ENDBERICHT

Vorhaben 03SF0683A – LEAP-RE ‘SunGari’

Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren

Teil I und II – zur Übermittlung an die TIB

GEFÖRDERT VOM
Bundesministerium
für Bildung
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Project Summary report (‘Teil I – Kurzbericht’)

Due to the international character of the research work this report is issued in english language.

Project name:	LEAP-RE; Joint project SunGari
Project #:	03SF0683A
Subproject:	Energetic Optimization of the Gari Processing

1.0. Project background and objectives

The SunGari project was commissioned from April 2022 to April 2024 to investigate the feasibility of using emerging solar technology (photovoltaic (PV), concentrated solar thermal, and PV to steam power with storage) to provide a modern cooking solution for African staple foods. Up to now typically fire wood was used to produce gari, which is a staple food based on cassava within Western Africa. The project partners were Agrartechnik Witzenhausen, University of Kassel (Germany), Simply Solar Technology Consulting GbR (Germany), University of Pretoria (South Africa), University of Limpopo (South Africa), University of Lome (Togo), and the University of Greenwich (UK).

The project had six work packages (WPs) that comprised the following tasks; WP1: Optimised process requirement for converting grated, dewatered, and fermented cassava mash (dry matter content 50%) into Gari (dry matter content 90%), WP2-3: Technical analysis of technologies such as concentrated solar power (CSP), photovoltaic (PV) thermal, and photovoltaic (PV) electric to supply the heat and electricity required by the Gari process, WP4-5: Develop, assemble, demonstrate, and test three different Gari roasting apparatuses and WP6-Coordination and dissemination of the project.

2.0. Methodology

In general, the project implementation used a multidisciplinary and participatory approach, with stakeholders involved in the equipment's design, implementation, and testing within the six work packages (WP) adopted. This included a baseline survey (needs assessment) using the Life Cycle Sustainability Assessment (LCSA), processing parameters optimization using traditional look-alike lab-scale roasting systems, and designing, and manufacturing.

3.0. Results achieved

The three gari roasting systems based on direct solar PV, direct steam and PV to steam have been installed and tested successfully at the demonstration site in Togo. It was found that the vessels can produce 0.51 to 1.87 kg per batch in 17 to 43 minutes (within the duration attained when using woodfuel).

The optimum parameters achieved are factors (131.08 ^{o}C temperature, irradiance 826.36 W m^{-1}, voltage 32.59 V, current 28.53 A, power 1068.70 W (String power), Energy supplied of 1.69

kWh. The optimum responses are 27.7 min roasting time, gari output 1.23 kg, productivity 2.79 kg hr^{-1}, yield 50.60 %, specific energy capacity 1.43 kWh $kg\text{-}gari^{-1}$ and efficiency of 53.05 %.

4.0. Impacts and achievements

- **Impact of science and technology:** Advancement in Renewable Energy: By utilizing solar PV technology in the cooking process, this innovation demonstrates its adaptability and lays the groundwork for further studies in sustainable cooking.
- **Increase in efficiency and storage**: The technology makes improvements in energy storage and photovoltaic efficiency, which are beneficial for other solar applications with high demand.
- **Catalyst for Research:** This service is unique and promotes more research into sustainable cooking services. Furthermore the research opportunity was used to strengthen international cooperation between the German and African partners on a future oriented topic.

Detailed project report (‘Teil II - Eingehende Darstellung’)

Due to the international character of the research work this report is issued in english language.

Project name: LEAP-RE; Joint project SunGari

Project #: 03SF0683A

Subproject: Energetic Optimization of the Gari Processing

Summary

The SunGari project's objective was to create and develop a Modern Energy Cooking Service (MECS) based on solar cooking (photovoltaic, solar PV to thermal and concentrated solar thermal) for cassava processing into gari in West Africa, and then to extend it to processing other staples in developing countries. The three gari roasting systems based on direct solar PV, direct steam and PV to steam have been installed successfully at the demonstration site in Togo. The systems were successfully developed and tested. It was found that the vessels can produce 0.51 to 1.87 kg per batch in 17 to 43 minutes (within the duration attained when using woodfuel). The optimum parameters achieved are factors (131.08 ^{o}C temperature, irradiance 826.36 W m^{-1}, voltage 32.59 V, current 28.53 A, power 1068.70 W (String power), Energy supplied of 1.69 kWh. The optimum responses are 27.7 min roasting time, gari output 1.23 kg, productivity 2.79 kg hr^{-1}, yield 50.60 %, specific energy capacity 1.43 kWh kg-gari^{-1} and efficiency of 53.05 %.

Project background and objectives

The mission of the SunGari project was to innovate and develop a Modern Energy Cooking Service (MECS) based on solar cooking (photovoltaics and concentrated solar thermal) for cassava processing into gari in West Africa and later develop it to processing other staples in the developing countries.

The project had six work packages (WPs) that comprised the following tasks:

- WP1: Optimised process requirement for converting grated, dewatered, and fermented cassava mash (dry matter content 50%) into Gari (dry matter content 90%).
- WP2-3: Technical analysis of technologies such as concentrated solar power (CSP), photovoltaic (PV) thermal, and photovoltaic (PV) electric to supply the heat and electricity required by the Gari process
- WP4-5: Develop, assemble, demonstrate, and test three different Gari roasting apparatuses.
- WP6 Coordination and dissemination of the project..

Methodology and work packages

Work package number 1 (WP1)

Objectives

- Determine the temperature and energy requirements for Gari roasting at the domestic/cottage and small and medium enterprise (SME) levels in Togo.
- To conduct optimisation of the Gari roasting process for optimal quality and minimum power consumption.

Work description: The work involved the optimization of the lab scale gari system mimicking the actual traditional processing setup in Togo and the base line survey of the current status of the cassava processing in Togo under the supervision of University of Lome.

Optimisation of the gari roasting process for optimal quality and minimum power consumption at laboratory scale

In April 2022 to September 2022, Unikassel carried out the laboratory scale cassava to gari process optimization experiments at University of Kassel.

Objectives: To determine the optimum temperature, energy, time and the agitation speed for gari roasting at standard physiochemical quality indicators.

Methods used: The I-Optimal design of two factors (Temperature and Stirring speed) by 25 runs comprising of nine responses (time (Y_1), energy (Y_2) final moisture content (Y_3), color components (L^* (Y_4) b^*(Y_5) and a^* (Y_6)) pH (Y_7), swelling index (SI) (Y_8) and texture (Y_9)) with five replicated runs. Data analysis/optimization was performed using JMP data analysis software [1]. The applied roasting temperatures ranged from 90 to 250 ^oC, with the number of replications per temperature level as follows: 5 at 250 ^oC, 7 at 210 ^oC, 2 at 170 ^oC, 7 at 130 ^oC and 7 runs at 130 ^oC. The stirring speed ranged from 10 to 50 revolutions per minute (RPM), with 5 runs at 10 RPM, 7 at 20 RPM, 2 at 30 RPM, 7 at 40 RPM and 4 at 50 RPM.

Regression analysis was applied to the experimental data. The robust regression techniques involving the centering by the median and scaling by the Interquartile range (IQR) for a second-order polynomial Equation 1, was used to fit the model and predict the responses under optimum roasting conditions.

$$\begin{aligned} Y_i = \beta_0 + \beta_1\left(\frac{X_1 - \tilde{x}_1}{IQR(X_1)}\right) + \beta_2\left(\frac{X_2 - \tilde{x}_2}{IQR(X_2)}\right) + \beta_{12}\left[\left(\frac{X_1 - \tilde{x}_1}{IQR(X_1)}\right) \times \left(\frac{X_2 - \tilde{x}_2}{IQR(X_2)}\right)\right] \\ + \beta_{11}\left[\left(\frac{X_1 - \tilde{x}_1}{IQR(X_1)}\right)^2\right] + \beta_{22}\left[\left(\frac{X_2 - \tilde{x}_2}{IQR(X_2)}\right)^2\right] + \varepsilon \end{aligned} \tag{1}$$

Where, X_1 and X_2 represented the two independent variables, temperature in degrees Celsius and stirring speed in RPM respectively. Y_1 denotes the responses, β_0 denotes the intercept term, β_1 and β_2 temperature and stirring speed linear coefficients respectively, β_{12} is interactions terms, β_{11}, and β_{22} are quadratic coefficients and script ε representing the errors. For the temperature median $=\tilde{X}_1$ and for stirring speed $=\tilde{X}_2$ while the Interquartile range for temperature = $IQR(X_1)$ and for stirring speed $IQR(X_2)$ [2–6].

The statistical significance of the regression coefficients was examined using the Analysis of Variance (ANOVA) at a 95% confidence level [2,3,7,8]. The coefficient of determination (R^2) was also used for verification.

A lot of instruments such as the temperature, energy and mass data loggers were used for data mining.

WP1: Determine the temperature and energy requirements for Gari roasting at the domestic/cottage and small and medium enterprise (SME) levels in Togo

From November 2022 to January 2023, Unikassel commissioned the field work in Togo.

Objective: (a). to determine the temperature, batch size and energy requirements for Gari roasting at the domestic/cottage and small and medium enterprise (SME) levels in Togo, (b) To determine the roasting pan specifications.

Methods used: The Material and Energy Flow Analysis (MEFA) techniques and the Life Cycle Sustainability Assessment methods were applied in three partner cooperatives facilities Togo's Maritime region

WP2-3: Technical analysis of technologies such as concentrated solar power (CSP), photovoltaic (PV) thermal, and photovoltaic (PV) electric to supply the heat and electricity required by the Gari process

Objective: WP2-3: Technical analysis of technologies such as concentrated solar power (CSP), photovoltaic (PV) thermal and photovoltaic (PV) electric to supply the heat and electricity required by the Gari process (Q1 2023). The design specifications for the roasting vessels were to be finalized based on the lab-scale data and the actual field needs assessment report.

Methods: Desk initial data analysis and online meetings.

WP4-5: Develop, assemble, demonstrate, and test three different Gari roasting apparatuses.

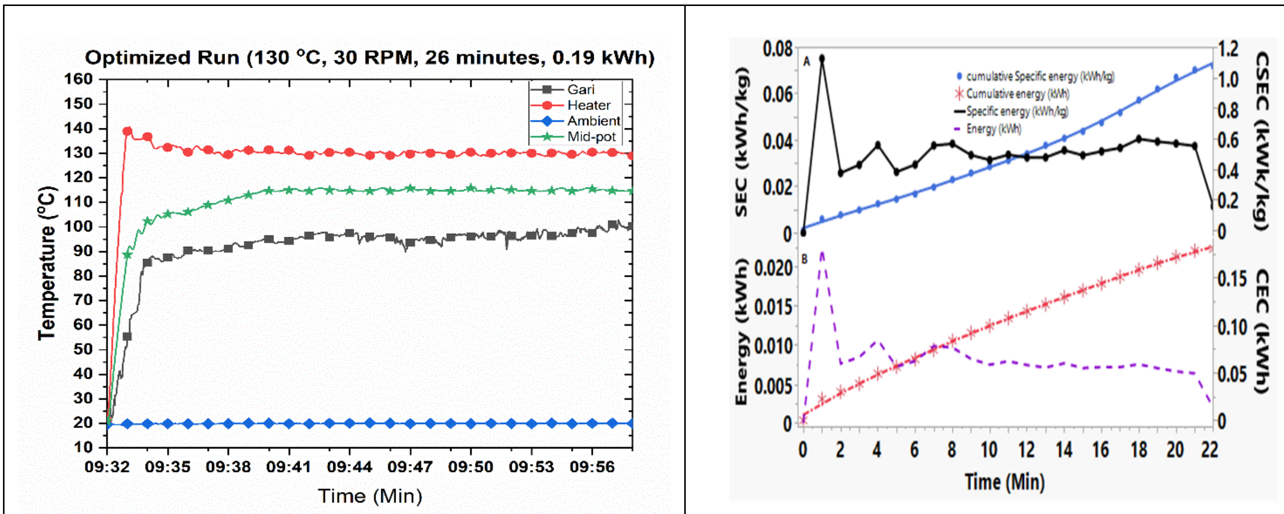
Objectives: Designing and construction of Solar PV/Thermal roasting units to install at university of Lome.

Methods: Bringing together the results of WP1, WP2 and WP3 to develop the final catalogue of detailed requirements the SunGari. This involved the working discussions between partners resulting in the final design. Detailed designs of test units where developed. The units were manufactured by South Africa Delphius Technology. The assembling and testing of the Solar Thermal and PV roasting vessels and other accessories assembling in Togo, was achieved in coordination with SimplySolar, Unikassel and University of Lome between October 2023 to April 2024. A user guide for the SunGari devices was prepared.

Main findings and results

WP1.1: Optimization of the process parameters on lab-scale

In Figure 1 (a) and (b) the optimized gari processing parameters on lab-scale are highlighted. The optimum temperatures attained was 130 °C at the cumulative energy consumption of 0.19 kWh translating into the specific energy consumption of 1.07kWh/kg-gari at the expense of 26 minutes. This energy is 700% less than the reported by the university of Ibadan in the short communication [9].



(a)

(b)

Figure 1: Lab scale; (a) temperature profiles and (b)-Energy profiles

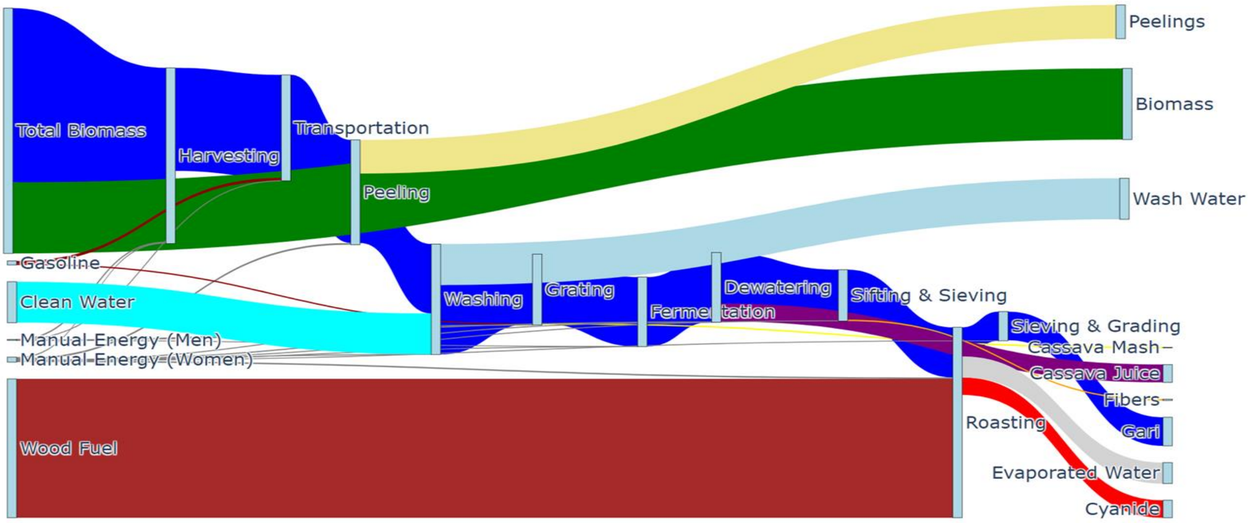
This data was considered during the final designing of the roasting systems. A scientific manuscript is currently under review in the Thermal Science and Engineering Progress.

WP1.2: Determine the temperature and energy requirements for Gari roasting at the domestic/cottage and small and medium enterprise (SME) levels in Togo (Baseline survey)

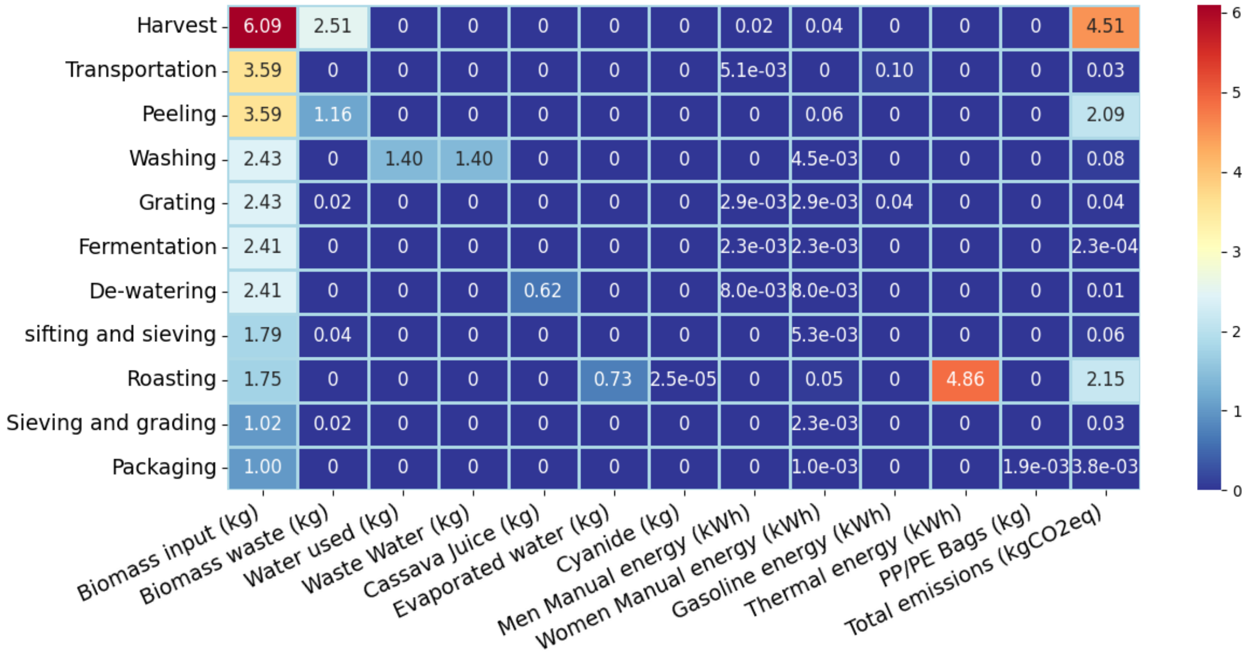
Overview of material, energy and emission flows

The MEFA of the cassava to gari processing system shows different patterns in material throughput, energy consumption, and waste/emission generation at each stage. The Sankey diagram (Figure 2(a)) depicts the system's numerous stages each of which contributes to the overall energy requirement, material transformation, and adverse environmental impacts.

This data takes into consideration all inputs and outputs flow to produce 1 kilogram of gari from cassava. The materials, energy, human hours and productivity achieved in this study are within the reported figures by other researchers [10,11].



(a) Cassava to gari Material and energy flow sankey diagram

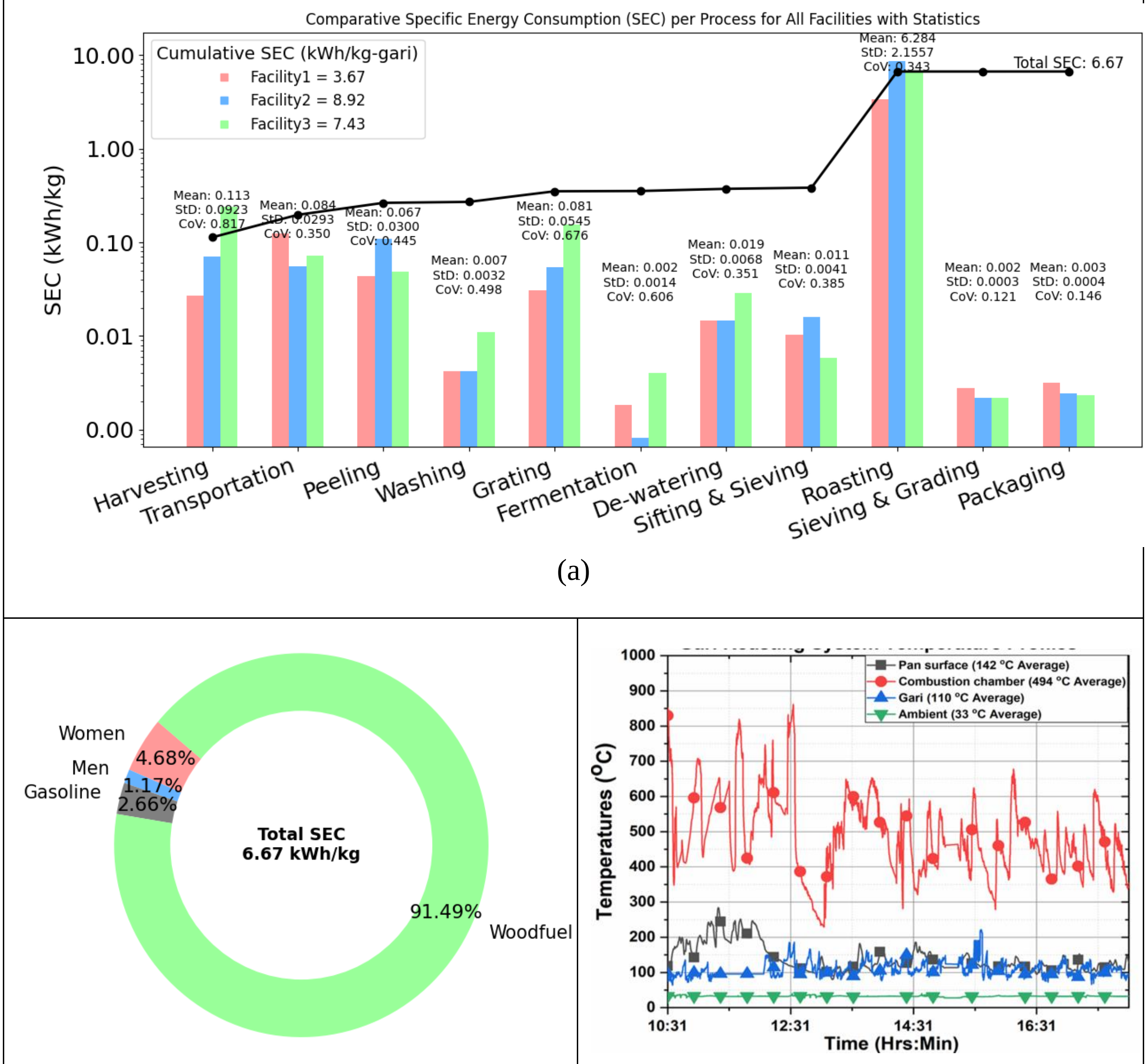


	Biomass input (kg)	Biomass waste (kg)	Water used (kg)	Waste Water (kg)	Cassava Juice (kg)	Evaporated water (kg)	Cyanide (kg)	Men Manual energy (kWh)	Women Manual energy (kWh)	Gasoline energy (kWh)	Thermal energy (kWh)	PP/PE Bags (kg)	Total emissions (kgCO2eq)
Harvest	6.09	2.51	0	0	0	0	0	0.02	0.04	0	0	0	4.51
Transportation	3.59	0	0	0	0	0	0	5.1e-03	0	0.10	0	0	0.03
Peeling	3.59	1.16	0	0	0	0	0	0	0.06	0	0	0	2.09
Washing	2.43	0	1.40	1.40	0	0	0	0	4.5e-03	0	0	0	0.08
Grating	2.43	0.02	0	0	0	0	0	2.9e-03	2.9e-03	0.04	0	0	0.04
Fermentation	2.41	0	0	0	0	0	0	2.3e-03	2.3e-03	0	0	0	2.3e-04
De-watering	2.41	0	0	0	0.62	0	0	8.0e-03	8.0e-03	0	0	0	0.01
sifting and sieving	1.79	0.04	0	0	0	0	0	0	5.3e-03	0	0	0	0.06
Roasting	1.75	0	0	0	0	0.73	2.5e-05	0	0.05	0	4.86	0	2.15
Sieving and grading	1.02	0.02	0	0	0	0	0	0	2.3e-03	0	0	0	0.03
Packaging	1.00	0	0	0	0	0	0	0	1.0e-03	0	0	1.9e-03	3.8e-03

(b) Cassava to gari Material and energy flow heatmap

Figure 2: MEFA visualization: (a) Material and energy flow sankey diagram, (b) (a) Material and energy flow heatmap

The heatmap in Figure 2(b) highlights the exact stage-wise breakdown of resources quantitatively. During the initial harvesting step, considerable amounts of biomass waste were generated, primarily in the form of cassava residual plant matter left in the field. When organic wastes decompose organically, they produce significant volumes of $kgCO_2eq$, adding to the overall carbon footprint of the system.



(a)

(b)

(c)

Figure 3: Energy Flow Analysis ((a) comparative specific energy consumption per process for all facilities, (b) Overall SEC contribution by source and (c) Roasting process temperature profiles

Figure 3 (a, b and c) illustrates the specific energy at each process stage, the overall energy contribution and the temperature profile achieved.

The study clearly shows that there is energy wastage in the real world and the development of the SunGari tool is important to ensure the mitigation of the effects of the all process on climate change. As Figure 2 (b) shows, the Global Warming Potential (GWP) associated with the cassava processing to a kg of gari of 9.02 kgCO_2eq, could be mitigated.

It has also been found that the most energy intensive stage is also the most costly in terms of the capital expenditure contributions. The Life Cycle Sustainability Analysis approach via MEFA adopted in this study establishes a critical holistic technique to monitoring the staple food processing.

WP2-4: Technical analysis of technologies such as concentrated solar power (CSP), photovoltaic (PV) thermal, and photovoltaic (PV) electric to supply the heat and electricity required by the Gari process and the development, assembling, demonstrating, and testing of the three different Gari roasting systems

Following completion of the design, the systems were manufactured by a South African company. Between November 2023 and June 2024, all the equipment was assembled in the demonstration facility at university of Lome and tested. Below is a discussion of the systems' specifics and functionality.

Roasting pans parameters

Direct Solar PV Vessel

Solar panels and control systems specifications;

- Type of solar panels: 24 x Victron 305Wp (3 strings of 8 panels)
- Total power (STC): 2.44 kWp
- Operating power: 2.17 kW
- Vmpp (60 ^{o}C): 54 DCV
- Impp (60 ^{o}C): 38.3 A

*(*Vmpp* = Maximum Power Point Voltage and *Impp* = Maximum Power Point Current).

Roasting vessels details;

The PV electric powered vessel is presented in Figure 4 and design details are as highlighted in Table 1.

Table 1: direct Solar PV vessel design details

Parameter	Specification
Supply voltage (DCV)	48
Supply Current (A)/element set	42
Power (W)	6000
Number of elements per 2000 W (sets)	3
Weight (kg)	20
Size (mm)	700*700*400
Material used	6 mm Aluminium

Figure 4: Direct Solar PV powered gari roasting pan

Scheffler solar reflectors powered Roasting Vessel

The specifications of the steam vessel, which is powered by six independent Scheffler solar concentrators, are listed in Table 2 and shown in Figures 5, A and B, respectively.

Table 2: Solar Steam (PV and)

Parameter	Specifications
Design steam gauge pressure (BarG) (Max)	1.5
Operating temperature (ºC)	130
Pressure relief valve (BarG) (Max.)	1.5
Drain and Vent Valves (inch)	1/2
Weight (kg)	30
Dimensions (mm)	700*700*400
Material	3mm, 302 stainless steel

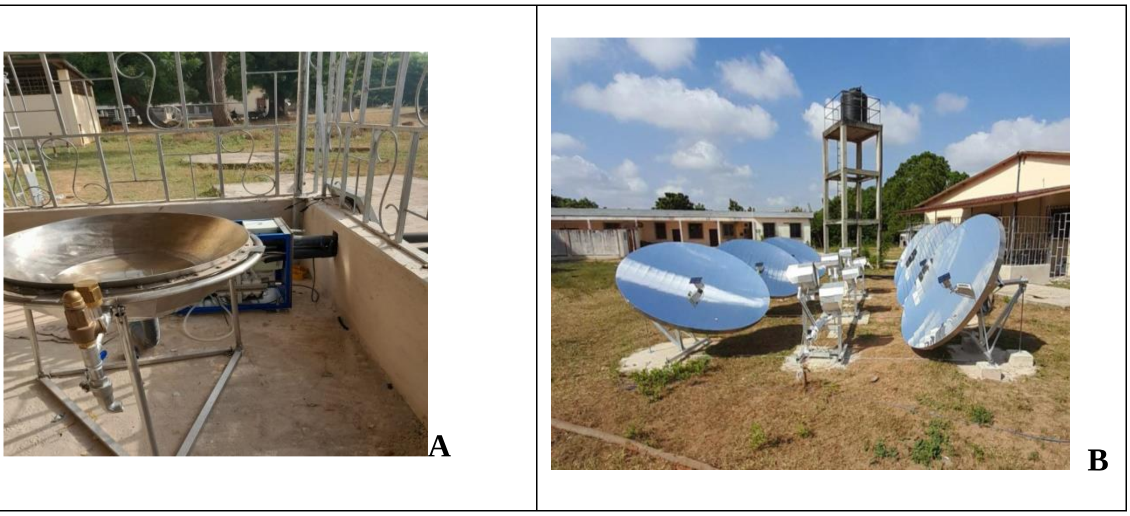


Figure 5 (A) SCSP reflector steam powered roasting pan and (B) Scheffler Concentrated Solar Power Reflectors (SCSP) for the steam powered roasting pan

Solar PV steam powered roasting Vessel

Solar panels and control systems specifications;

- Type of solar panels: 24 x Victron 305Wp (4 strings of 6 panels each).
- Total power (STC):1.83 kWp
- Operating power: 1.63 kW
- Vmpp (60 ^{o}C): 54 DCV
- Impp (60 ^{o}C): 28.7 A

*(*Vmpp* = Maximum Power Point Voltage and *Impp* = Maximum Power Point Current).

Figure 6: Solar PV-steam powered gari roasting panel

Performance evaluation

Direct PV system

Both semi-controlled water boiling tests and actual cassava mash roasting to gari were used to evaluate performance. Pictured in Figure 7 at the University of Lome demonstration site in Togo is a skilled gari producer from one of the cooperatives roasting gari using one of the roasting pans.

Table 3 highlights the general performance of the PV roasting vessel during gari roasting.

Table 3: General performance of the PV powered cookstove (Irra = irradiance, SEnergy = Supplied energy, SEC = Specific energy consumption, UEnergy = Used energy by roasting gari)

Parameter	Mean	Standard Deviation	Min	Max
Time (Min)	28.13	7.38	17.00	43.00
Batch Size (kg)	2.39	0.79	1.09	3.60
Gari pro. (kg)	1.22	0.45	0.51	1.87
Productivity (kg/Hr)	2.72	0.90	1.21	4.07
Yield (%)	50.68	3.99	42.78	57.84
Irra. (W/m2)	840.94	92.65	246.34	1116.28
Voltage (V)	32.61	6.63	20.10	38.57
Current (A)	28.55	5.79	17.59	33.75
Power (W)	1068.50	225.79	652.40	1301.53
SEnergy (kWh)	1.72	0.55	0.75	2.68
SEC (kWh/kg)	1.45	0.31	1.01	2.33
UEnergy (kWh)	0.88	0.28	0.42	1.32
Efficiency (%)	52.00	7.54	40.91	64.20
Ambient (°C)	34.64	1.80	32.12	39.80
Gari Temp (°C)	93.2	20.79	34.56	169.90
Outside pan Temp (°C)	66.73242	6.76773	32.11	76.9
Pan Surface Temp (°C)	129.48	20.25	32.80	203.20

Figure 7: Gari processing by an operator from one of the partner gari processing co-operatives in Togo

System temperatures

The mean PV roasting pan surface, gari and ambient temperatures were 129.48, 93.2 and 34.64 °C, respectively as highlighted in Table 3. Figure 8 and 9 present the thermal performance of gari roasting.

Figures 8 and 9 show a quick and substantial decline in roasting vessel temperatures from around 200 °C at S1 to 130 °C after introducing the cassava mash (CM), whose average initial temperature at T1 was 34.56 °C. The CM temperature rose to 99.7 °C within 4. The reduction in the vessel surface temperature could have been due to the sudden absorption of heat energy by the wet CM. This is known as the “change temperature stage,” in most of the roasting procedures [12,13].

The temperature of the cassava mash increased over time, reducing moisture content, as illustrated in Figure 8. As the gradient of the vessel's surface temperature decreased, the temperature loss to the cassava mash decreased.

At T3, the temperature of the vessel's surface began to rise rather than fall. This point, at which the pan surface temperature stops cooling and begins to rise with temperature of the cassava mash now almost turning into gari is known as the turning point.

The moisture content of the cassava mash keeps on reducing with a valid increasing rate of temperature as shown from T2 to T3 in Figure 8. The rate of the temperature increase, which is known as the Rate of Rise (ROR) depends on a lot of factors such as power supply to the roasting pan, the change in temperature, the number of agitation by the operator and the initial moisture content of the cassava mash [13,14].

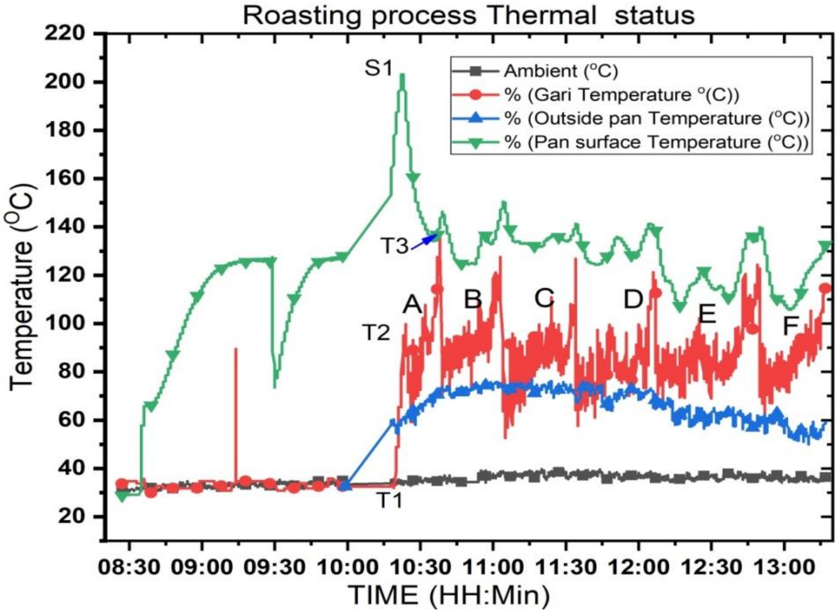


Figure 8: temperature performance on 19 December 2023 (Batch A to Batch F)

The angle of the ascending slope of the gari temperature curve is directly related to the RoR and the higher it is, the more temperature the gari or cassava mash will gain per unit time, and the steeper the curve will be. This explains why batch E took long to conclude the roasting process as shown in Figure 9.

The peaks and trouphs temperature trends in each batch feed and roasting process are comparable to those in batch A, as seen in Figures 8, 9, 10, and 11. The roasting vessel's surface temperatures decreased with each new feed.

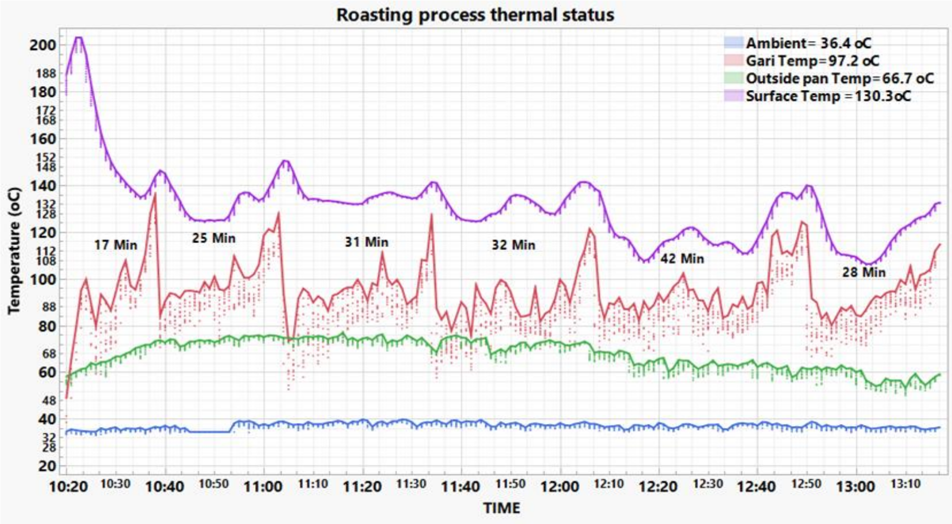


Figure 9: Temperature as a function of time for the roasting process

Figure 10 highlights the batches achieved on 16 December 2023 with the same trends of the runs discussed above

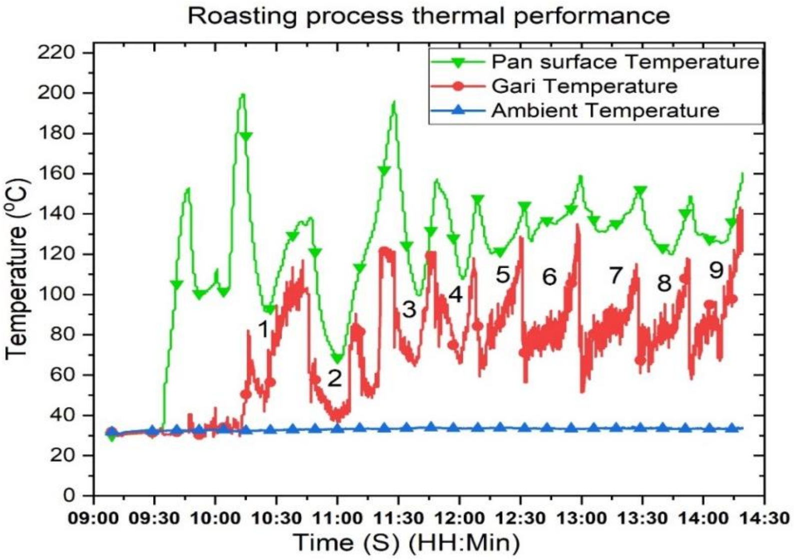


Figure 10: Temperature performance on 16 December 2023. (batch1 to batch9)

Effects of irradiance on the temperature and roasting time

Figures 11 and 12 depict the system temperatures (ambient, pan surface, and gari temperatures) and energy components (irradiance, current, voltage, power, and energy) as they relate to the roasting time.

As can be seen in Figure 8 and mirrored with irradiance curve in Figure 11, the minimum temperature for batches A and B, were between 126 and 135 ^{o}C, at stable irradiance of 850 to 930 W/m^2 (From 13:00 on figure 12, high spikes of irradiance were observed).

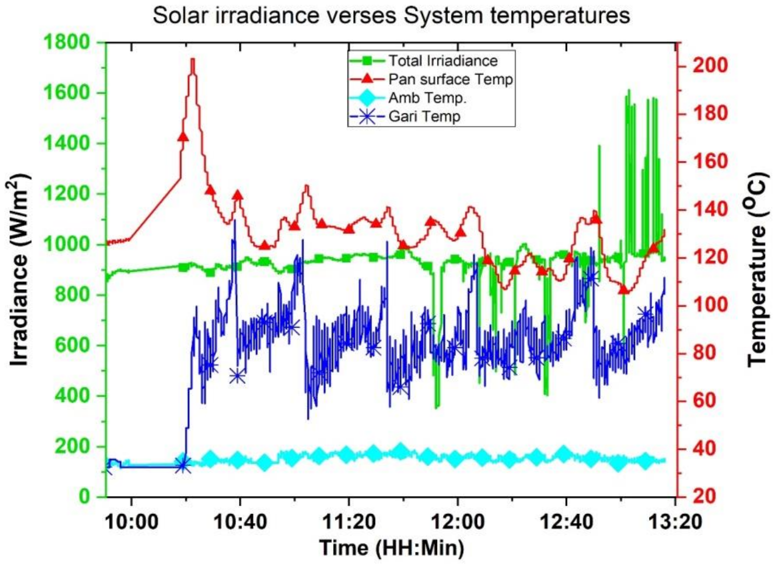


Figure 11: Temperature and irradiance as the function of the time during roasting

Nevertheless, the irradiance decreased to 359.95 W/m^2 during batch D at 11:52, from a peak of 985.21 at 11:40 (118 to 138 °C). As a result of this decrease, the pan surface temperatures decreased from about 138 to 125 °C and from about 100 to 80 °C, respectively.

In batch E, the irradiance, pan surface temperatures and the gari temperatures peak and troughs effect was even more telling. The effect resulted in the prolonged roasting duration. Nevertheless, batch F saw the spiking peaks in the irradiance to the highest of around 1500 W/m^2 that resulted into the increase in the pan surface temperature from around 110 to around 130 °C by the end of the batch. The solar irradiance achieved in this study is within the reported [15].

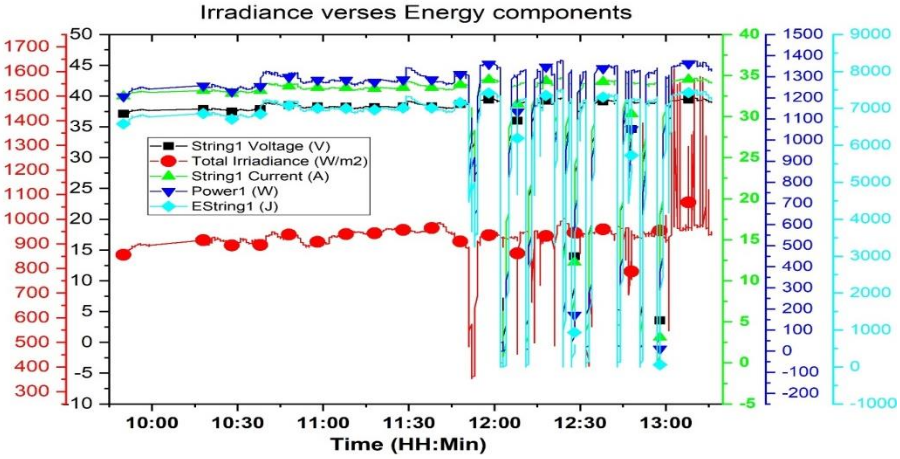


Figure 12: Voltage, Irradiance, current, power and energy as the function of the time (EString1 = energy in string 1)

The causes in the reduction of the system temperatures could be explained by using Figure 12. It could be seen that as the irradiance dropped, also the string voltages and currents dropped. It was observed that the highest string peak power of 1378.38 W was achieved when the voltage, current and irradiance were 39.69 V, 34.73 and 980 W/m^2 respectively. This power was the actual consumed by each of the 3 strings of the PV roasting pan.

The lowest kicking-in parameters found to have an activating effect on the power increase on the PV roasting pan were voltage 0.06 V, current 0.05 A, and irradiance 453.67 W/m2 (Table 4 and Figure 13). The DC/DC converter shut off when the irradiance fell below 453.67 W/m2.

Table 4: Minimum and maximum energy components achieved per string

Minimum kicking parameters		Maximum parameters achieved	
Irradiance (W/m^2)	453.67	Irradiance (W/m^2)	1611.01
Voltage (V)	0.06	Voltage (V)	39.69
Current (A)	0.05	Current (A)	34.73
Power (W)	0.003	Power (W)	1378.38

*This figures represent the average of 3 strings. Total achieved should be multiplied by 3

✓ Total power gained by the PV roasting pan was the sum of 3 strings.

General optimization: energy and temperature components

The general optimization details are highlighted in Table.

Table 5: Optimized parameters for the PV roasting vessel

Factors		**Responses**	
Parameter	Optimum	Parameter	Optimum
Pan surface Temp (ºC)	131.08	Roasting time (Min)	27.74
Irradiance (W/m^2)	826.36	Out-put gari (kg)	1.23
Voltage (V)	32.59	Productivity (kg/hr)	2.79
Current (A)	28.53	Yield (%)	50.60
Power (W)	1068.70	Specific energy capacity (kWh/kg)	1.43
*Supplied energy (kWh)	1.69	*Used Energy (kWh)	0.89
In-put cassava mash (kg)	2.40	Efficiency (%)	53.05

NOTE: *Energy supplied is the total from the 3 strings supply of the heating elements and for the total consumption to roast gari (Energy used)

As expected, greater pan surface temperatures, voltage and current (Power), and high irradiance all resulted in shorter roasting times. The energy efficiency decreased as the pan received more energy and the cassava mash absorbed less energy. This is because efficiency is the ratio of energy utilized to energy supplied.

The highest efficiency of 63.8 % was attained by a batch that received 1.23 kWh PV energy and consumed 0.83 kWh to produce 1.27 kg gari from 2.35 kg cassava mash. The specific energy consumption was 1.02 kWh at a total roasting duration of 21 minutes in line with other reported durations [16–19]. The efficiency range of 41.2 to 63.8 % is within the electrical powered cookers [20–23].

The specific energy consumption is almost 7 times lower than the base line highlighted in the report on Gari processing analysis in Togo, and in agreement with the lab scale optimization analysis carried out at the University of Kassel [24].

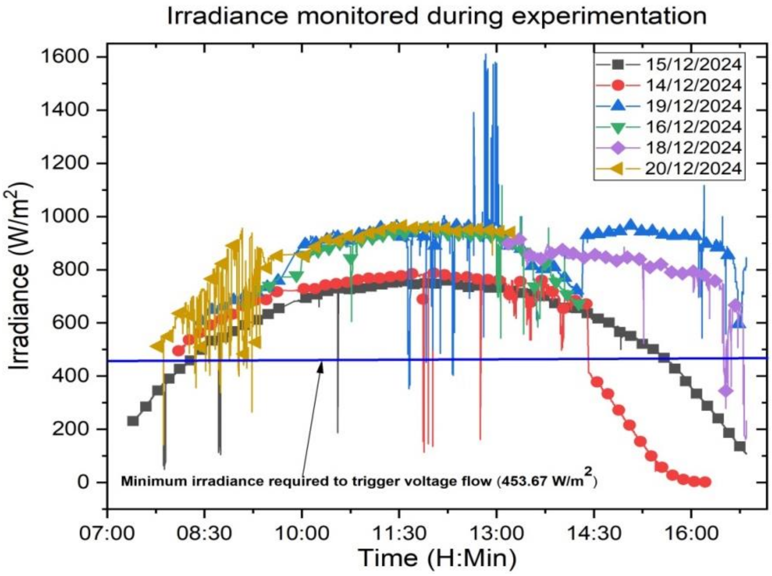


Figure 13: Irradiance for different days in December 2023

Productivity

The maximum and minimum input and outputs achieved were 3.6 to 1.09 kg (cassava mash) and 1.9 to 0.51 kg (gari) respectively. This translated into mean productivity and yield of 2.8 kg hr^{-1} and 51.7 % respectively (Figure 14).

Based on field observations, roasting may commence at 09:00 am and conclude at 15:30 pm (6 hours) at certain instances, as seen in Figure 13. Thus, 7.26 to 24.42 kg of gari each day or around 2,000–6,000 kg annually, might be produced by the PV-powered system.

The PV roasting system has the potential to reduce firewood consumption by 3,000 to 10,000 kg annually, which could result in financial gains and environmental benefits for both the operators and the environment.

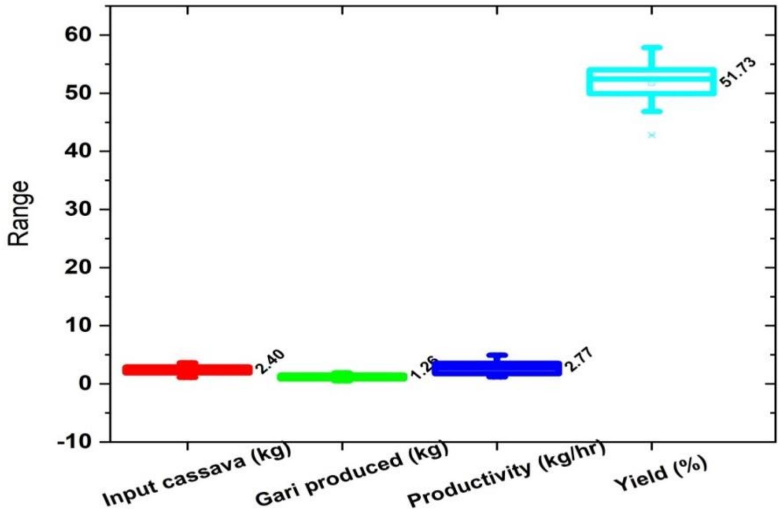


Figure 14: Productivity achieved

Energy required heating the vessel from cold start

When compared to other cooking methods like induction, wood-fuel cookstoves, and gas, electrical elements are linked to slow heating. The primary reason for this is that heat must first be transferred to the element's body before it can be transferred to the cooking surface. A crucial step in determining how much energy an appliance uses for self-heating and how much it loses to the environment is to perform boiling tests (cold and hot start) [22].

Water boiling tests

Cold start: Figure 15 to 17 highlights the cold start results achieved on different days as indicated.

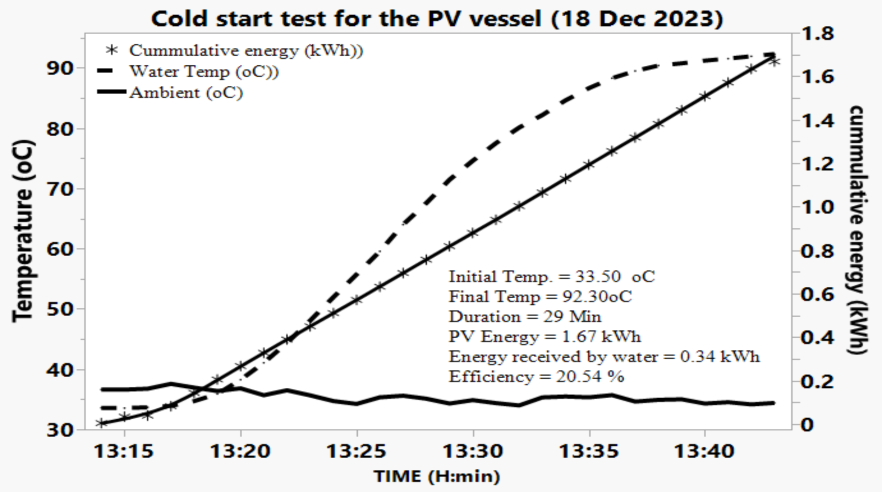


Figure 15: Cold start temperature and energy matrix achieved on 18 December 2023

Table 6 illustrates that the PV-powered roasting vessel required an average of 34.67 minutes to raise the water's temperature from 31.15 to 92.97 ^{o}C, using 1.81 kWh of energy at 3.24 kW power. At 0.36 kWh vessel to water energy absorption rate, the energy transfer efficiency between the PV roasting vessel and the water was 20.14%.

Furthermore, it was observed that at lower irradiance, the time to boil the water was higher as observed in Figure 16 where irradiance was 777.72 W/m^2. This further resulted into higher energy demand (2.08 kWh), higher specific energy consumption (0.42 kWh/kg) but lower power demand of 2.66 kW and low efficiency of 17.23 %. The observation could be attributed to lower energy PV system yield associated with lower irradiance [25].

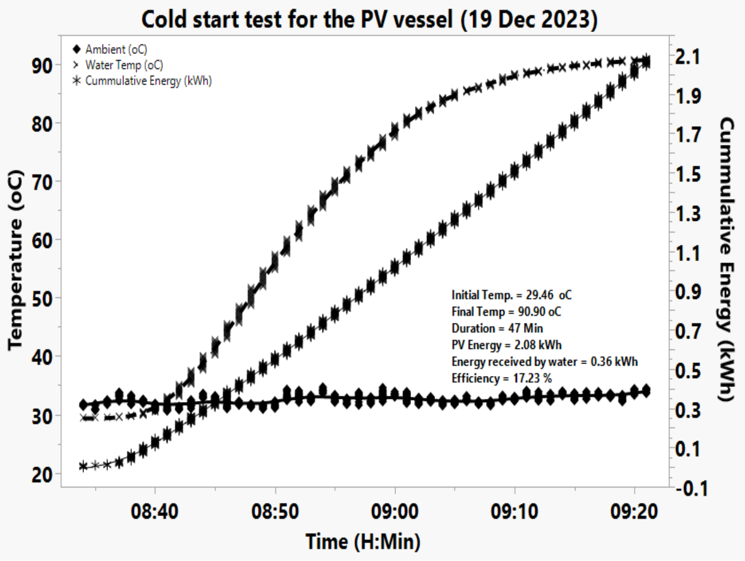


Figure 16: Cold start temperature and energy matrix achieved on 19 December 2023

Hot start: Figure 18 highlights the performance of 8 hot start runs (WB1 to WB8) on 20 December 2023.

On average, it took 17.38 minutes for 5 kg of water to absorb 0.36 kWh energy from the total 1.56 kwh supplied by the PV system translating into 22.89 % energy efficiency. The power achieved was 5.41 kW (0.64 kW/kg specific power capacity) as shown in Table 6.

Table 6: Achieved thermal and energy figures during Cold start

Parameters	Mean	Standard Deviation	Minimum	Maximum
E_{PV} (kWh)	1.81	0.23	1.67	2.08
Time (Min)	34.67	10.69	28.00	47.00
Power (kW)	3.24	0.51	2.66	3.60
Final Temp (ºC)	92.97	2.47	90.90	95.70
Initial Temp (ºC)	31.15	2.10	29.46	33.50
Energy gained by the water (kWh)	0.36	0.02	0.34	0.38
E_{losses} and E_{vessel} (kWh)	1.45	0.24	1.30	1.72
Efficiency (%)	20.14	2.73	17.23	22.64
irradiance (W/m^2)	891.72	98.90	777.72	954.64

Cold start V Hot start

Generally, the efficiency of hot start boiling tests was 2.75 % higher than the cold start. Lower efficiency of around 22 % of all the runs could be attributed to the lower quantity of water (5Kg) used. Efficiency is said to increase with increased volume of medium been cooked [22].

To warm the water almost to the same temperature as the hot start, the cold start runs consumed 99.5 % more time, resulting into 70 % less power. This could be attributed to the fact that energy supplied by the PV system to the heaters goes to heat the vessel body first and then get absorbed by the water, while some is lost to the environment. As the duration of heating water to 90 degrees increased, the energy losses and energy consumed by the vessel body remain approximately constant [22].

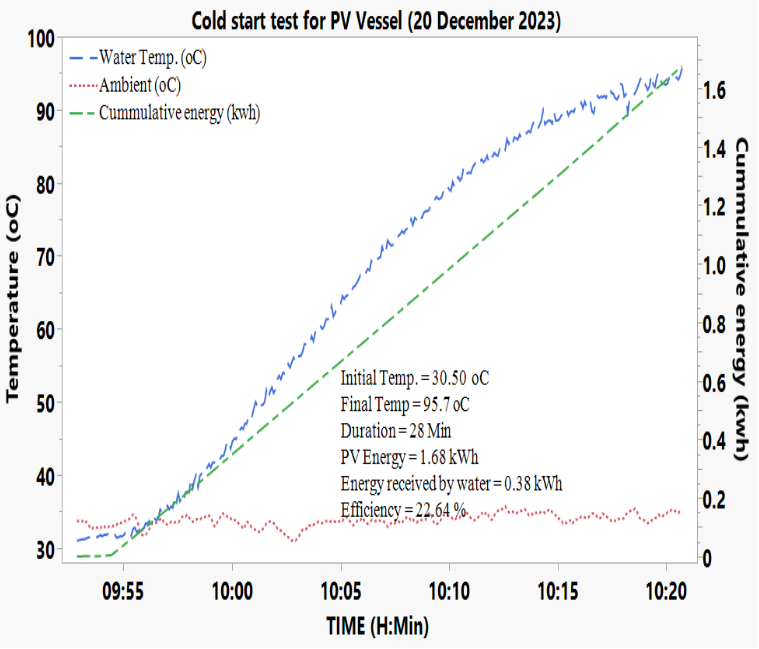


Figure 17: Cold start temperature and energy matrix achieved on 20 December 2023

As can be seen from Table 5 and Table 6, the temperatures (final and initial), energy gained by the water and irradiance were not significantly different. However, the time, energy, power and efficiency was significantly different.

Table 7: Hot start achieved thermal and energy figures

Parameters	Mean	Standard Deviation	Min	Max
PV Energy Supplied (kWh)	1.56	0.08	1.46	1.72
Time (Min)	17.38	1.69	16.00	21.00
Power (kW)	5.41	0.42	4.48	5.72
Final Temp (°C)	92.15	1.40	90.80	94.40
Initial Temp (°C)	31.18	0.42	30.60	31.70
Actual Energy gained by the water (kWh)	0.36	0.01	0.34	0.37
E_{Losses} and E_{vessel} (kWh)	1.17	0.05	1.16	1.25
Efficiency (%)	22.89	1.22	20.54	24.66
irradiance (W/m^2)	948.77	14.22	917.49	957.71

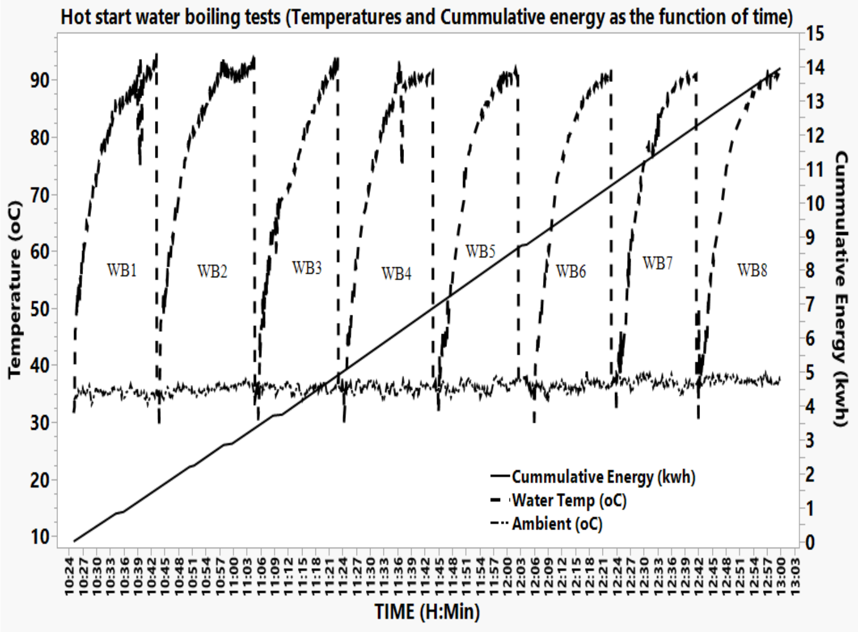


Figure 18: Representative Runs for hot start temperature and energy matrix achieved on 20 December 2023

Scheffler Steam powered roasting pan

Figure 19 highlights the thermal performance of the direct steam roasting vessel. The average Scheffler temperatures monitored were almost 3 times higher than the steam. In some instances as shown in Figure 19 label E to F, the water temperature was observed to be more than the pan surface temperature.

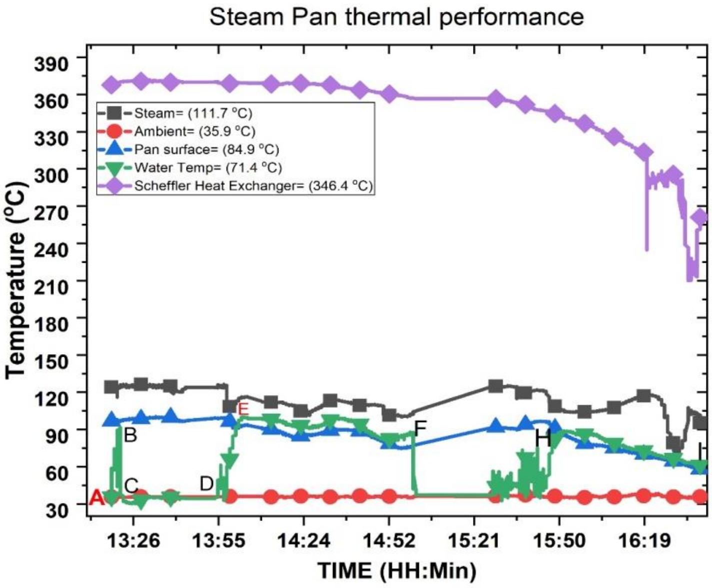


Figure 19: Temperatures on Scheffler steam roasting vessel

This may be explained by the fact that heat moves from the hotter materials in the steam to the cooler material (the roasting pot). The steam condenses as the energy is absorbed by the roasting vessel's surface as it transfers its latent heat there. At times a thin layer of vapor forms between the condensed water and the hot surface of the vessel and acts as an insulator. It could be also possible that the condensed water in the steam chamber was more than required and insulated the system [26–28].

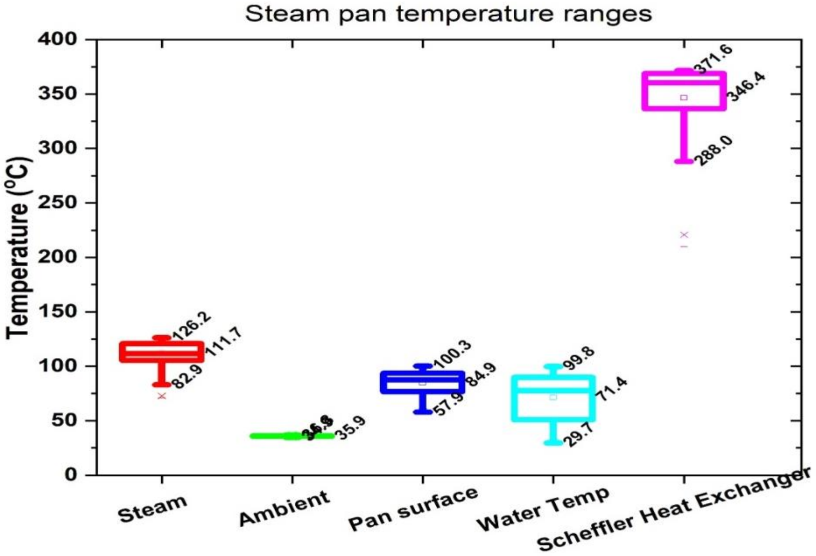


Figure 20: Steam roasting vessel performance

Training and capacity building

Students, some members of partner cooperatives and members of staff where trained on how to operate the equipment and basic maintenance.

Figure 21: Inducting the CEO of Atelier Associatif Experience 07 from Anfoin Togo, one of the local gari equipment manufacturers on the technical operation of the SunGari vessels

Members of the partner cooperatives and manufacturers have expressed interests in adopting this technology in Togo.

Impact and benefits

Scientific and technological impact

- **Impact of science and technology:** Advancement in Renewable Energy: By utilizing solar PV technology in the cooking process, this innovation demonstrates its adaptability and lays the groundwork for further studies in sustainable cooking.
- **Increase in efficiency and storage**: The technology makes improvements in energy storage and photovoltaic efficiency, which are beneficial for other solar applications with high demand.
- **Catalyst for Research:** This service is unique and promotes more research into sustainable cooking services.

Economical and societal impacts

- **Fuel cost savings**: Reduces reliance on costly fuels such as gas, saving money for households, particularly in low-income or off-grid locations. Health and environmental benefits include lower indoor air pollution from traditional fuels, which improves health and quality of life.
- **Health and environmental benefits:** Reduces interior air pollution caused by traditional fuels, thus enhancing health and quality of life. This technology have the capacity to save carbon emissions and deforestation associated with the use of woodfuel.
- **Job creation:** Provides opportunities for installation and maintenance, hence boosting local economies.
- **Energy independence:** Reduces dependency on woodfuel and imported fuels, increasing environmentally friendly energy consumption.

Future Applications

The University of Kassel is investigating the potential of utilizing an inexpensive heating silicon pad to generate high temperatures for cooking, roasting, processing honey, and making popcorn. The technology's potential for the future are as follows:

- **Smart grids and hybrid systems:** Microgrids integration of PV cooking can aid in energy load balancing.
- **Expansion to other household and food processing needs:** facilitates the transition to totally solar-powered households by readily adapting to other high-energy

appliances, such as water heaters. It could also be used to decarbonize the honey processing sector in Africa that mainly depends on firewood.

- **Emergency and remote applications:** Provides off-grid cooking in disaster or isolated areas where fuel is scarce.
- **Regional customization**: It easily adapts to many climates and cultural needs, making it feasible globally.

Conclusion

This innovation, which develops solar-powered cooking services, is a significant step forward in sustainable energy solutions for cottage to small-scale industrial processes. Being the first to use solar technology in the production of staple foods, this initiative shows how renewable energy may revolutionize conventional processing techniques and provide a robust, cost-effective, and clean substitute for fossil fuels and hard to source woodfuel. As a ground-breaking application in food processing, the incorporation of a Life Cycle Sustainability Assessment (LCSA) as a baseline survey further demonstrates this project's dedication to sustainability and makes it possible to fully comprehend the social, economic, and environmental effects of staple food production.

The solar cooking service lowers operating costs for processors and increases their resilience by substituting renewable energy sources for non-renewable ones, thereby supporting SDG 7 (Affordable and Clean Energy), which is in line with several other Sustainable Development Goals (SDGs) of the UN [29]. Additionally, it satisfies SDG 3 (Good Health and Well-Being) by lowering air pollution from conventional fuels, which benefits local communities and employees alike. SDGs 1 (No Poverty) and 8 (Decent Work and Economic Growth) are supported by the financial savings provided by solar energy, which also advances SDG 12 (Responsible Consumption and Production) by guaranteeing sustainable resource usage.

Beyond its immediate effects, this project lays the groundwork for expanding the use of solar energy in a variety of small-scale sectors, such as food production and other vital energy-intensive processes. It has the potential to assist SDG 11 (Sustainable Cities and Communities), strengthen local economies, particularly in isolated or energy-constrained places, and promote resilient, sustainable growth.

This project demonstrates solar energy’s revolutionary significance in small-scale industries, setting a precedent for sustainable industrial practices and contributing to a more equitable, clean-energy future. Continued investment and innovation in this field will magnify its good effects, allowing more communities to thrive sustainably.

Financial issues

All expenses where used according the proposal and have been necessary to reach the aim of the research work. Main costs resulted from staff salary, other expenses have been spent to buy material for experimental work. Travel was necessary to do the field tests as described in the proposal.

Publications

[1] M. C. Mwape, A. Parmar, F. Roman, Y. O. Azouma, N. M. Emmambux, and O. Hensel, "Determination and Modeling of Proximate and Thermal Properties of De-Watered Cassava Mash (Manihot esculenta Crantz) and Gari (Gelatinized cassava mash) Traditionally Processed (In Situ) in Togo," *Energies 2023, Vol. 16, Page 6836*, vol. 16, no. 19, p. 6836, Sep. 2023, doi: 10.3390/EN16196836.

Tropentag conference

[2] M. C. Mwape *et al.*, "Evaluation of Temperature and Energy Requirements for Gari Processing at standard quality parameters in Togo," *Tropentag*, 2023, Accessed: Feb. 12, 2024. [Online]. Available: https://www.tropentag.de/2023/abstracts/posters/420.pdf

Under review

M. C. Mwape, A. Parmar, F. Roman, N. M. Emmambux, and O. Hensel,Modeling and Optimization of Energy Efficiency and Product Quality in Staple Food Roasting: A Case Study on Cassava Processing Manuscript Number: TSEP-D-24-02641

To be submitted

M. C. Mwape, A. Parmar, F. Roman, Y. O. Azouma, N. M. Emmambux, and O. Hensel, "Life Cycle Sustainability Assessment of Staple Food Processing: Integrating Material and Energy Flow Analysis, Double and Dynamic Materiality with Python Computational Modeling,"

References

[1] S. Reyniers, N. De Brier, K. Brijs, B. De Ketelaere, W. Akkermans, S. Matthijs, J.A. Delcour, P. Goos, I-optimal design of split-plot mixture-process variable experiments: A case study on potato crisps, Food Qual. Prefer. 101 (2022) 104620. https://doi.org/10.1016/J.FOODQUAL.2022.104620.

[2] F. Mansouri, A. Allay, A. Ben Moumen, C. Benkirane, Y. Taaifi, K. Belhaj, M. Addi, C. Hano, M.L. Fauconnier, H.S. Caid, A. Elamrani, Laboratory-Scale Optimization of Hemp Seed Roasting Temperature and Time for Producing a High-Quality Pressed Oil, J. Food Process. Preserv. 2023 (2023). https://doi.org/10.1155/2023/8261279.

[3] M. Özdemir, O. Devres, Analysis of color development during roasting of hazelnuts using response surface methodology, J. Food Eng. 45 (2000) 17–24. https://doi.org/10.1016/S0260-8774(00)00036-4.

[4] S. Sun, G. Li, H. Chen, Y. Guo, J. Wang, Q. Huang, W. Hu, Optimization of support vector regression model based on outlier detection methods for predicting electricity consumption of a public building WSHP system, Energy Build. 151 (2017) 35–44. https://doi.org/10.1016/J.ENBUILD.2017.06.056.

[5] Y. Wang, Y. Zhang, F. Zhang, J. Yi, Robust quadratic regression and its application to energy-growth consumption problem, Math. Probl. Eng. 2013 (2013). https://doi.org/10.1155/2013/210510.

[6] J. Luo, T. Hong, S.C. Fang, Robust Regression Models for Load Forecasting, IEEE Trans. Smart Grid 10 (2018) 5397–5404. https://doi.org/10.1109/TSG.2018.2881562.

[7] R.K. Raigar, R. Upadhyay, H.N. Mishra, Optimization of microwave roasting of peanuts and evaluation of its physicochemical and sensory attributes, J. Food Sci. Technol. 54 (2017) 2145–2155. https://doi.org/10.1007/S13197-017-2654-0/FIGURES/3.

[8] T. Nurkhoeriyati, B. Kulig, B. Sturm, O. Hensel, The Effect of Pre-Drying Treatment and Drying Conditions on Quality and Energy Consumption of Hot Air-Dried Celeriac Slices: Optimisation, Foods 2021, Vol. 10, Page 1758 10 (2021) 1758. https://doi.org/10.3390/FOODS10081758.

[9] R. Akinoso, W.O. Kasali, Energy Expended in Processing Gari (Cassava Flakes) Manihot esculenta Crantz, Using Three Levels of Mechanization, Pakistan J. Sci. Ind. Res. Ser. B Biol. Sci. 55 (2012) 114–116. https://doi.org/10.52763/pjsir.biol.sci.55.2.2012.114.116.

[10] A. Bouniol, L. Adinsi, F. Hotegni, A. Delpech, N. Akissoé, G. Fliedel, T. Tran, D. Dufour, Assessment of the processing ability of improved cassava varieties into a traditional food product (Gari) in Benin, (2020).

[11] A. Bouniol, H. Ceballos, A. Bello, B. Teeken, D.O. Olaosebikan, D. Owoade, A. Afolabi, A. Fotso Kuate, T. Madu, B. Okoye, M. Ofoeze, S. Nwafor, N. Onyemauwa, L. Adinsi, L. Forsythe, D. Dufour, Varietal impact on women’s labour, workload and related drudgery in processing root, tuber and banana crops: focus on cassava in sub-

Saharan Africa, J. Sci. Food Agric. 104 (2024) 4498–4513. https://doi.org/10.1002/JSFA.12936.

[12] R.J. Sorita, A Guide to Bean Temperature & The Coffee Roasting Curve - Perfect Daily Grind, Perfect Dly. Grind (2020). https://perfectdailygrind.com/2020/02/bean-temperature-the-coffee-roasting-curve-and-roast-graph/ (accessed March 7, 2024).

[13] M. Enrique, Explaining The Importance Of Roast Curves For Coffee Roasters, MTPAK COFFEE (2023). https://mtpak.coffee/2020/12/explaining-roast-curves-coffee-roasters/ (accessed March 7, 2024).

[14] L.L. Pereira, D.G. Debona, P.F. Pinheiro, G.F. de Oliveira, C.S. ten Caten, V. Moksunova, A. V. Kopanina, I.I. Vlasova, A.I. Talskikh, H. Yamamoto, Roasting Process, Food Eng. Ser. (2021) 303–372. https://doi.org/10.1007/978-3-030-54437-9_7/FIGURES/59.

[15] World Bank, Global Solar Atlas, ESMAP (2024). https://globalsolaratlas.info/map?c=6.008776,0.480652,9&s=6.130419,1.215829&m=site (accessed March 8, 2024).

[16] S. Sobowale, S. Awonorin, T. Shittu, E. Ajisegiri, O. Adebo, O. Olatidoye, Modeling of the Garification Process of Fermented Cassava Mash, J. Bioprocess. Biotech. 07 (2017). https://doi.org/10.4172/2155-9821.1000311.

[17] A. Bechoff, K.I. Tomlins, U. Chijioke, P. Ilona, B. Bennett, A. Westby, E. Boy, Variability in traditional processing of gari: a major food security product from cassava, Food Chain 8:1 (2019) 39–57. https://doi.org/10.3362/2046-1887.18-00015.

[18] S.A. Adegbite, W.B. Asiru, M.O. Salami, C.F. Nwaeche, K.K. Ebun, A.A. Ogunbiyi, Design and Development of Power Driven Gari Fryer, J. Eng. Res. Reports 4 (2019) 1–15. https://doi.org/10.9734/JERR/2019/v4i216898.

[19] S.. Ejiko, D. Oigbochie, A.. Emmanual, Design of A Semi Mechanize Gari Fryer, IOSR J. Mech. Civ. Eng. e-ISSN 15 (2018) 23–30. https://doi.org/10.9790/1684-1502042330.

[20] M. Dupuis, H. Jun, Energy saving from a reduction pot, 2012. https://www.researchgate.net/publication/298352314.

[21] H.C. Liu, Y.L. Chang, C.W. Lin, Y.Y. Chen, C.W. Lin, Y.C. Lin, M.S. Huang, H.Y. Hsu, Experimental and numerical multidisciplinary methodology to investigate the thermal efficiency of boiling pot on induction system, Case Stud. Therm. Eng. 36 (2022) 102199. https://doi.org/10.1016/J.CSITE.2022.102199.

[22] H.R. Rose, R.O. Morawicki, Comparison of the energy consumption of five tabletop electric cooking appliances, Energy Effic. 16 (2023) 1–10. https://doi.org/10.1007/S12053-023-10181-X/FIGURES/6.

[23] J.A. Mathias, K.M. Juenger, J.J. Horton, Advances in the energy efficiency of residential appliances in the US: A review, Energy Effic. 16 (2023) 1–21. https://doi.org/10.1007/S12053-023-10114-8/TABLES/3.

[24] M.C. Mwape, A. Parmar, F. Roman, N. Emmambux, O.Y. Azouma, O. Hensel, Material and Energy Flow Analysis of Cassava (Manihot Esculenta Crantz) Processing Techniques to Gari (Gelatinized Cassava Mash), (2023). https://doi.org/10.2139/SSRN.4671240.

[25] F. Mavromatakis, F. Vignola, B. Marion, Low irradiance losses of photovoltaic modules, Sol. Energy 157 (2017) 496–506. https://doi.org/10.1016/J.SOLENER.2017.08.062.

[26] J.P.J. Oule, VIII. On the surface-condensation of steam, Philos. Trans. R. Soc. London 151 (1861) 133–160. https://doi.org/10.1098/RSTL.1861.0009.

[27] K.S. Liang, Peter-Griffith, Experimental and analytical study of direct contact condensation of steam in water, Nucl. Eng. Des. 147 (1994) 425–435. https://doi.org/10.1016/0029-5493(94)90225-9.

[28] E. Mura, P. Massoli, C. Josset, K. Loubar, J. Bellettre, Study of the micro-explosion temperature of water in oil emulsion droplets during the Leidenfrost effect, Exp. Therm. Fluid Sci. 43 (2012) 63–70. https://doi.org/10.1016/J.EXPTHERMFLUSCI.2012.03.027.

[29] UN, THE 17 GOALS | Sustainable Development, (2020). https://sdgs.un.org/goals (accessed January 19, 2021).

Photos

Figure 22: Cassava harvesting- Coopérative des femmes NOVIVA de Tokpo

Figure 23: Cassava peeling Agro Pastoral (Ganave)

Figure 24: Cassava grating

Figure 25: Cassava mash fermentation Coopérative des femmes NOVIVA de Tokpo

Figure 26: Cassava mash de-watering Adamah TETEVI-(Individual processor in Ganave)

Figure 27: Breaking and sieving of cassava mash cake Coopérative d'Action pour le Développement (CAD) de (Wogba, Vagan)

Figure 28; cassava mash roasting Coopérative des femmes NOVIVA de Tokpo

Figure 29: Gari sieving (Grading) and packaging Coopérative des femmes NOVIVA de Tokpo