*Science Journal of Energy Engineering*
2024, Vol. 12, No. 4, pp. 67-80
https://doi.org/10.11648/j.sjee.20241204.11

Research Article

# A New Approach to Integrating Renewable Energies in the Design of a Shea Kernel Solar Mill

**Yamako Soungalo Soulama[1, *], Frederic Bationo[2], Tchamye Tcha-Esso Boroze[1]**

[1]Department of Rural Engineering and Agricultural Machinery, University of Lome, Lome, Togo
[2]Institute for Research in Applied Sciences and Technologies, National Center for Scientific and Technological Research, Ouagadougou, Burkina Faso

## Abstract

The development of the agri-food sector in West African countries is limited by energy and technological factors. As a result, the main shea nut producers in these countries, Burkina Faso, Nigeria and Mali, export their production to the benefit of large industries in northern countries. One of the most difficult operations involved in transforming shea nuts into shea butter is grinding. Processing shea kernels into shea butter requires a mill or grinder. The types of energy (diesel and electricity) used by these mills are fossil-based, difficult to access and pose huge environmental issues. The objective of this work is to design a mill, operating with photovoltaic solar energy as an energy source, in a design approach using design rules and industrial engineering tools. To this end, a survey on the practices of the networks of agri-food equipment stakeholders on the use of renewable energy and the characterization of the network of solar mill stakeholders were carried out. The results of the surveys and the network characterization of the stakeholders, combined with those of the literature review, made it possible to define rules for integrating renewable energy into the design of the solar mill. The use of functional analysis and a tool to help choose energy-efficient technological solutions enabled to apply the rules for integrating renewable energy into the design of the shea kernel solar mill for validation purpose. The results of the functional tests of the solar mill showed a production capacity of 270 Kg of shea kernel paste, a solar energy consumption of 11,532 kWh equivalent to an energy consumption of 1.82 USD in 6 hours operational time per day.

## Keywords

Agri-Food Equipment Design, Solar Mill, Socio-Technical Network, Solar Energy, Shea Butter, West Africa

## 1. Introduction

According to the World Bank report, West African Countries (WAC) have the lowest access rate to electricity in the world in 2022, estimated at 42% for the general population and only 8% for the rural population. On average, these countries experience power outages of up to 80 hours per month [1]. This factor is a hindrance to the development of the agri-food industry, as all activities require the use of energy [2]. The West African agri-food industry is faced with a lack of access to energy-appropriate, affordable and climate-resilient equipment.

Burkina Faso is one of Africa's largest producers of shea kernels with approximately 190 million shea trees [3] and only

*Corresponding author: soulamayamako@gmail.com (Yamako Soungalo Soulama)

**Received:** 10 September 2024; **Accepted:** 8 October 2024; **Published:** 22 November 2024

processes 8% of its production. This low processing rate is linked to the limited availability of energy-efficient equipment, especially in the case of widespread equipment such as the shea kernel mills [4]. The mills run on diesel or electricity from thermal power plants, which are polluting and expensive energy sources. Indeed, shea butter which is widely consumed around the world is obtained according to the following stages of processing shea kernels: drying, crushing, roasting, grinding, churning or pressing, etc. [5]. It is used in several fields including the food industry, the cosmetic industry, medicine and has great economic potential. Its production is energy-intensive and consumes enormous quantities of wood energy [5, 6]. Processing 100 kg of fresh shea kernel requires 28.34 kg of wood, corresponding to 0.0045 ha of deforested forest cover and results in average carbon dioxide emission from wood combustion of 46.8 kgeq $CO_2$ [7]. In addition to wood energy consumption, crushing and grinding operations use electric motors from 5.5 to 7.5 KW or 10 to 22 hp diesel engines [4]. Grinding is a step usually present in several agri-food transforming processes for oilseeds as well as cereals, which is why we will use it as an application case to provide solutions to these constraints. Several design tools in response to the problem of equipment design in West Africa have been the subject of many works based on the analysis of the needs of the African socio-technical and socio-economic context. Examples include the design method in southern countries, CESAM method, the integration of manufacturing and maintenance in the design of agri-food equipment the inclusion of the socio-technical networks of maintenance and the application of specific maintenance-oriented design rules in the design of equipment the integration of industrial engineering tools in the optimization of the design of dryers for agri-food products in tropical climates, and the proposal for an Eco-design approach to agri-food equipment [8-11] etc. All these works have helped to integrate the socio-economic environment into the design of WACs, but energy issues have not been sufficiently addressed, especially with respect to Renewable Energy (RE). As for the energy issue, a number of studies have provided technical and organizational solutions for improving the energy efficiency of production processes in agri-food processing industries. In particular, wood energy is replaced by biomass briquettes from food and agricultural production waste, fossil energy is replaced by photovoltaic (PV) solar energy for the operation of agri-food equipment, the multi-criteria analysis tool for choosing energy-saving technological solutions (ASTEE), the promotion of solar mills, imported from Europe or Asia [13-15]. However, not all these approaches include the stakeholders of the socio-technical networks of local Agri-food Equipment (AE) manufacturers [10]. In fact, these stakeholders ensure maintenance and technical monitoring of the equipment and they facilitate the appropriation of agri-food technology by the beneficiaries. For instance, it appears that the promotion of imported solar mills in WACs is limited by the appropriation of the technology by agri-food units.

In order to help meet the various technological, energy and transfer constraints of agri-food technologies in West Africa, this study aims at proposing a design approach for the network which can take into account the technical and human environment, the stakeholders of the socio-technical networks of renewable energies (RESN). This approach will make available energy-efficient and climate-resilient equipment for the benefit of small agri-food units in Burkina Faso and West Africa.

## 2. Methodology

### 2.1. Development of Rules for Integrating RE into the Design of the Solar Mill

Surveys carried out among stakeholders composed of Agri-food Equipment Manufacturers (AEM), AE Users of Agri-food Equipment (UAE) and Renewable Energy Service Providers (RESP) in two WACs, Burkina Faso and Togo, shed light on the constraints limiting the integration of RE in the design of AE in WACs. These constraints have an impact on the quality of WAC shea butter production. [5]. The analysis of these constraints led to the characterization of the environment of the network of shea kernel solar mill stakeholders. This approach made it possible to define the socio-technical network of the solar mill with the practices which allowed for the development of the rules for integrating RE into the design of the solar mill. This approach is consistent with that of which defined the rules for integrating maintenance into the design of AEs based on the practices of socio-technical maintenance networks (DFMsn) [14].

### 2.2. Socio-Technical Network Concept

The network approach is defined as a method of description and inductive modelling of a relational structure between a group of stakeholders [16]. It is used in an empirical approach to characterize the social and technical environment of the stakeholders of an innovator network or any other organization. The social network is a set of relationships based on social and technical links (trust, support, technical advice, etc.) between a group of stakeholders. Its analysis highlights the types of repetitive relationships that govern the structure of a social organization [16]. The design rules for the socio-technical network of renewable energies (RESN), is the proposal of the social and technical capital of the socio-technical networks of RE, as a tool for integrating RE into the design of AEs. This approach is in agreement with those of who developed a tool for integrating maintenance into the design of AEs [15, 16].

### 2.3. Modelling the Network of RE Stakeholders

The practices of the stakeholders of the solar mill, coupled with the documentary review, made it possible to model the exchanges between the stakeholders of the RE network. Table

1 Below shows the modelling of exchanges between network stakeholders. This model is used here to characterize the specific and technical environment of renewable energy stakeholders. We call it the "Socio-technical Network of Renewable Energies RESN" [16].

***Table 1.*** *Modelling model of the socio-technical network of AEs RE stakeholders.*

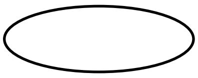
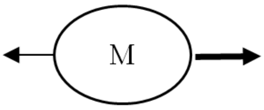
| Symbol | Meaning |
|---|---|
|  | Represents agri-food equipment |
|  | Represents agri-food equipment, a stakeholder |
|  | The letter represents the flow of exchange between the actors. M=work material, S=Specific parts, C=component, T=Technology, E=Equipment. The thickness of the arrows shows the frequency of exchanges, more frequent 1 to months, less frequent 3 to 6 months. |
|  | Intervention on equipment. The thicknesses have the same meaning as that of the flows of exchanges between stakeholders. |

Table 1, shows the modelling figures of the RE stakeholders of the AEs. This modelling presents the EAs, the stakeholders, the nature of exchange flows in social and technical capital and the frequencies of exchanges. It was used to characterize the network of solar mill stakeholders. This approach to characterizing the environment of the RE stakeholders of the solar mill, is in line with that of the socio-technical network of AEs maintenance of [10].

***Table 2.*** *Network stakeholders and their role.*

| Network stakeholders | Roles |
|---|---|
| Welding workshop with 3 mill manufacturer welders (AEM) | Participating in the manufacturing of the shea kernel mill, installations and functionality tests. Ensuring mechanical maintenance |
| A company (Africa solar) supplying and installing photovoltaic solar energy equipment, the team of which is made up of 2 solar engineers and 3 solar equipment installer technicians (RESP) | Participating in the sizing of the PV solar energy generator and installation. It ensures the maintenance of PV solar energy production equipment. |
| A research center for appropriate technologies and renewable energies, Albert Schweitzer Ecological Center (CEAS Burkina) NGO with a team of 2 engineers in RE, 2 mechanical engineers, 2 in industrial engineering and 5 qualified workers holders of a Vocational certificate. | Responsible for research, planning and execution. The design and integration of renewable energies RE was carried out by its team. |
| Garango Women's Union *UFG* | Requester for the solar mill from the NGO CEAS Burkina. Carrier of the shea butter production unit. It is in charge of operating the solar mill. |
| Sellers of work materials, components, specific parts | Sale of manufacturing materials, mechanical and specific parts. |
| Shops selling photovoltaic (PV) solar energy equipment | Sale of RE renewable energy equipment and components |

Table 2, presents the stakeholders of the shea kernel solar mill network. The practices of these stakeholders, the flows of exchanges between the members of the network (from the design to the use of the solar mill) were modelled to present the socio-technical network of RE of the shea almond solar mill. The network's practices have been developed into rules for integrating RE into the design of AEs.

## 2.4. Calculation Formulas and Sizing

***Table 3.*** *Sizing formulas for PV solar components and equipment.*

| N ° | Calculation elements | Formulas, calculation method and comment |
|---|---|---|
| 1 | Determination of daily energy needs (Bej) | $Ej = \sum Pu * Nbr * dt$<br>Ej= Daily energy consumption in (Kwh/j)<br>Pu: Unit power in (W)<br>Nbre: Number of devices<br>dt: Daily usage time in hours<br>It will make it possible to calculate the mill daily photovoltaic solar energy need. This calculation method is consistent with that used by to size a medium power PV solar installation [17]. |
| 2 | Calculation of the average solar energy of the area | The sunshine data are expressed in KWh/m ²/d. They can be recorded on site. Software can be used to calculate the values on the inclined plane. In Burkina Faso, the average solar irradiation is estimated at 5.5 kWh/m$^2$/day according to [2] |
| 3 | Step Calculation of the PV generator power | $Pg = \frac{Et}{k \times Ens}$<br>Pg: Peak power (Wc)<br>And: Total energy consumed<br>K: Correction factor (it depends on the efficiency of the equipment used such as an inverter, regulator, batteries)<br>Ens: Sunshine (kWh/m$^2$/Day).<br>This calculation method is in agreement with the methods of [17] to size a medium-power PV solar installation and lighting system. |
| 4 | Calculation of storage capacity | The formula for the work of [3] used in the sizing of a hybrid PV electrification system was used to calculate the storage capacity.<br>$C_{Bat} = \frac{E_{Tot} \times J_{Aut}}{DOD_{max} \times V_{Bat}}$<br>$C_{Bat}$: Battery Capacity<br>$E_{Tot}$: Total energy<br>$J_{Aut}$: Autonomy day<br>$DOD_{max}$: Discharge depth<br>$V_{Bat}$: Battery voltage<br>The formula will be used to calculate the supply batteries of the equipment, the inverters, the bulbs and the lighting, because the mill will operate according to the daily sunshine. |
| 5 | Choice of inverters | Inverters convert direct current into alternating current [17]. The calculation method is the same as that used by [17] to size a medium-power PV solar installation.<br>$P_{Ond} = P_{max} + 10\% P_{max}$<br>$P_{Ond}$: Inverter power<br>$P_{max}$: Maximum power of all equipment |
| 6 | Production of PV solar energy | Monthly energy production = GHI × A × Dm × η<br>GHI: Monthly average solar irradiation (kWh/m$^2$/day);<br>A: Surface area of the PV panel (m$^2$);<br>Dm: Number of days in a month (30 days);<br>$\eta$PV: PV conversion efficiency<br>This is the method used by to evaluate the economic profitability of a PV electrification system. It will be used to calculate the production of PV energy [3]. |

The formulas in Table 3 were used to size and calculate the energy needs of PV solar energy components and equipment in the application of the rules for integrating RE into the design of the solar mill.

### 2.5. AF Tools in the Design of the Shea Kernel Solar Mill

We used the tools of external functional analysis (horned beast and octopus) to define the different functions (main and constraint) and draw up the Functional Specifications (CDCF) of the solar mill. These enabled to carry out the technical functional analysis and to develop the Technical Function and System Analysis diagram (FAST) of the solar mill. The FAST diagram made it possible to define the functions of services, techniques and technological solutions. From the FAST, a new technical function has been added to the operation of the mill, to allow the use of an asynchronous motor with an energy requirement compliant with the solar mill CDCF. The CDCF and FAST were used, on the one hand, to filter the rules for integrating RE into the design of the shea kernel solar mill and, on the other hand, to apply these rules through the choice of operating principles and the sizing of mechanical, electrical, ER components, etc.

### 2.6. Functionality Test of the Solar Shea Kernel Mill

A protocol for producing shea butter paste with the solar mill has been developed. The production parameters collected are the different weights of the shea kernels (crushed and roasted), the paste obtained, the solar PV energy consumed and the grinding time was timed. The shea kernels (Vitellaria paradoxa) were crushed and roasted before grinding. The paste obtained followed the shea butter production process by churning to certify the proper operation of the solar mill in order to validate the rules for integrating RE. This process of transforming shea kernels into shea butter is in line with that applied during the study on shea butter production processes in Burkina Faso [4].

## 3. Results and Discussions

### 3.1. The Socio-technical Network of RE of the Solar Mill

Based on the modelling tools presented in Table 1 the socio-technical RE network of the shea kernel solar mill was modelled. We started from the ordinary mill network by integrating RE stakeholders into this network [14]. Figure 1 shows the socio-technical renewable energy network of the solar mill.

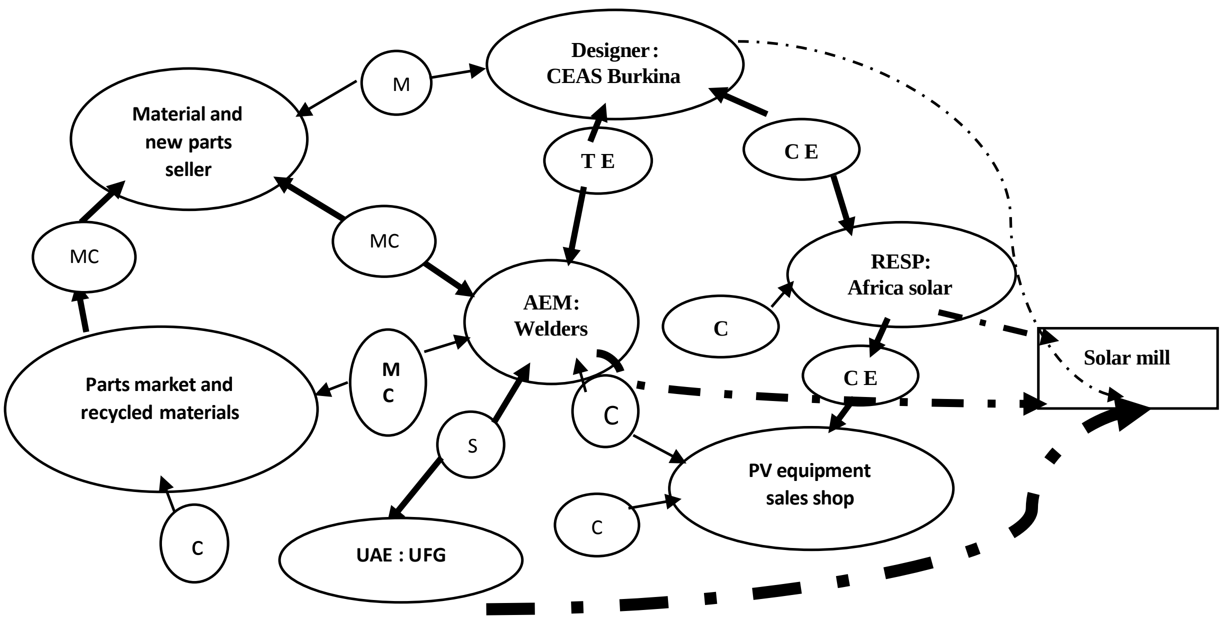



***Figure 1.*** *Socio-technical network of renewable energies of the shea kernel solar mill.*

Figure 1 shows that the solar mill was designed and manufactured by the NGO Albert Schweitzer Ecological Center of Burkina (CEAS Burkina) through the RESN. It ordered an ordinary shea kernel mill from an AE manufacturing workshop (welders). In addition, CEAS Burkina worked on the mill by integrating new technical functions to operate the mill with solar PV energy. To do this, it requested the expertise of Africa Solar for the supply of PV solar energy components and equipment (CE). All stakeholders were involved in the installation of the solar mill by collaborating in a complementary way. Users frequently intervene on the solar mill for their shea butter production operations. If necessary, they call on Africa Solar welders or technicians depending on whether the breakdown is mechanical or electrical. During operation, CEAS Burkina intervenes less on the solar mill. The solar mill technology is transferred to local AEMs and the RESPs through training. The RESP works between local AEMs to promote solar mills. This socio-technical network approach allows innovators (artisans) to create and accumulate resources in the form of social capital, which will make it possible to innovate the solar mill with the view responding to new technological and energy constraints. This RESN result of the solar mill is in line with the socio-technical network concept of [15]. The RESN model is in agreement with that of [14] relating to the socio-technical networks of AE maintenance in West Africa. The difference between these two networks is the inclusion of new RE stakeholders, who are essential for the maintenance of the solar PV production equipment. The equipment belongs to an RESN family which maintains social and technical links (manufacturing, use, maintenance, exchanges based on trust, etc.) for the production of shea butter with a mill that runs on solar PV energy. The characterization of the practices of the RESN stakeholders of the added solar mill, the use of AF and the multi-criteria analysis tool for choosing energy-saving technological solutions (ASTEE), made it possible to develop and apply the rules for integrating RE into the design of the solar kernel mill. The results achieved are consistent with those of during the design of the mill with the socio-technical network approach to maintenance [15]. The RESN in figure 1 constitutes the design and operational team of the solar shea kernel mill.

## 3.2. Functional Analysis (AF)

1. CDCF functional specifications for the shea kernel solar mill

The horn beast tools and octopus diagram were used to draw up the CDCF. Analysis of each factor in the mill's operating environment led to the definition of the main functions and constraints. The octopus diagram shown in Figure 2.

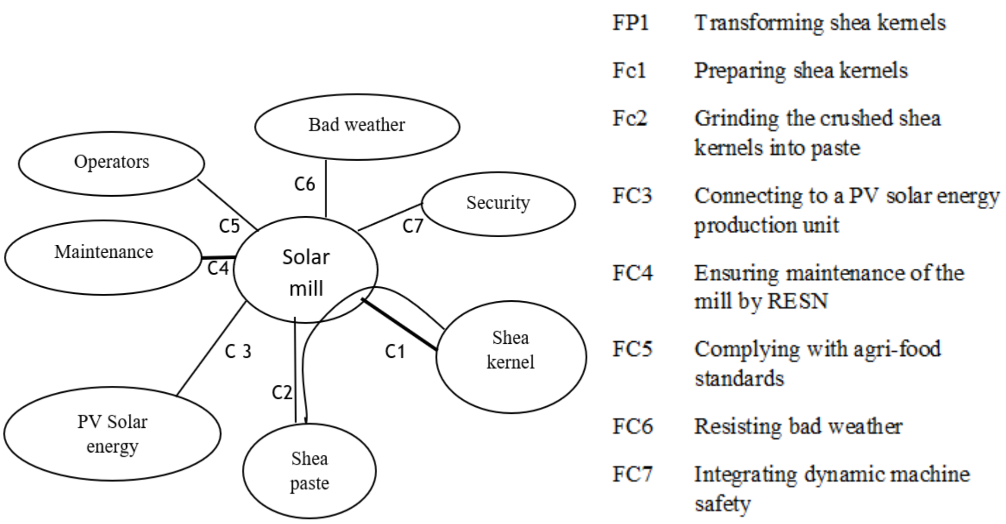



*Figure 2. Octopus diagram.*

*Table 4. Outlines the functional specifications of the solar mill.*

| Main functions and constraint | Criteria | Level | Flexibility thresholds |
|---|---|---|---|
| FP1: Transforming the shea kernel into paste | C1.1. Hourly capacity for grinding crushed shea kernels per day | 45 kg/h | ±5 |
| | C1.1. Daily operating time | 5 am | ±1 |
| FC1: Preparing the shea kernels | C2.1: Grind and roast the shea kernels | | |
| FC2: Grinding the crushed shea kernels into a paste | C3.1: Spacing and tightening of grinding chamber millstones | 5 mm | ±1 |
| FC3: Connecting to a PV solar energy production unit | C4.1: Produce on average a photovoltaic solar energy | 1922.5 Wh | ±177.5 |

| Main functions and constraint | Criteria | Level | Flexibility thresholds |
|---|---|---|---|
| FC4: Ensuring the maintenance of the mill by RESN | C5.1: Use the rules for integrating renewable energies into the design of RESN agri-food equipment | - | |
| FC5: Complying with agri-food standards | C6.1: Comply with the quality NBF 01-004-2006 on shea kernels and the Burkinabe standard NBF 01-005-2006 on unrefined shea butter | | |
| FC6: Resisting bad weather and protecting the environment | C7.1: Install the mill in a facility that can withstand all types of weather. | | |
| FC7: Integrating dynamic machine safety | C7.1: Put protection on all dynamic parts of the mill. | | |

The characterization of each function and the daily shea kernel paste needs of the agri-food unit were used to draw up the functional specifications for the solar mill. The results obtained are comparable to those of the flour processing unit and the tools to assist in the design of dryers [8, 9].

2. CDCF Functional Specifications

Table 4, shows the main functions and constraints of the solar mill with their applicability criteria, operating values (level) and the limits not to be exceeded (flexibility). The CDCF clearly defines the needs for solar PV energy, the functions to be performed by the solar mill, the parameters and indicators of proper functioning of the mill, etc. The results are comparable to those of CDCF's energy-saving dryer design [10]. The parameters related to the solar PV energy functions of the CDCF are in agreement with those of the classic solar mill and Zebra, according to a study of solar mills in WACs. Compared with the functions of ordinary mills, these results are in agreement with the operating principles of shea mills of the works of [11].

3. Analysis of Functions and Technical Systems (FAST)

From the FAST diagram, we have defined the components or technological solutions that will contribute to the performance of the various technical functions and fulfil all the service functions of the subsystems of the solar mill. Figure 3 shows the FAST diagram for the solar mill, different functions (main, services, technical) and technological solutions.

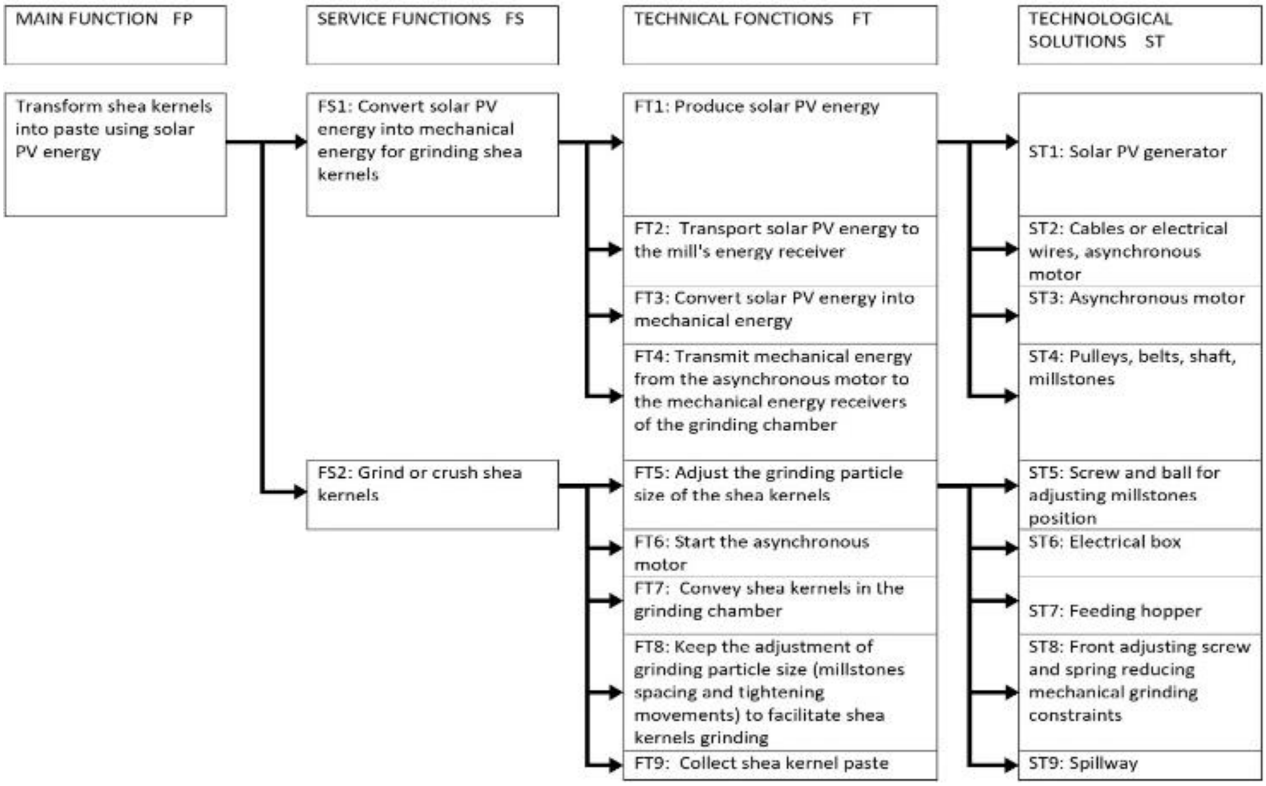



***Figure 3.*** *FAST of the solar.*

From the main function, 2 service functions (FS) were defined to perform it. The FS1 produces solar PV energy and the FS2 transforms shea kernels into paste. From FS1 and FS2, the technical functions (FT) and technological solutions (ST) of each of the two FS have been defined. The FT, ST and the operating parameters of each of the functions defined in the CDCF of the solar mill were used for filtering and applying the design rules of the shea kernel solar mill. The FAST of the solar mill is comparable to that of the energy-saving dryer [10].

## 3.3. Rules for Integrating RE into the Design of the Shea Kernel Solar Mill

The RSER practices of the solar mill, combined with the exploitation of the design method for socio-technical maintenance networks ($DFM_{SN}$) [14], the AF tools (CDCF, FAST) and the ASTEE of the literature review, made it possible to develop the rules for integrating RE into the design of the solar shea kernel mill. The indicators of rules 1 and 2 come from $DFM_{SN}$ and those of rules 3 to 6 were defined on the basis of the sizing work of solar PV installations [17, 18]. Table 4 presents the rules for integrating the RE of the solar mill.

Table 5, presents the rules for integrating RE into the design of the solar mill drawn from the practices of RSER stakeholders and the literature review. Six (6) rules for integrating solar photovoltaic (PV) energy into the design of the solar mill have been defined. The results obtained, rules 1 to 2 are in accordance with the rules of the work of [14] rules for integrating maintenance into the design of AEs, rules 3 to 6 are in agreement with those used by [2, 10] to integrate solar PV energy into the design of an agricultural product dryer.

***Table 5.*** *Rules for integrating RE into the design of the solar mill.*

| Rules for integrating RE into the design of the solar mill | Rule indicators and application threshold | Sources of rules and indicators | Interaction of rules with FAST and CDCF |
|---|---|---|---|
| Rules 1.2: Filter operating principles or technological solutions | | | |
| Rule 1: Avoid complex and energy-intensive operating principles; in the event of simple principles not being found, consider questioning the corresponding technical function. | $I_{DA}$, $I_{CP}$ | [14] and practices of the solar mill RSER | FS2 |
| Rule 2: Choose energy-saving technological components using the ASTEE energy-saving technological solutions choice analysis method | $I_{DA}$, $I_{CP}$ | | TF3, FT4, FT5 |
| Rules 3,4,5: Filter modes of RE use | | | |
| Rules 3: Convert solar energy into PV electrical energy from photovoltaic cells to power the solar mill STs | Solar potential is between (0-6kWh/m$^2$ /day) in the PAO | [17, 18] and practices of the solar mill RSER | FT1, FT2, CDCF |
| Rules 4: Orient the absorbers of solar rays towards the direction and rotation direction of the sun, thanks to the appropriate inclination of the collectors. | Angle of inclination (14-15°) in WACs | | FT1 |
| Rules 5: Avoid shading on the installation site, especially on the surfaces of the collectors by installing them on perimeters exposed to solar radiation. | The solar potential received by the PV modules (0-6 kWh/m$^2$ /day) in the WACs | | FT1 |
| Rule 6: Filter of beneficiaries support modes for optimal AE use | | | |
| Rules 7: Train beneficiaries in the use and maintenance of AEs and RE through training and equipment use materials. | Optimization of production by beneficiaries | [14] and practices of the solar mill RESN | FT5, FT6, FT6, FT7, TF8, FT9 |

## 3.4. Implementation of Rules in Mill Design

*Rule 1: Avoid complex and energy-intensive operating principles; in the event of simple principles not being found, consider questioning the corresponding technical function.*

The design team is made up of members of the RESN see figure 1. The application of rule 1 has not basically modified the operating principle of the ordinary mill. Indeed, the design of the mills was the subject of several works (Bationo, 2007; Marouzé, 1999) which made it possible to design and transfer the mill technology to the AEMs. The principle of grinding by friction is used by ordinary mills and new solar mills imported from Europe or Asia, according to a study of solar mills in WACs. As a result, an ordinary mill was manufactured by the AEMs without any modification for the application of the rules for integrating RE into its operation. The manufacturing time was thirty (30) days. The principle of friction operation has remained the same. On the other hand, the application of FT3, FT4 and FT5 of the FAST and the parameters of the CDCF have led to modifications on the operating principle of the ordinary mill.

*Rule 2: Choose energy-saving technological components using the ASTEE energy-saving technological solutions choice analysis method.*

Rule 2 made it possible to choose the STs that could accomplish FT3, FT4, TF5 and FT7 in order to respond to the need expressed to CEAS Burkina, by the agri-food unit for the production of shea butter, to have a solar mill, operating on solar PV energy, with a capacity of 50 kg/h and a budget of less than approximately 11,568 USD.

The tools of AF (CDCF and FAST) combined with that of ASTEE, made it possible to choose three three-phase asynchronous motors of 2 kw, 3 kW and 4 kW respective power to carry out the shea kernel grinding tests. The three-phase motors have a current draw lower than a single-phase one. They save the energy of solar generators. Several shea kernel grinding tests were carried out with these three (3) engines operating on energy supplied by thermal power plants. The shea kernel grinding tests with the first two motors of 2 kw and 3 kw were unsuccessful. These two engines were unable to process the shea kernels into a homogeneous and fine paste for the extraction of shea butter. With a motor power of 3 kW the budget for the various installations was almost at the limit of the planned budget of 11,568 USD.

Therefore, the design team carried out discussions in a brainstorming process for five (5) days. Two solutions resulting from the discussions were applied without success (use of a reduction motor and increase in motor torque by a transmission chain) for a period of 3 months. An in-depth diagnosis of the results of the tested solutions allowed the team to question the adjustment mechanism of the grinding millstones during grinding operations. In fact, the quality of the shea kernel paste depends on the adjustment (particle size) of the millstones during the grinding operations. The more homogeneous and fine the kernel grinding, the higher the current draw. The friction grinding principle requires friction between the two (2) millstones to crush (grind) the shea kernels. The friction between the wheels requires energy. This demand for energy during friction forces EA manufacturers to use engines with power greater than 5.5 kW [11] for the operation of shea kernel mills regardless of the needs of the agri-food unit. To overcome this constraint, the design team installed a spring reducing mechanical grinding constraints on the shaft carrying the mobile grinding millstones. The spring eases friction between the grinding millstones through its states of compression and elongation successively during grinding operations. The integration of this technological solution made it possible to reduce the current demand, carry out grinding operations with the 3 kw motor and obtain a satisfactory shea kernel paste with a capacity of 35 Kg /h. The choice of the spring was the same as that of the motor using the ASTEE tool. The tests carried out with the 4 kW motor enabled to increase the production capacity from 35 to 50 Kg/h maximum while remaining within the planned budget. This new capacity of the mill has led to a reduction in the volume of the hopper (ST7) (from 10 kg to 3 kg of shea kernel) to facilitate continuous feeding of the grinding chamber and avoid jams. This design approach by integrating ST to improve the operation of AE is in agreement with that used by [10] when designing the energy saving dryer. Figure 4 describes the different components of the shea kernel mill.

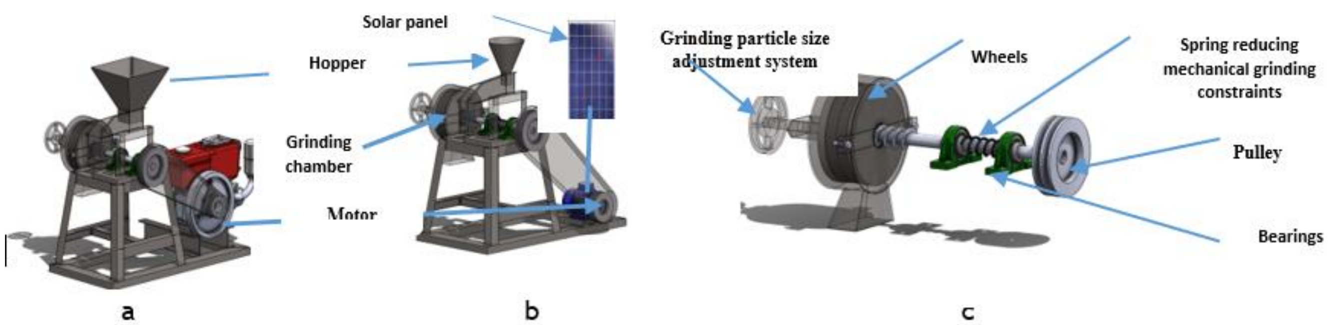



***Figure 4.*** *Description of the different components and integration work of RE in the operation of the shea kernel mill.*

Figure 4 shows the ordinary mill (4a), the solar mill with the different modifications (4b), the integration of the friction forces damping spring and the grinding millstones (4c). The AF tools (CDCF and FAST) and ASTEE made it possible to apply rule 2 for integrating RE into the design of the shea kernel solar mill. The application of these rules allowed to add a technological solution (ST8 of FAST) and to modify ST7 which enabled to operate the solar mill with a 4 KW asynchronous motor (ST3 of FAST) figure 4b. The major innovation is the integration of the spring which made it possible to grind shea kernel with a power of 3 kw. The results are in agreement with those of the works of [10] who used FAST to integrate a new function into the operation of a dryer. In addition, the report on solar mills in WACs shows solar mills operating with 3 KW motors.

*Rule 3 Transform solar energy into PV electrical energy from photovoltaic cells to power the solar mill STs.*

The RESP worked with its various members to implement rule 3. The design and sizing work was carried out by CEAS Burkina and Africa Solar. The energy requirement of the solar mill defined in the CDCF constituted the main data for the implementation of rule 3. It enabled to add the FS1 in the FAST of the solar mill and to define its FTs from FT1 to FT4 with their technological solutions ST1 to ST4. These data made it possible to dimension PV solar energy components and equipment. On the basis of technological solutions ST1 to ST4, the solar PV energy components and equipment of the solar PV generator were sized using the formulas in table 3.

Formulas 1 to 3 were used to calculate solar PV energy needs, the power of the PV generator and the sizing of solar PV energy production equipment. With a 4 kW, 380 V motor and a daily operation of 6 hours, See the CDCF, the daily need is estimated at Ej=24 kWh/d. Taking into account sunshine and climatic hazards, the solar PV generators were estimated at Pg= 6,210 Wp.

***Table 6.** PV solar energy production equipment and components.*

| Designation | Characteristics | Quantity |
|---|---|---|
| Hybrid inverter | TBB Solar 5 kVA | 3 |
| Solar modules | Suntech 345 Wc superpoly | 18 |
| Battery | 200 Ah AGM | 4 |
| DC box | Midnite Solar + lightening conductor | 3 |
| But fuse | Midnite Solar 175 A | 3 |
| AC Box | Circuit breaker 32 A + lightening conductor | 1 |
| Dimmer | Three-phase 4 kW | 1 |

The working time is 6 hours a day and during daytime

The data in Table 6 was used to draw up the wiring diagram for the solar PV generator shown in Figure 5.

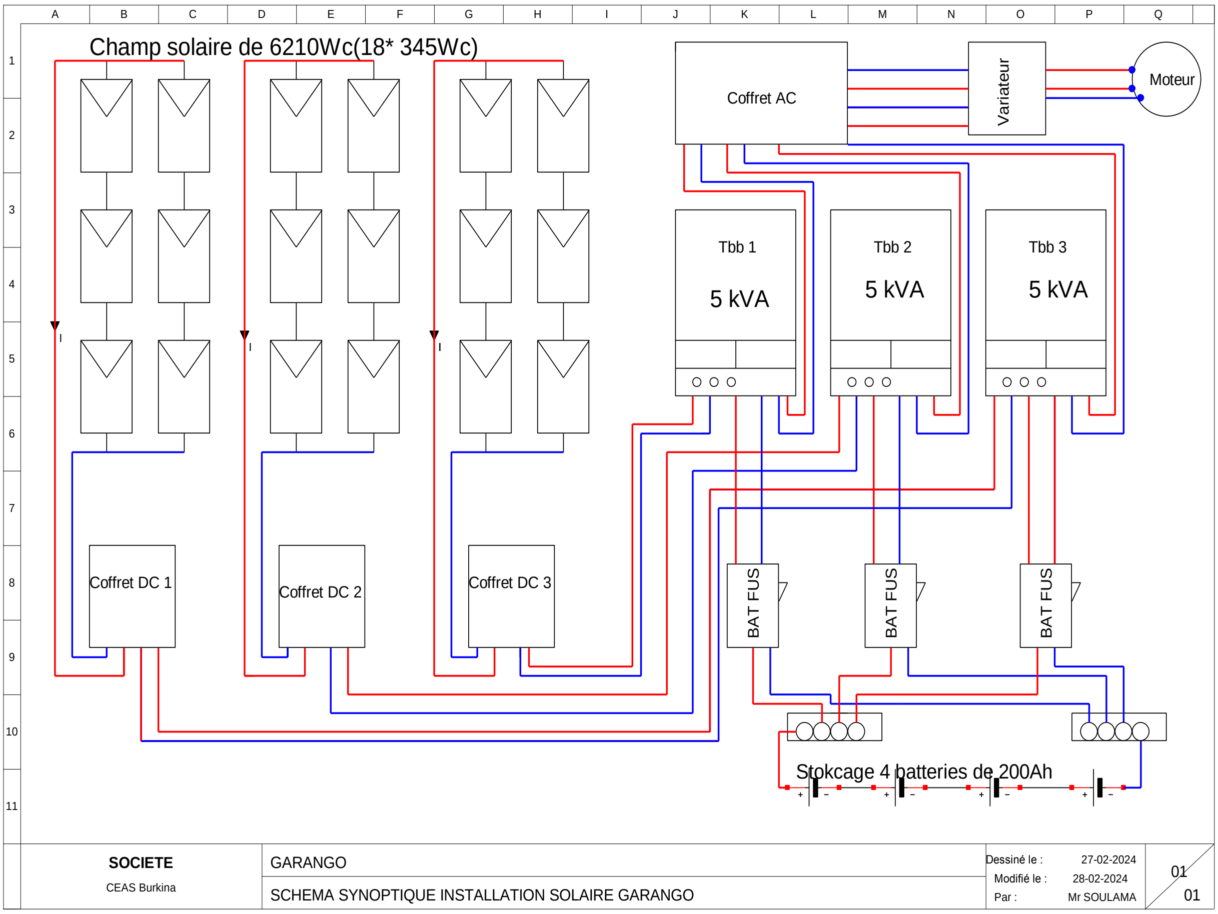



***Figure 5.** Layout diagram of the mill's PV solar generator.*

Formulas 4 and 5 were used to size the batteries and inverter. It should be noted at this level that the energy from the batteries is used to power the inverter and site lighting. Table 6 presents the ER equipment.

From Table 6 to Figure 5 the different components and equipment of the production unit have been dimensioned, quantified and schematized. The wiring diagram of the solar PV generator results from the implementation of rule 2. The solar field is made up of 18 PV modules, connected in series forming 6 strings of 3 PV solar modules. The strings are connected in parallel 2 by 2, thus forming 3 outputs which are each connected to a 5 KVA inverter. Each of the outputs of the 3 inverters supplies one phase of the three-phase motor of the mill passing through the electrical box and a speed drive which regulates the starting current. The design team did not face any major difficulty in applying rule 2. This is explained by the fact that the RESP stakeholders within the RESN have proven expertise in PV sizing and installation. It is important at this level to take into account the expertise and specialty of the RESN stakeholders in the implementation of design rules. The application of rule 2 lasted approximately 1 month. This duration is linked to the choice of the model of some components (inverter, battery and solar module) and their availability on the market (rule 2). The efficiency and the proper operating temperature of the RE components are factors to take into account in the sizing and choice of solar PV components and equipment. The results obtained from the application of rule 3 are in agreement with those of [18] to size or evaluate solar PV power plants. The application of rule 3 made it possible to integrate the FS1 with its TF and ST into the operation of the shea kernel mill. These results are in agreement with those of [13] when integrating the forced convection function into the operation of the energy-saving dryer.

*Rule 4 Orient the absorbers of solar rays towards the direction and rotation direction of the sun, thanks to the appropriate inclination of the collectors.*

From Figure 4, the RE equipment was installed by the RESP stakeholders of the RESN of the solar mill. The solar modules were installed in the North South direction to capture the maximum amount of solar rays. This model of installation of PV modules is consistent with that of the works of [18] relating to the evaluation of the performance of a solar PV plant.

*Rule 5 Avoid shading on the installation site, especially on the surfaces of the collectors by installing them on perimeters exposed to solar radiation.*

The mill was installed in a building and the solar field on the roof of the building to avoid shading (application of rule 5). The installations lasted 10 days with functionality tests. This model of installation of PV modules is in agreement with that of the works of [17] relating to the evaluation of the performance of a solar PV plant.

*Rules 6: Train beneficiaries in the use and maintenance of AEs and RE through training and equipment use materials.*

Rule 4 was applied during installations and functionality tests. UAE of the RESN of the solar mill were trained in the use and maintenance of the mill and solar PV equipment. FAST FT7 and FT8 have been implemented. This approach to supporting beneficiaries to make better use of AE is in line with that used by [15] on press improvement work the for the benefit of a women's group in Benin.

## 3.5. Description of the Solar Mill

The solar mill consists of a feeding hopper, a grinding chamber, a spillway and an electric motor (see Figure 4b). Its motor is powered by a generator that produces solar PV energy. Once the energy is available, we adjust the spacing of the millstones and introduce the kernels into the hopper FT8. Through the hopper dosing machine, the shea kernels are conveyed into the grinding or crushing chamber FT7. The grinding millstones are repeatedly tightened and retightened to produce the shea paste FT8. The shea paste is collected in a dish through the spillway FT9. This mode of operation is in accordance with the mill [4] defined in their feasibility study for the establishment of a shea butter production workshop.

## 3.6. Shea Kernel Grinding or Crushing Tests

A total of five grinding tests of crushed and roasted shea kernels were carried out following the protocol defined in point 2.2 of the design method. Figure 6 shows the curve of photovoltaic solar energy consumption during shea kernel grinding operations to obtain paste.

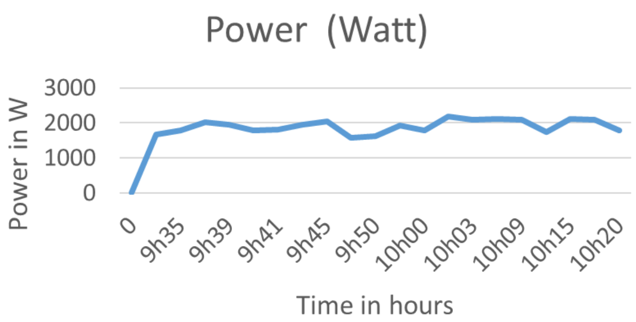



***Figure 6.*** *Photovoltaic solar energy consumption by the solar mill.*

We see that the energy consumption of the mill is between 1672 and 2173 W through Figure 3. The growth of the curve at start-up from 0 W to 1672 W is due to the start-up current draw of the mill. The 1672 W starting power is much lower than 15 kVA which is the rated power of the AC inverter with a maximum power of 30 kW. The solar field therefore allows to support the start-up current and guarantee better operation of the mill depending on the sunshine of the day from 9 a. m. to 3 p. m. in Burkina Faso and depending on the periods of the year. These results are in agreement with those of [19] which confirm that the operating power of equipment must be lower than the power of the supply source. They are used to validate the rules for integrating solar PV energy into the design of the shea kernel solar mill.

### 3.7. Technical Characteristics of the Solar Mill

***Table 7.*** *Technical characteristics of the solar mill.*

| Settings | Technical specifications |
|---|---|
| Shea kernels grinding capacity | 45 ±5 kg/h |
| Gap between grinding millstones | 4 mm |
| Grinding rate | 100 % |
| Loss rate | 4% |
| Texture of the shea almond paste | Fine |
| Average solar energy consumption | 1922.5Wh |
| Dimensions (L x l x h) (mm) | 1255 x 922 x 1435 |
| Voltage measure | 390 V |
| Nominal motor voltage | 380 V |
| Rated motor power | 4 KW |
| Motor speed | 1470 tr/min |
| Daily production capacity | 270 Kg /6h of shea kernel paste |
| Daily solar energy consumption | 11,532 kWh |
| Economical energy gain | 1.82 USD compared to the price of KWh in Burkina |

The characteristics of the mill are very satisfactory for the shea butter production unit of the UFG association. In fact, such production capacity allows the unit to process a maximum of 300 kg of shea kernels per day, or 270 kg / 6 hours of butter paste per day. This capacity enables them to satisfy their annual production. The technical characteristics of the solar shea kernels mill are in agreement with the technical characteristics of the solar cereal mills of the works, according to a study of solar mills in WACs, who showed that the solar mill, from the Solar Milling brand, has a performance of 40 to 200 Kg/h for grinding cereals with a 3 kW PV generator. The SUNGUF S-75 V model has a production capacity of 50 to 75 Kg/h for milling cereals with a 4 kW solar generator. Table 7 also shows an economic gain of 1.82 USD due to the non-connection of the shea butter production unit to Burkina's national electricity supply network. This result is in agreement with those of [21] who showed economic gains of 23,828.8 USD and 27,553.1 USD when drying tomatoes and carrots with a dryer using solar PV energy. From the above, we can conclude that the rules for integrating RE applied to the solar mill through the tools of the AF (CDCF and FAST) and ASTEE, make it possible to integrate RE into the operation of the mills of small agri-food processing units in West Africa. These results are in agreement with those of [7, 12] validation works on the socio-technical network-oriented design method with the mill and the press. This design approach is in line with DFX of [20].

## 4. Conclusion

As a result of our work, rules for integrating solar PV energy were developed and applied in the design of the shea kernel solar mill. Shea kernel grinding functionality tests showed an average capacity of 45 Kg/h of processed shea kernel and a solar PV energy consumption of 11,532 kWh equivalent to an energy consumption of 1.82 USD compared to consumption energy of ordinary mills. The implementation of the rules for integrating RE into the design of AEs requires specialty-oriented collaboration of each member of the RESN. The most complex phases are the choice of energy-saving solutions that will enable RE to be integrated into the operation of the EAs. It is important to carry out a sound diagnosis of existing EAs in order to provide appropriate solutions for integrating RE into the design of AEs.

This approach allows, on the one hand, for the adaptation of the technology to its socio-technical environment and, on the other hand, the appropriation of the technology by the network stakeholders. At this stage of ours works, the results obtained confirm that we can develop rules for integrating RE into the design of AEs from the practices of RESN of AEs and apply them using the tools of the AF (CDCF and FAST) and ASTEE. Admittedly these results help respond to the problems of appropriation of technologies by RESNs, access to energy for small agri-food units, and reduction in the production of greenhouse gases. But for a better adoption of this approach and the design of new AE technologies using RE as an energy source, our next works will propose an RESN-oriented design approach ($DF_{RESN}$). The development of this approach will involve the definition of integration rules for other forms of RE (solar thermal energy and bioenergy) with the indicators and their threshold of application in the WACs.

## Abbreviations

| | |
|---|---|
| AF | Analysis Fctional |
| ASTEE | Tool to Help Choose Energy-Efficient Technological Solutions |
| AEM | Agri-Food Equipment Manufacturers |
| AE | Agri-Food Equipment |
| CDCF | Functional Specifications |
| CESAM | Design Method in Southern Countries, Method |
| ER | Renewable Energy |

| | |
|---|---|
| FAST | Technical Function and System Analysis Diagram |
| FS | Service Functions |
| RESN | Socio-technical Networks of Renewable Energies |
| ST | Technological Solutions |
| WAC | West African Countries |

## Author Contributions

**Yamako Soungalo Soulama:** Conceptualization, Project administration, Writing – review & editing

**Frederic Bationo:** Conceptualization, Project administration, Validation, Writing – original draft

**Tchamye Tcha-Esso Boroze:** Conceptualization, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing

## Conflicts of Interest

The authors declare no conflicts of interest.

## References

[1] Totouom, A., Les obstacles au développement industriel de l'Afrique. L'Actualité économique, 2018. 94(3): p. 363-387. https://doi.org/10.7202/1068043

[2] Gérardin, H. and O. Damette, Quelle transition énergétique, quelles croissance et développement durables pour une nécessaire transition écologique ? Présentation. Mondes en développement, 2020. 192(4): p. 7-23. https://doi.org/10.3917/med.192.0007

[3] Bass, H. -H., *Promoting the Production of Cashew, Shea, and Indigenous Fruits in West Africa.* 2013. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-338461

[4] Lovett, P. N. (2015). Shea butter: Properties and processing for use in food. In *Specialty oils and fats in food and nutrition* (pp. 125-158). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-376-8.00005-3

[5] Goumbri, W. B., et al., *Procédés d extraction et qualité physicochimique du beurre de karité du Burkina Faso utilisé comme matière première pharmaceutique et agroalimentaire.* 2 ème Congrès International de la Société Ouest Africaine de Pharmacie galénique et Industrielle (SOAPGI), 2021. https://hdl.handle.net/2268/292696

[6] Elsewedy, H. S., T. M. Shehata, and W. E. Soliman, *Shea Butter Potentiates the Anti-Bacterial Activity of Fusidic Acid Incorporated into Solid Lipid Nanoparticle.* Polymers (Basel), 2022. 14(12). https://doi.org/10.3390/polym14122436

[7] Noumi, E. S., M. -H. Dabat, and J. Blin. *Développement durable de la transformation traditionnelle du karité en valorisant énergétiquement les résidus organiques. Page de garde du CIFEM*. 2012. https://agritrop.cirad.fr/577010

[8] Marouzé, C., *Proposition d'une méthode pour piloter la trajectoire technologique des équipements dans les pays du Sud. Application au secteur agricole et agroalimentaire*. 1999, Paris, ENSAM. https://theses.fr/1999ENAM0032

[9] Azouma, Y. O., *Intégration de la fabrication et de la maintenance dans une démarche de conception pluridisciplinaire d'équipements agricoles et agroalimentaires pour l'Afrique*. 2005, Besançon. https://theses.fr/2005BESA2006

[10] Boroze, T. T. E. (2011). Outil d'aide à la conception de séchoirs pour les produits agricoles tropicaux Université de Lom. https://agritrop.cirad.fr/567901/

[11] Hounsounou, J., *Proposition de Méthode pour une Approche Intégrée d'Eco conception d'Equipements dans les PMEs de Manufacturing d'Agroéquipements au Bénin.* 2022, Université d'Abomey-Calavi (Bénin). https://hal.science/tel-03747022v1

[12] Handra, N. and A. Indra, *Briquette of Empty Fruit Bunch Fiber as an Alternative Substitution for Binderless Fuel Methods.* Makara Journal of Technology, 2023. 27(3): p. 1. https://doi.org/10.7454/mst.v27i3.1455

[13] Soulama, Y. S., Bationo, F., & Tapsoba, F. W. B. (2024). Evaluation of the Performance of the ATESTA Forced Convection Dryer when Drying Pineapples. *Indian Journal of Science and Technology*, *17*(14), 1252-1262. https://doi.org/10.17485/IJST/v17i13.2626

[14] Bationo, F., Marouze, C., Boujut, J. F., & Giroux, F. A. (2009). Socio-technical networks: a tool for integrating the maintenance dimension in the design of equipment for small food-processing units in Western Africa. *Journal of Design Research*, *8*(1), 23-41. https://doi.org/10.1504/JDR.2009.030998

[15] Bationo, F., *Taking maintenance sociotechnique network into account of the equipment design (Prise en compte du réseau sociotechnique de maintenance dans la conception d'équipements)*. 2007, Institut national polytechnique de Grenoble, Université de Grenoble. https://theses.fr/2007INPG0026

[16] Hoareau, É., *sociotechnique et Innovation: le cas du réseau QualiREG. Gestion et management* 2014, Université de la Réunion. https://theses.hal.science/tel-01171770v1

[17] Sanwogou, Y., et al., *Conception d'un système solaire photovoltaïque pour alimenter le laboratoire de physique de l'Université de Kara, Togo.* Afrique SCIENCE, 2019. 15(5): p. 238. https://www.researchgate.net/publication/379875098

[18] Palm, S. F., et al., *Performance Evaluation of Burkina Faso's 33 MW Largest Grid-Connected PV Power Plant.* Energies, 2023. 16(17): p. 6177. https://doi.org/10.3390/en16176177

[19] Hounkpatin, H. W., et al., Techno-Economic and Environmental Feasibility Study of a Hybrid Photovoltaic Electrification System in Back-up Mode: A Case Report. International Journal of Renewable Energy Development, 2023. 12(2). https://doi.org/10.14710/ijred.2023.46372

[20] Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for 'X': concepts, applications, and perspectives. *Computers & industrial engineering*, *41*(3), 241-260. https://doi.org/10.1016/S0360-8352(01)00045-6

[21] Rulazi EL, Marwa J, Kichonge B, Kivevele TT. Techno-economic analysis of a solar-assisted heat pump dryer for drying agricultural products. *Food Science & Nutrition*. 2024; 12(2): 952–970. Available from: https://doi.org/10.1002/fsn3.3810

## Biography

**Yamako Soungalo Soulama** is a PhD student enrolled at the University of Lome, in the industrial engineering sector. He holds a master's degree in industrial engineering and renewable energies. He has 3 scientific articles published in indexed journals. He is currently appointed Director of Centre Ecologique Albert Schweitzer of Burkina Faso.

**Frederic Bationo** is a senior researcher at the Institute of Applied Sciences and Technologies of National Center for Scientific and Technological Research of Burkina Faso. He has worked on equipment design approaches, tools and methods of industrial engineering, as well as on equipment process engineering. Bationo obtained his doctorate in industrial engineering from the Grenoble Polytechnic Institute in France, as well as his post-graduate diploma. He has participated in numerous international collaborative research projects in recent years, and has published several scientific articles.

**Tchamye Tcha-Esso Boroze** is Professor-Researcher, Faculty of Science, University of Lomé in Togo. Researcher at the Solar Energy Laboratory (LES) of the University of Lomé (UL) and at the Unesco Chair on Renewable Energies (CUER) of the UL. He obtained this PhD in applied physics in 2011 at the University of Lome. He has participated in many international collaborative research projects in recent years and has published several scientific papers.

## Research Field

**Yamako Soungalo Soulama:** Industrial engineering, renewable energies engineering research.
**Ferderic Bationo:** Industrial engineering, electric power generation.
**Tchamye Tcha-Esso Boroze:** Applied physics, renewable energies engineering research.