lower in these areas. Additionally, in these remote areas, there may be competition from cheaper, incumbent small-scale diesel equipment that offers flexibility in terms of operational use and mobility.

Figure 2. Sub-Saharan Africa (Small-Scale) Agro-Processing Market Projection, 2018-2030



Source: International Finance Corporation. The Market Opportunity for Productive Use. (2019).

11. The Market Opportunity for Productive Use Leveraging Solar Energy (PULSE) in Sub-Saharan Africa, IFC (2019): https://www.lightingglobal.org/resource/pulse-market-opportunity/.
12. Efficiency for Access Coalition, Solar Milling: Exploring Market Requirements to Close the Commercial Viability Gap (2020): https://efficiencyforaccess.org/publications/solar-milling-exploring-market-requirements-to-close-the-commercial-viability-gap.
13. IFC, 2019.
14. Small community here representing a group of households.
15. IFC, 2019.

BOX 1


Photo Credit: Agsol

Tanzania

INNOVATIVE EFFICIENCY GAINS

In collaboration with mini-grid operator PowerGen and mill manufacturer Agsol, the Mini-Grid Innovation Lab[20] customised off-the-shelf mills to meet output quality required by Tanzanian customers and built on Efficiency for Access' work by matching energy efficiency specifications. The lab installed larger pulleys to the mills, which increased throughput by 50%. They also improved efficiency by adding a switch to run the mill's rice huller and maize grinder separately. Soft starters minimised the surge in power draw when the mills turn on, and smaller 0.8 mm sieves were used to produce the finer flour customers desired.

The resulting mills are four times more efficient than the diesel mills on the market, achieving 90 kg/hour throughput at a power rating of just 2.2 kW. While this is less than the 120 kg per hour target throughput, it translates to only three minutes of additional customer waiting time. The Lab is building on that success to develop agricultural machinery with local and international manufacturers (e.g., Agsol). Their work aims to provide the data, analysis and funding needed to design mills and other agricultural income-generating machinery that work for mini-grid developers, customers and appliance operators in rural Africa.

Milling on mini-grids shows great promise and could be a game-changer for mini-grid profitability. Although mini-grids are struggling with demand creation,[16] mill operators are an ideal customer: they are reliable, high-earning and high energy consuming. Additionally, milling demand is highest during daylight hours, matching the cheapest time of day for a solar mini-grid to provide energy.

There is some emerging activity in East Africa on solar milling. Outside East Africa, however, the picture is mixed. Senegal is in late-stage piloting and early deployment, and other countries, like Zimbabwe and Cote d'Ivoire, show little to no activity. There is potential to displace incumbent fuel milling in these nascent markets, but few technology or business models have been tested. Additionally, local processing may focus on staple foods that require other types of processing, such as crushing. Mills are then modified to account for grain type or local preferences in milling texture.

Sub-Saharan Africa imports mills[17] and mill components primarily from China, and increasingly from India. The Asian milling market has a longer history of mechanisation and is closer to the manufacturing base, but the markets are not homogenous. In India, for example, solar milling is a high-value rural income-generating activity.[18] As a result, there has been a boom in local manufacturing of mills, which in turn lowers the entry price. Organisations such as SELCO Foundation are working with manufacturers and financiers to develop products and provide financing options for small-scale milling. In the Philippines, there is great potential for solar-powered rice mills in off-grid areas. There is also potential on small islands where production quantities are low, or where rice is transported over long distances for processing, usually in a diesel-powered mill. However, technology adoption is low due to lack of awareness, low efficiency, poor coverage of supply and maintenance networks and difficult access to credit for potential adopters.[19]

16. Benchmarking Africa's Minigrids, AMDA (2020): https://africamda.org/index.php/press-release-africa-minigrid-benchmarking-report-launched/.
17. In West Africa, expert interviews suggested that only motors are imported with the other components produced locally.
18. Sanchit Warray, Sasmita Patnaik and Abhishek Jain, Clean Energy Innovations to Boost Rural Incomes, Council on Energy, Environment and Water (2018): https://www.ceew.in/publications/clean-energy-innovations-boost-rural-incomes.
19. "Cost of Clean Energy Technologies in the Philippines' Rice Value Chains," FAO (2018): https://www.fao.org/publications/card/en/c/19040EN/.
20. Established in 2018 by CrossBoundary and The Rockefeller Foundation with support from Energy4Impact,DFID and Shell Foundation.
21. Innovation Lab, Milling on Mini-Grids: How Africa's Largest Crops Could Go Diesel-Free, CrossBoundary (2020): https://www.crossboundary.com/wp-content/uploads/2020/04/CrossBoundary-Innovation-Lab-Off-Grid-Electric-Mills-Blog-Final-15-Apr-2020.pdf.

Consumer Impacts

In off-grid areas, milling has the potential to enhance farming efficiency, increase farmer revenue and promote food security. This is particularly important for securing livelihoods in rural areas with few other economic activities apart from farming. Grain production and processing are some of the most important productive uses of energy (PUE) for off-grid smallholder farmers in rural Africa. Nearly every rural Tanzanian village, for example, has at least one grain-miller. In Nigeria, on the other hand, there are often multiple millers in one village. Maize production in East Africa accounts for nearly one-third of the continent's annual harvest.

Diesel mills may not viably serve small communities because they are often large machines with high operations and maintenance (O&M) costs and require specific technical expertise. As a result, they only make business sense in market/town centres. This makes it difficult for people living in small communities to access essential milling services. As a result, with the mills located in market towns, the money moves from small to large communities.

Solar mills allow for a constant and reliable source of energy, and rural milling enterprises can save money through lower operation costs, which can enhance their livelihoods. There are also safety, health and environmental benefits from reduced use of diesel fuel. For example, solar-milling operations do not create greenhouse gas (GHG) emissions. Emissions from production of components such as batteries and solar panels are usually small compared to the manufacturing of a diesel engine and the continuous emissions from fuel combustion required to run it.[22]

Women are usually tasked with household food processing, from walking long distances to access a mill, to the more arduous job of manual milling using a pestle and mortar. Introducing mechanical milling significantly reduces their workload. In Senegal, millet milling is a painful task that can also lead to respiratory problems, such as eye infections, skin problems, back pain and hand pain.[23]

Potential female mill customers who viewed four solar-powered mills in operation at demonstration sites in Kenya and Uganda found the solar mills more comfortable to operate than diesel mills.[24] Solar-powered mills also have a user-friendly design that allows women to operate and maintain the mill. For example, a starter switch replaces the physically difficult hand crank that is needed for a diesel engine to power a diesel mill. Finally, in off-grid areas, solar milling reduces the time spent travelling to purchase fuel. Reducing the time spent on milling would allow women and girls to spend more time on their education or other income-generating activities.

Current Successes and Remaining Challenges

Despite low adoption rates, solar mills have significant market potential. Milling represents the largest single use of stationary energy in off-grid areas. Several new companies have entered the solar milling market. Agsol and Nadji.Bi Senegal, which are supported by the Efficiency for Access Research and Development Fund, are making strides in research and development (R&D) and business model evolutions to better target their consumers. Agsol has developed a solar micro-mill that optimises the throughput of solar mills with lower power input. Nadji.Bi Senegal is digitising solar milling to improve the overall economic viability and inclusion of women. Companies such as Asaga are adapting mills used in Chinese medicine and focusing on household mills/grinders used on mini-grids. There is also work at the sector level, led by the Mini-Grid Innovation Lab, to develop a solution for mini-grid powered milling.

Even with current innovations, to date, solar mills have failed to demonstrate commercial viability. To close the commercial viability gap:

1. **Create technological solutions that balance the performance characteristics within a given context:** Solar-powered agro-processing units such as grain mills do not currently match the entry price and throughput of diesel-powered units. However, considering other key metrics, solar mill prototypes outperform diesel incumbents in energy efficiency, lower operation cost and more beneficial unit economics, notwithstanding social and environmental gains. High capital costs, however, are a barrier to entry. There are also difficulties in matching technology to use case, as a majority of use cases and associated value chains have not been mapped or tested in sufficient depth.

2. **Establish a viable catchment area, both in terms of quantity of cereals and customers:** Without sufficient aggregation of people or produce, the economics for commercially run small-scale mills may not add up. Standard solar mill profitability (where tariffs are favourable) is based on high utilisation; idle mills may never pay back the high initial cost of acquisition. Additionally, proximity to other milling services reduces each mill's catchment area and creates stiff competition. The value proposition must be even higher in such instances.

3. **Strengthen customer willingness and ability to pay:** High capital costs are prohibitive for the rural poor without appropriate financial support. For the same capital cost, diesel engine-driven mills have a greater capacity

22. FAO, 2018.
23. Nadji.Bi, Solar Platform for Millet Transformation: Milestone 1-Synthetic Report, 2020.
24. Efficiency for Access Coalition, Solar Milling, 2020.

BOX 2

Photo Credit: Nadji.Bi Senegal solar mill

Senegal

RESHAPING LIVELIHOODS

GPF Aga Biram millers used to mill maize, millet and sorghum using manual and diesel grinding. The mill owners, through a hybrid franchised ownership model with local bank financing, purchased a solar mill.

They have been operating the solar milling machine since 2016. The mill is in operation for two to three hours, 250 to 260 days per year. It mills 100 to 200kgs and serves between 10 to 20 customers per day, with an average of 6kgs sold per customer per day. The solar system also powers a freezer that has been running since 2018 and is available seven days a week. The freezer stores around 30 ice creams and 20 ice blocks per day and serves between 10 to 20 customers per day.

"With the diesel milling machine, we were tired due to the smell of diesel. We had difficulties to eat our couscous. And the machine never lasted more than six months. We had difficulties buying fuel, due to the distance and the cost. And we couldn't repair it. Once it had a problem it almost never worked again. With manual milling, we were tired and our chest hurt, we had wounds on our hands, we had pain everywhere. The solar-powered grain mill is really good. We can wake up later now and we sleep much better and our girls can study peacefully now."

and higher output than solar mills, limiting consumer willingness to pay. Affordability and lack of consumer financing is a key constraint that limits the serviceable markets. Access to credit is a particular problem that needs a solution, especially for farmers who do not own their land, as they cannot use land as collateral.

4. **Create and test innovative business models:** The commercial value proposition of solar mills compared to incumbent technologies is not always clear, especially given the longer return on investment period compared to other PUE technologies like solar water pumps. The aptitude of entrepreneurs is also key, as business acumen is crucial for profitability and thus, ability to finance assets. More innovation is possible, for example, to transfer asset ownership to a third-party organisation rather than individuals. This innovation can lower the financial barrier and ensure continued support for small-scale commercial millers. Additionally, the market may be too nascent for the B2B models suggested for other PUE technologies like solar water pumps. Vertical integration may be a beneficial entry model to prove viability and establish a market.

5. **Set up incentives to move away from manual and fuels-based approaches:** Incumbent milling technologies have been in place for a long time and will require concerted effort to displace. Low awareness of electric and solar milling and their potential benefits is limiting this switch over. Since the new technology is also more expensive, customers need a push to adopt.

Other challenges include unfavourable policies (especially tax and duties), lack of appropriate testing frameworks and dearth of options (brands) available in local markets.

Continue R&D for technological innovation

Programmes such as the Efficiency for Access Research & Development Fund have already supported manufacturers to develop the first prototype of efficient, high quality solar mills, like the Agsol micro-mill. However, sustained support is required to develop commercially ready products and find viable business models for a risky and nascent market.

Deploy rapid product assessment

Testing and quality assurance procedures exist for some milling components (e.g., motors), but few protocols test the full assembly. For example, grain moisture content and variety are extremely specific to geography and have a great impact on mill throughput. Some mills have even reported breaking down when attempting to mill grains in a different geography than where they were tested. A rapid product testing protocol that can accommodate local context would eliminate this costly.

Increase market intelligence

The sector needs more pilots and detailed case studies across a range of products and geographies. A specific example of needed market intelligence is an investigation of PM motors. Companies need insight on approaches to reduce cost of PM motor integration in mills, while also ensuring maintenance and operation sustainability. Companies are still choosing less advanced motors, as the efficiency versus cost balance does not add up for their geographic contexts. Beyond case studies and pilots, more data is needed on which markets and value chains are viable. This data can help form a baseline for incumbent technologies and characterise demand for household, community and productive use mills.

Enable long term financing

Risk capital and consumer financing to mitigate high solar mill capital costs are critical to unlock the market potential for solar milling. Risk capital, in the form of patient, seed, working capital and grants, should be available to entrepreneurs, suppliers and manufacturers. This risk capital can enable them to develop and commercialise more efficient solar mills and specific market-led designs and business models. Consumer financing would enable existing and potential mill operators to mitigate the capital cost of electric mills and incentivise them to make the switch from diesel.

Discover and test innovative business models

In order to make solar mills commercially viable, rural consumers need proximity to vital grain milling services—not just the mills—or to become milling entrepreneurs themselves. Discovering other innovative business and financial models apart from the pay-as-you-go (PAYGo) or entrepreneur models will enable scale. Existing entrepreneurial models could benefit from commoditising milled products. For example, Nadji.Bi Senegal sees potential in training women's groups to transform flour into other value-added products. More investment is needed in technical assistance to tailor technologies and business models and to support technology upgrading and skills transfer.

Redirect subsidies and policy incentives

Solar mills are a good candidate for government and donor enabled subsidies and other incentives. The positive effect for women and girls alone (if translated into income) would represent much more than the cost of the subsidy investment required. Additionally, setting a price on carbon would enable solar mills to benefit, fiscally, from emissions saved. Pricing other benefits of milling machines, such as women's time and reduced drudgery, would also be an interesting avenue to pursue. To achieve maximum impact, subsidies should be considered in tandem with appropriately tested, minimum product standards.

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