Innovate UK Energy Catalyst Round 6
Project 105643

“Smart Integrated Community Energy in Northern Tanzania”

2.2kW Solar Powered 3-phase Agsol Hammer Milling Machine – Pilot Study Results
October 2020

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(project internal use only)
Summary

This report describes the results of tests conducted to assess the viability of an electric 3-phase 2.2kW Agsol hammer mill, imported from Kenya, for use in rural Maasai communities in Simanjiro, Tanzania. The objectives of the tests were to assess for various hammer mill settings:

1. Speed of milling,
2. Quality of flour output

These two indicators of hammer mill performance were investigated through variation of (a) screen hole size and (b) maize feed rate (through varying the feed aperture). Resulting flour samples were ranked and evaluated by local cooks, and directly compared with a locally milled flour sample. Results confirm that quality of output is directly related to screen coarseness; only flour obtained with the finest screen (0.8mm apertures) was deemed of a quality adequate for cooking. A correlation between maize feed rate and flour quality could not be reliably drawn from the data. Milling speeds ranged from 1.7 times to 11.7 times slower than the existing diesel-fed milling machines found in the market (310kg/hr), with fastest milling speeds obtained using coarser screens, and increased feed rate. However, at higher speeds, the machine became very hot, so we predict that only 5-10 times slower than current market milling speeds is sustainable for continuous use.

We conclude that this hammer mill may be viable and acceptable in the target use case if users are willing to accept a decrease in milling speed of 5-10 times in exchange for potentially higher quality flour, a machine which can be run on demand, and a method that uses a cheaper and cleaner electricity source.

1. Introduction

The main focus of SVRG’s current work is in systems and innovative technologies for community development in sub-Saharan Africa. We adopt a holistic approach, integrating fundamental enabling technologies such as energy and ICT with more use-case and impact focussed solutions for productive use, economic development and community service technologies.

Many of the communities we work with are agricultural, with maize flour contributing to an integral part of their diet. Maize milling is therefore a strong potential productive-use application of energy access projects. In the rural maasai Tanzanian communities we work with, villagers often have to travel to neighbouring towns to access a milling machine. This matches the Access to Energy Institute’s Productive Use report, in which interviewed mill customers in rural Tanzania reported walking up to 10km in order to reach the closest mill, ultimately costing them their entire day. These diesel-powered machines are large, and fast, but the cost, reliance on diesel, and health impacts of the exhaust fumes from poorly maintained diesel engines, leaves room for improvement. There is also anecdotal evidence that the user experience can involve long waiting periods for enough customers to arrive, for it to be worth the operator switching on the machine, due to the inefficiencies of the diesel engines, especially at startup.

Our first envisioned application of an electric milling machine is at an existing solar-powered productive use site, in Ormoti, Tanzania. The system, installed to run a borehole pump and a range of other productive uses, consists of a large solar array powering a Grundfos RSI solar pump inverter (VFD),

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1 Access Energy Institute, Productive Use Report, E. Avilla, A. Garties, B. Mohamed, J. Lin
which produces balanced three phase power. Our hypothesis therefore was that the excess solar energy could be used to power a maize milling machine for community members, thus helping grow the Ormoti site as a business and social hub for the surrounding villages. If successful, it would prove that this type of solar-powered milling machine was a viable productive-use, can be powered from this type of installation, and could be encouraged alongside future solar installations to increase the economic capacity of communities to make repayments and provide this important community service.

Little information was available online regarding the performance of existing, small-scale electric milling machines, and there were concerns that the quality of flour may not meet locals’ expectations, as very small DC and single phase mills have sometimes had a bad reputation in this regard. Larger electric milling machines (from 7.5kw upwards), which do have a good reputation, require disproportionately expensive power systems to power them in off-grid locations, which unlike the diesel-powered mills would require a very high utilisation factor to allow them to break even.

This report describes the results of tests conducted to assess the viability of a 2.2kW electric 3-phase Agsol hammer mill, imported from Kenya, for use in rural communities. The multi-feedstock mill is capable of processing a range of cereals and dried tubers to fine or coarse flour for human or animal consumption. It is commonly used to process maize, cassava, sorghum and millet, though our tests focussed on maize milling for human consumption. The tests assessed (1) speed of milling, and (2) quality of output, for different hammer mill settings, and compared these results with community expectations.

2. Method

Before installation at the solar productive use hub site, the milling machine was tested using electricity from a three-phase generator. Two variables were investigated to give the range of flour quality obtainable:

1. The coarseness of the screen inside the milling machine drum
2. The speed with which maize was fed into the machine

The machine was supplied with 4 screen sizes: 0.8mm, 1.0mm, 2.0mm and 3.0mm. The difference between the finest and coarsest screen size can be seen in Figure 1.

![Figure 1: Milling Machine with different screens installed: The coarsest screen at 3.0mm (left) and the finest screen at 0.8mm (right)](image)

The speed with which maize was fed into the machine was varied by adjusting the size of the entrance aperture. There were two sheets that could be adjusted to do this. The first was a metal sheet which had...
a straight edge. The second was a plastic sheet with a notch cut out of it, overlaid onto the metal sheet. This acted to limit the maize entry to just the central portion of the feed entrance. Experience suggested this was necessary to prevent overloading the motor, so it was kept in place for all tests, and the feed tray width was modified to help channel all maize through the central hole. The metal sheet was used to vary the (already constrained) feed hole between fully open and fully closed. These modifications can be seen in Figure 2.

For each test, a measurement was made on the time taken for a 2kg bucket of maize kernels to completely empty from the feed tray. The maize was added gradually to avoid overflowing the feed tray, whilst ensuring there was always sufficient to maximise maize entry through the feed hole. Factors such as approximate current draw, temperature and motor noise were noted, along with the quantity of maize left in the drum once the machine was turned off. Flour was collected in a bag by holding the bag around the outlet funnel. It was later learned from the manufacturer that tying a bag around the outlet in this way could have reduced airflow and flour production, but the method was kept consistent across all tests, enabling a fair comparison between tests.

The first test was done with unprocessed maize kernels. Following advice from local milling experts, subsequent tests were done after sieving the maize kernels to remove impurities (twigs, and corn cob particles), as would be done in practice. Nine tests were done in total, using eight different setting combinations (1 test was a repeat of the ‘best’ setting to check repeatability).

Samples of flour from each test were placed into separate cups, with a cup of locally milled flour included as a reference sample. The samples were presented to a group of 3 local cooks who were asked to rank the flour in order of best to worst, separating out the flour samples that were of too low a quality for cooking (In practice these would be used to make animal feed). The separate rankings for each flour
were combined to give an overall flour quality score. The details on each flour sample were not disclosed to the cooks to ensure it would not affect their rankings. The ranking process can be seen in Figure 3.
3. Results

The results are shown in Table 1, with flour samples ordered from best to worst according to the sum of the cook’s rankings. Each row corresponds to a different flour sample. Rows highlighted in red correspond to flour samples unanimously deemed of a quality too low for cooking. More detail on the individual cook’s rankings is available in Appendix 1. The results are shown graphically in Figure 4.

Table 1: Milling Machine Flour sample ranked results, with poor quality flour highlighted in red.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Total Score</th>
<th>Flour milling settings</th>
<th>Milling speed (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>0.8mm</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.8mm</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
<td>0.8mm</td>
<td>0.33</td>
</tr>
<tr>
<td>D</td>
<td>12</td>
<td>2-stage: 3.0mm followed by 0.8mm</td>
<td>0.33</td>
</tr>
<tr>
<td>E</td>
<td>14</td>
<td>0.8mm</td>
<td>0.33</td>
</tr>
<tr>
<td>F</td>
<td>18</td>
<td>0.8mm</td>
<td>0.33</td>
</tr>
<tr>
<td>G</td>
<td>21</td>
<td>1.0mm</td>
<td>0.33</td>
</tr>
<tr>
<td>H</td>
<td>24</td>
<td>1.0mm</td>
<td>0.5</td>
</tr>
<tr>
<td>I</td>
<td>27</td>
<td>1.5mm or 2mm</td>
<td>15kW Diesel machine in market</td>
</tr>
<tr>
<td>J</td>
<td>30</td>
<td>3.0mm</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Figure 4: Graphical representation of results.
Left: Flour sample quality vs feed rate.
Right: Milling speed vs feed rate.

Note that the milling speed may not be fully representative, as it was not possible to measure when all the maize had exited the machine with the equipment available at the time. By measuring the time taken for the feed tray to empty, not-fully milled maize could still be present inside the drum. This was especially evident for the finer screens (0.8mm and 1mm) whereupon opening the drum following the test, often some maize remained, as shown in Figure 6. As a result, it is likely the milling speed of the finer meshes was overestimated in our tests, particularly for test A, for which a significantly large quantity of flour still remained in the drum.
Power consumption of the machine during testing was not precisely measured. Once installed at the Ormoti site, the VFD indicated the milling machine used 0.7kW under no load (no maize), and around 1.7kW when fed slowly with the 0.8mm screen. Assuming a milling rate of around 30-60kg/hr, in line with our average test milling speeds with the feed rate ⅓ to ½ open, this gives a 18-36kg/kWh efficiency. The manufacturer claims a 44kg/kWh efficiency rating. This discrepancy could be explained by the test set-up, with the output flour bag tied around the machine, restricting air-flow, or due to inaccurate estimation of the milling speed.

4. Discussion

4.1 Flour quality

- Results indicate that screen size is the most important factor influencing flour quality. Only the finest screen (0.8mm) produced flour of a quality judged to be high-enough for cooking. However, it should be noted that 'acceptability’ could also be affected by the convenience factor, and if flour milling was possible more locally, then poorer quality flours may also be accepted.
- The cooks unanimously ranked samples G to J of a quality too low for cooking (samples obtained using coarser screens of 1.0mm and larger), but disagreed on the specific ranking order for samples A to F (using the 0.8mm screen, but different feed rates). In addition, the difference in scores between C and F, which were done using identical milling machine settings, is much
greater than the difference in score between many tests with different feed rates, for example samples A to C. This could be a result of the inherent variability of the milling machine, or the similarity of the samples, limitations of the ranking system, and the subjective nature of preference testing. Only screen size could be distinguished by user testing, not feed rate. Consequently, we cannot draw a conclusion that feed rate affects flour quality.

- According to the cooks, the lower quality flour could still be used for cooking, but would require a slightly different cooking technique, and would result in a more textured ‘ugali’ (traditional maize dish).
- Flour for a baby’s porridge needs to be extremely fine, and is beyond the capabilities of our milling machine.
- The quality of flour obtained from the 3-phase electric milling machine was able to surpass the quality of the existing diesel machine in the local market when the finest mesh was used, so flour quality would not be a barrier to implementation of the machine as a productive use. Although a taste test was not conducted in this specific experiment, the manufacturer claims that customers consistently comment on how flour from their, and other electric mills, don’t have the taint of diesel present, adding to the improved quality.

4.2 Milling speed

- Milling speed depends on both the screen size, and the size of the feed aperture opening.
- The feed aperture opening is the most important factor for milling speed: increasing the aperture opening from 1/3 to fully open can increase milling speed up to 5 times. The fastest feed rate (feed aperture fully open) was noticed to put strain on the motor (operating around 3 times above the motor rating according to the manufacturer), resulting in current and power increases (which were variable) and heat generated from the motor, drum, and flour outflow. The manufacturer advised this could lead to motor damage and may result in larger solar arrays being required to meet the power requirements. He also believed it should have slowed the motor (milling head), slowing the hammer tip speed and resulting in a coarser particle distribution, however flour quality tests could not reliably discern a difference in this respect. This setting should not be used if the machine is to be operated for any reasonable continuous length of time. We would recommend keeping the feed hole opening at or below 50% at all times, to prevent machine damage, even if this increases milling time.
- Increasing the coarseness of the screen marginally increases milling speed. Data from the manufacturer states that there is a non-linear relationship between screen size and flour output while keeping power consumption constant (i.e. correct loading for motor’s power rating). E.g. going from a 1mm to 1.2mm (20%) yields a ~35% gain in production rate, whilst going from 1mm to 1.5mm (50%) yields ~100% gain in production rate. Our tests did not demonstrate such a significant change in productivity. This may have been due to an unrepresentative timing method, as some unmilled maize remained in the drum when the test was stopped, especially for the finer screens. This unmilled maize was not taken into account when calculating the milling speed based on input maize, not on output flour. This 3-phase electric milling machine is significantly smaller than most milling machines we’ve seen in rural markets, and consequently the milling speed cannot compete. Milling speeds ranged from 1.7 times to 11.7 times slower than the existing diesel-fed milling machines found in the market (310kg/hr). When operating at our recommended settings (0.8mm screen size, feed aperture 50% open to prevent overworking the motor), the speed is 5 times slower than the local market machines. However, the increased energy efficiency, cost effectiveness and convenience of the electric milling machine could outweigh the speed being a barrier to acceptability by local people.

4.3 Milling Efficiency

As measurements on power consumption (kW) and milling speed (kg/hr) were never taken simultaneously, an accurate estimate of milling machine efficiency cannot be made. Rough estimates indicate an 18-36kg/kWh efficiency (see ‘Results’) which is below Agsol’s claimed 44kg/kWh. A typical 10HP (7.5kW equivalent) diesel mill with a 1mm screen has an efficiency of 20-24kg/kWh, which is
lower than Agsol’s claimed efficiency, but it is impossible to conclude from our data whether the electric mill is more efficient, under our test conditions.

4.4 Ormoti Installation and VFD control

Given flour quality standards were met, the milling machine was connected to the VFD solar pump inverter at the Ormoti borehole site, in parallel with the borehole pump\(^2\). The AgSol milling machine comes with a bundled soft starter, which enables it to be started and stopped whilst the borehole pump is running. Since the VFD essentially acts as a soft starter, however, we believe that the VFD controls could be used to operate the milling machine without the soft starter, albeit only either together with, or separately from, the pump. Changing the combination of pump & milling machine would require the VFD to be powered down and restarted after appropriate circuit breakers and switches had been set.

As expected, the VFD was able to power the milling machine without problem. The interaction between the milling machine soft starter and the VFD was an interesting one - activation of the milling machine (via the soft starter switch) while the pump is running results in the power output of the VFD temporarily dropping to a low level (<1kw) before it recovers to the combined power of the pump and milling machine. Stopping the milling machine via the soft starter controls just allowed the VFD to reduce power to the regular pump power. But at no time did this cause the VFD to fault or stop.

We believe this is a significant finding - ability to power a small milling machine through a VFD solar pumping inverter is a very efficient system design (since the system requires no batteries or charge controllers - just the solar array, VFD and safety components). If milling machines that produce high quality flour can be powered with the same technology off-grid, it potentially makes them more accessible to remote rural locations. And the finding that they can easily be powered alongside existing 3 phase pumps powered with VFD solar inverters (provided the VFD is rated at least 3kw, in this case, above the pump power) makes them an easy addition to existing water pumping systems.

Despite the slower milling rates, the machine has proven a success, with an average of 6 customers each day, bringing between 10-18kg of maize. Significantly, on the same day the machine was installed, it milled 200kg of flour from locals, based purely on word of mouth. Feedback has been extremely positive, with people amazed that such a small machine can produce such high-quality flour, without the noise of a diesel generator. It is also convenient having the milling machine next to the borehole, as people already need to travel there regularly to collect water.

4.4 Pricing

The borehole operator has been charging 1000TSH per 20L bucket of maize (approx 18kg) for use of the milling machine, compared with local rates of 1500TSH at the market (plus an optional 750TSH to remove the husk). The Agsol machine is unable to remove the husk from the maize, which the larger machines can often do, but the frequency of customers shows that although this is a desirable extra feature, it is not vital for acceptability and use. The machine cost around £710 to import and install. With revenue from customers on average £1.48 per day (6 customers with 10-18kg of maize), the payback time is just under 1.5 years. Note this does not include the cost of electricity as it is currently surplus generation in this particular installation, and operator/maintenance costs have also not been included. Seasonal effects on customer demand are also not yet known; these demand figures are from the dry season when the milling machine was first installed.

\(^2\) Current system configuration is a 37kw Grundfos RSI VFD powering, amongst other things, a 7.5kw Grundfos submersible borehole pump (running consumption 6.5kw)
Appendix 1: Results table with individual cook rankings

Note that cook ‘A’ was introduced as a ugali³ expert cook, which may make their rankings of higher credibility than the other two cooks.

Table 2: Milling Machine Flour ranking results

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Flour milling settings</th>
<th>Milling</th>
<th>Ranking (1=best, 10=worst)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>speed</td>
<td>Cook A</td>
<td>Cook B</td>
</tr>
<tr>
<td>A</td>
<td>0.8mm</td>
<td>1</td>
<td>sieved</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>0.8mm</td>
<td>0.5</td>
<td>sieved</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>0.8mm</td>
<td>0.33</td>
<td>sieved</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>3.0mm followed by 0.8mm</td>
<td>0.33</td>
<td>sieved</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>0.8mm</td>
<td>0.33</td>
<td>unprocessed</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>0.8mm</td>
<td>0.33</td>
<td>sieved</td>
<td>6</td>
</tr>
<tr>
<td>G</td>
<td>1.0mmt</td>
<td>0.33</td>
<td>sieved</td>
<td>7</td>
</tr>
<tr>
<td>H</td>
<td>1.0mm</td>
<td>0.5</td>
<td>sieved</td>
<td>8</td>
</tr>
<tr>
<td>I</td>
<td>Local sample Diesel</td>
<td>sieved</td>
<td>310</td>
<td>9</td>
</tr>
<tr>
<td>J</td>
<td>3.0mm</td>
<td>0.33</td>
<td>sieved</td>
<td>10</td>
</tr>
</tbody>
</table>

Appendix 2: Additional media

Additional photos and videos of the construction, testing, and use of the milling machine are available in the following folder:
https://photos.app.goo.gl/eTGp29YmatynvtJYC

Appendix 3: Agsol Hammer Mill Product Catalogue

Figure 5 shows the hammer mill specification, as given in the agsol product catalogue.

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³ Ugali is a traditional maize flour porridge, popular in East Africa.
HAMMER MILL

A multi-feedstock mill capable of processing a range of cereals and dried tubers to fine or coarse flour for human or animal consumption. It is commonly used to process maize, cassava, sorghum and millet.

The machine is optimised for efficiency, durability, and safety.

Offered with brushless DC or AC motors

<table>
<thead>
<tr>
<th></th>
<th>DC 48V BLDC</th>
<th>AC 1-Phase</th>
<th>AC 3-Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Rating [kW]</td>
<td>1.3</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Production rate [kg/hr]*</td>
<td>50</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Efficiency [kg/kWh]</td>
<td>48</td>
<td>50</td>
<td>39</td>
</tr>
</tbody>
</table>

* Based on maize milling with 1mm screen. Production rate for cassava is x2 and millet is x3

Dimensions: 670 x 360 x 700mm
Approx. net weight: 40kg

Figure 6: Excerpt from Agsol Product Catalogue, showing imported Hammer Mill specification