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Computational sizing of solar powered peanut oil extraction in Senegal using a synthetic load profile

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Title Page

Computational sizing of solar powered peanut oil extraction in Senegal using a synthetic load profile

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To the Editors
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Dear Editors,
On behalf of the authors, we hereby submit our research paper entitled:
Computational sizing of solar powered peanut oil extraction in Senegal using a synthetic load profile.

This paper presents a comprehensive approach for sizing a hybrid photovoltaic system designed for a small-scale peanut oil processing company located in rural Senegal. The central focus of our research is to provide valuable insights into the feasibility and economic viability of using solar energy for plant oil processing. In this study, we developed a predictive model of the electrical load of a service-based plant oil processing company by conducting a thorough diagnosis of the small industry. The simulated load profile was further used for sizing and identifying the characteristics of the most profitable hybrid photovoltaic systems. Our results demonstrate the potential of renewable energy solutions for small-scale industries in rural areas. Our study not only highlights the economic feasibility but also provides valuable insights into the sizing of hybrid photovoltaic systems. The findings in this paper have broader implications for rural regions seeking sustainable and cost-effective solutions for small-scale industries.

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Yours sincerely,

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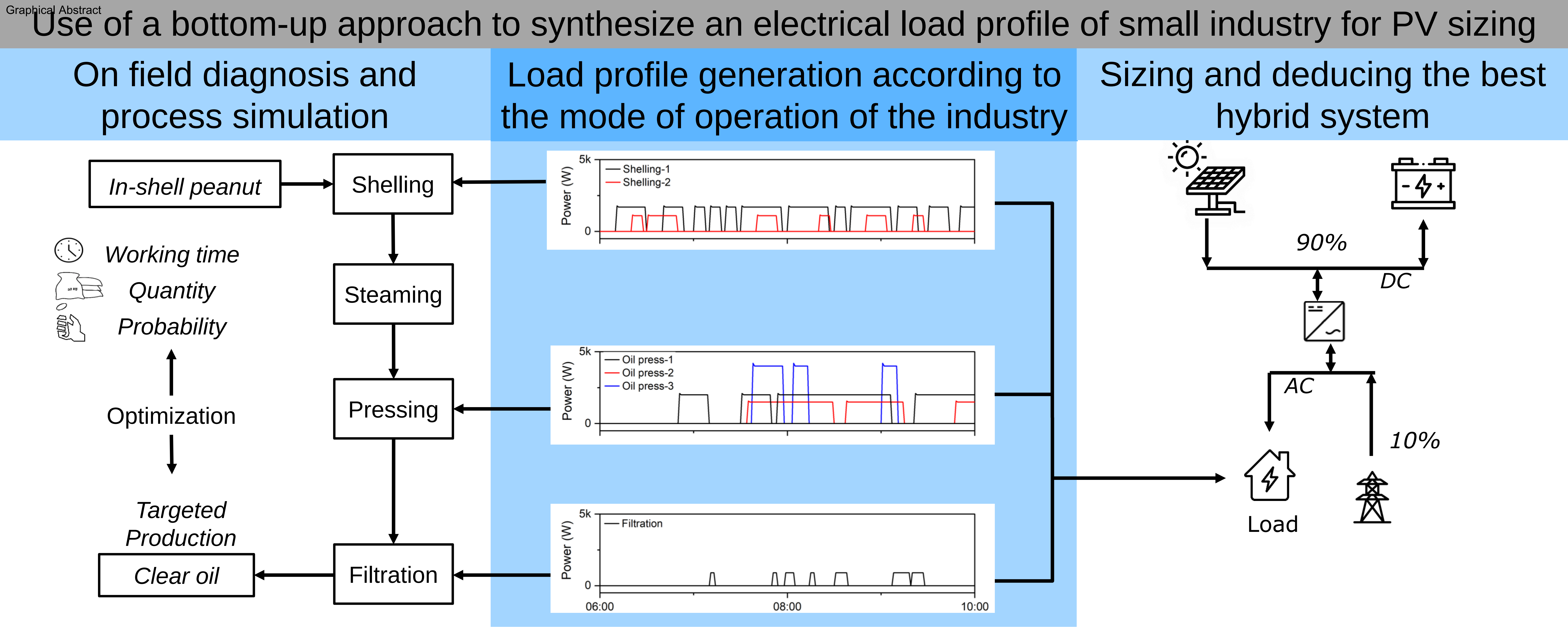
Graphical Abstract



Highlights

- A predictive model of electrical load for a typical peanut oil processing was developed
- The model was suitable to identify the most profitable hybrid photovoltaic system
- Appropriate sizing reduces net present cost, operating cost, and cost of energy
- Using solar energy for peanut oil processing in Senegal would be profitable.

Abstract

This paper presents an approach for sizing a hybrid photovoltaic system for a small-scale peanut oil processing company (Yaye Aissatou, Passy) in rural Senegal using a synthetic load profile. In this study, a predictive model of the electrical load of a service-based plant oil processing company was developed through a diagnosis, to evaluate the extraction process. The mass and energy balance were measured, and the process was implemented into MATLAB Simulink. The simulated load profile was implemented in HOMER Pro and the characteristics of the most profitable hybrid systems were identified. The results showed that the lowest net present cost over 25 years was found with a PV/battery/grid-system with 18.6 kW_p solar panels, 16 kWh of storage, and an initial investment of 20,019 €. Compared to a grid-only scenario, this solution reduces the net present cost from an initial 72,163 € to 31,603 €, the operating cost from 3,675 € per year to 590 € per year, and the cost of energy from 0.29 to 0.13 €/kWh. The renewable fraction of the proposed system is 90.0% while the expected payback period is 6.2 years. The study demonstrates the economic feasibility of using solar energy for plant oil processing.

Keywords: feasibility study, HOMER Pro, hybrid system, mechanical pressing, Monte Carlo simulation, plant oil.

1. Introduction

Access to energy is one of the most important current challenges for developing countries. By 2030, 1.2 billion people in the world, mainly in Sub-Saharan Africa, with 85% of them in rural areas will lack access to electricity [1]. To enhance economic and social development, electricity should be more affordable and reliable. Renewable energy is presented as a solution to improve energy access. It provides an answer to two issues: local energy supply on one hand, and sustainable development on the other hand. Photovoltaics (PV) is one of the fastest-growing industries in the world and is well spread in sub-Saharan countries. It presents today several possible applications to face energy challenges [2]. During the last decades, the price of PV cells has significantly decreased, and solar energy is now considered cheaper than fossil energy [3].

PV systems can be classified as either on-grid or off-grid installations. While on-grid solutions can help mitigate grid failures and instability and reduce dependency, off-grid installations are standalone systems ideal for rural areas without access to the grid. [4] However, they require more investment for storage capacity.

In addition to meeting household energy needs, energy is also required for productive activities in rural areas. To be profitable, a sizing approach that considers energy generation capacity and economic aspect should be employed. Different approaches exist for sizing a PV system. Barra et al. [5] made a classification of the sizing optimization approaches and shows 12 categories including the conventional ones. Those are the analytical method, the numerical method, the probabilistic method, the intuitive method, and the deterministic method [6]–[12]. More recently, the artificial intelligence method is been used as alternative [13]. Moreover, a combination of two or more of these approaches can be carried out.

Several PV software exist, each with different specificities. They can be classified into four groups. The simulation tools simulate and predict the performances of a specified power system. The economics evaluation tools include an economic analysis of the system. The planning and analysis tools help in planning, designing, and optimizing different energy sources, and finally, the solar radiation maps are used for a good understanding of solar resources over the world [14]. Lalwani et al. [15] investigated 12 major solar PV software and evaluated them according to their availability, cost, platform, capacity, and scope. Additionally, predictive models for PV systems exist and are used in software. The author in [16] presents a review of existing models, with a state-of-the-art approach using artificial neural networks (ANN). Further research shows a review of the existing models and did a comparison between the most commonly used models in MATLAB, PVsyst and INSEL software [17]. The software hybrid optimization model for electric renewables (HOMER) simulates grid-connected and standalone systems combined with other energy sources and performs optimization and sensitivity analysis, to find the optimal combination from a cost perspective. It is among the most commonly used software for PV sizing, and the most suitable for hybrid configuration [5], [16], [18]–[23].

To find the ideal size of a PV system, an optimization problem must be solved based on various criteria, including location and meteorological data, electrical demand, technical considerations, economic considerations, reliability considerations, and environmental considerations [5], [11]. The meteorological data varies around the world, affecting the performance of a PV system. The electrical demand is characterized by the load profile, peak power, average consumption, and expected growth. A yearly load profile is necessary to evaluate the performance of a PV system throughout the year, with daily or hourly time steps. Thus, a smallest time step of the profile (minute or second), yields a more accurate optimization. The technical configuration of the system must meet the specifications of all components, with reliability being essential given the intermittent nature of solar energy. For critical weather conditions, a PV system can be oversized to include a security margin to meet requirements. Depending on the type of application, a reliability factor is defined, with a higher factor required for telecommunications, and a reduced factor for rural households. To minimize costs and consider revenue, the budget, installation, maintenance and operation costs, and replacement cost should be minimized, with energy selling revenue expected to be considered. Additionally, environmental impact should be mitigated.[5]

Understanding the load profile is then essential for PV sizing. This can be achieved through long or short-term measurements or predictions [25]. Previous studies present models for energy profiles prediction based on consumer parameters, using regression analysis, decision trees or an ANN [24]–[26]. ANN has been successful in forecasting household electric energy consumption and load profiles [27]. Moreover, authors in [28], [29] propose a mathematical model to predict the random behaviour of residential buildings in energy consumption based on a bottom-up approach.

The bottom-up approach is commonly used in the literature to simulate household electricity consumption and has proven its reliability [28]. Its principle is to construct the total load profile from the profiles of elementary components, which can be a household or a single electrical device, depending on the objective. This approach allows for the analysis of the effect of the operation of elementary equipment on the total load profile. Ogwumike et al. [30] made a model on MATLAB Simulink of the profile of a residential load profile and perform an optimization on the scheduling appliances to minimize the costs of electricity. Some studies present standardized load profiles for domestic or industrial applications, such as [31], [32] which use segmentation to determine similarities in household load profiles. Sandhaas et al. [33] developed a model generating synthetic load profiles for 11 industry types based on the normalized load profiles of eight electrical end use applications. However, the study is related to German industry. Latest versions of HOMER software have a standard profile for commercial, industrial or household activities. Unfortunately, most studies that evaluated load profiles focus on households, while the few examples that examined industrial activities are not relevant to small and medium-sized enterprises (SME) in rural areas, especially in West Africa.

In this study, the objective was to design a tailor-made hybrid PV solution for a typical small peanut oil processing SME in Senegal. A bottom-up approach was used to simulate the load profile on MATLAB Simulink, considering the variability of customers. The resulted load profile was used in the HOMER Pro software to size a PV system.

2. Materials and Methods

2.1. Material

2.1.1. Location

This study focused on evaluating a peanut oil production SME located in Passy, Senegal (13°58'47.4"N 16°15'36.5"W). The diagnosis was conducted during the dry season (April) under typical production conditions. The main activity is the processing of peanut seeds into edible oil, on a service basis. Customers bring their peanuts to the site for processing and pay based on the number of oil bottles filled and the amount of press cake taken home. During the peanut oil production season, from October to May, the demand for processing services is very high, with workdays often extended until 23:00, resulting in almost 16 hours of operation per day. The SME had an average capacity of 4 tons per day of processed in-shell peanuts.

2.1.2. Raw material

In-shell peanuts were used as raw material for the production of peanut oil in the SME. It is packed in 50 kg bags when the customers are arriving at the SME. About 2 kg of raw material was collected and transported for further analysis to the laboratory at the University of Hohenheim (Stuttgart, Germany). A water content of 3.7% d.b. and an oil content of 49.0% d.b. were determined according to [34] and [35] in three repetitions.

2.1.3. Process description

The site is equipped with two shellers, six steamers, three presses and a filter. On-site measurements were conducted during operation to determine electrical consumption, material throughput, process efficiency, and duration of each equipment. The equipment is listed in **Table 1**.

Table 1. List of equipment used in the peanut oil extraction SME in Passy, Senegal

Equipment	**Type**	**Origin**
Shellers 1+2	Blowers and rotating cages	Local
Steamers 1-6	Cylinder on rocket stove	Local
Oil press 1+2	Screw press, extraction at the near end of the screw	China
Oil press 3	Screw press, extraction at the far end of the screw	China
Filter	Plate filter	China

The process begins with the in-shell peanuts being shelled using one of the two available shellers. The resulting kernels are then sent for steam treatment in one of the available steamers. The recovered shells are either reused in the steamers' burner or mixed with the steamed kernels for pressing at a later time. The steaming is done in batches of approximately 80 kg and takes around 1.5 h to be completed. Once steamed, the kernels are mixed with 15% of shells and pressed in one of the available presses. The shells are added to form microchannels in the cake to support the flow of oil. The crude oil obtained from the oil press is then filtered using a plate filter with an associated pump (**Figure 1**).

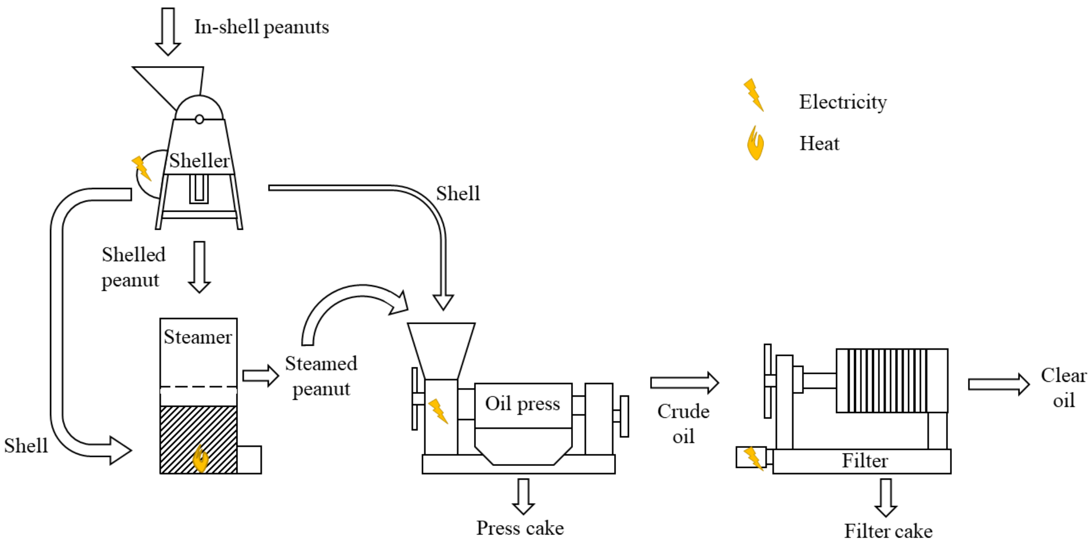


Figure 1. Unit operation in the peanut oil production process

2.2. Method

2.2.1. On-site measurement

During two subsequent days in April 2022, on-site measurements were conducted to complete a mass balance of each unit operation. As the daily routine is the same throughout the season, several processing batches were monitored as a baseline for simulating the entire production year. The energy requirement of each unit operation was measured, and the process was followed to measure the mass flow of each operation, as well as the operation duration. A weighing tray with a precision of 1 kg was used to weigh the input before and after processing operations, and samples of each by-product were taken for laboratory analyses. Electrical power was measured with a current clamp (testo 770-3, Testo SE & Co. KGaA, Dubai, United Arab Emirates) associated with a data logger (testo 400, Testo SE & Co. KGaA, Dubai, United Arab Emirates). Additional information on the SME's mode of operation, average daily production, and average daily electricity consumption were obtained through interviews.

2.2.2. Modeling load profiles

MATLAB Simulink 10.5 (MathWorks®, Natick, Massachusetts, USA) was utilized to simulate the peanut oil production process and evaluate the electric load. The Simulink block model is presented in **Figure 2.** It consists of five main blocks: material receipt, shelling, steaming, oil pressing, and filtration.

Abbreviation	Parameter
m	Raw material
TPSh	Throughput of sheller
P_Sh	Electrical power of sheller
TPS	Throughput of steamer
TPOil	Throughput of oil press
P_Oil	Electrical power of oil press
TPFP	Throughput of filter press
P_FP	Electrical power of filter press

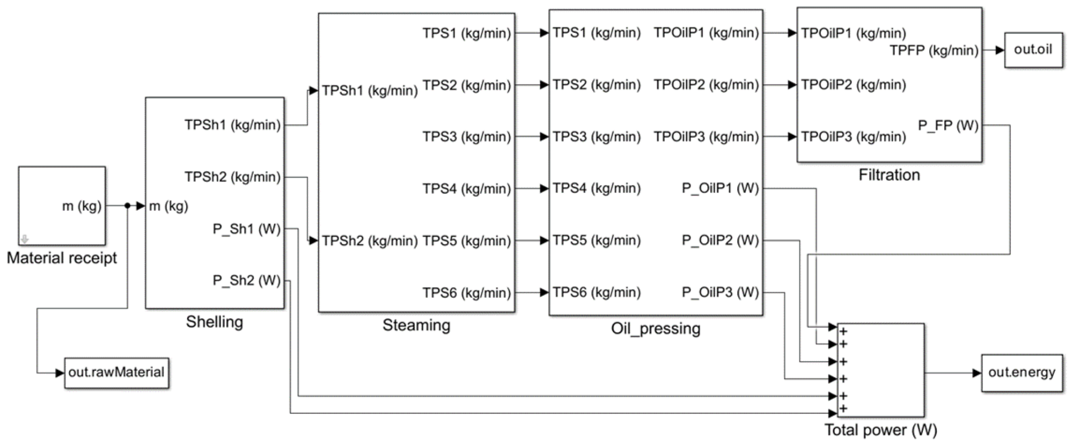


Figure 2. Peanut oil process Simulink block model

In the material receipt block, the operation strategy is defined through three major parameters affecting the operations commands: (i) the randomly arriving customers, (ii) the weekly schedule with start and stop times as well as weekends and (iii) the typical months which represents the production season. The SME operates on a service basis. In order to accurately simulate the production process and account for the randomness of activities, parameters such as the maximum order size per customer, the customer arrival probability, and the customer acceptance time window were taken into consideration. These parameters are crucial for understanding the demand of the operation and simulating the variability of the production process.

The simulation model was implemented with a set of algorithms, starting with the material receipt:

$$m_i = CAI_i \times n_i \times 50 \quad (1)$$

where m_i (kg) is the mass of the receipted in-shell peanut in the SME at a time step i, CAI_i is the customer arrival indicator being 1 if a customer arrives at the SME and 0 otherwise, and n_i is the order size as an integer in a range of 1 to 10 of 50-kg-bags of in-shell peanuts, that a customer can bring to the SME for processing at any given time. The probability of a new customer arriving at the SME for processing within a 10-minute-interval during the acceptance window is expressed as:

$$P(CAI_i) = \begin{cases} p_c & , \ CAI_i = 1 \\ 1 - p_c & , \ CAI_i = 0 \end{cases} \quad (2)$$

where p_c is the customer arrival probability and $i \in [T_{start};T_{end}]$, the interval of customer acceptance, with T_{start} as the time at which the SME begins accepting customers and their material for processing and T_{end}, as the time at which the SME stops accepting customers.

The shelling, steaming, oil pressing, and filtration blocks share the same configuration. To understand when and how an operation runs, it is important to consider various parameters such as the output of the previous operation, the moment it occurs, and the specific parameters of the operation itself.

The instant power was calculated as

$$P_{k,i} = C_{k,i} \times P_k \quad (3)$$

The peak power when the engine start was integrated by a multiple n as:

$$P_{k,i} = r \times C_{k,i} \times P_k \ if \ P_{k,i-1} = 0 \quad (4)$$

where $P_{k,i}$ (W) is the instant power of the operation k at a time step i, r is the peak to average power ratio, $C_{k,i}$ is the command from the operation strategy, taking the value 0 when the operation k is running and 1 when the operation k is not running and P_k (W) the averaged electrical power of the operation k engine.

The throughput of transformed product $Tp_{k,i}$ was expressed as follow:

$$Tp_{k,i} = C_{k,i} \times Eff_k \times Tp_k \quad (5)$$

where $Tp_{k,i}$ (kg/min) is the throughput of processed material of operation k at a time step i, and Eff_k, (kg/kg) is the transformed product per kg of raw material, i.e. the operation yield.

The transformed material in an operation is stored temporarily before going to the next operation. This intermediate storage is given by:

$$S_{k,i} = \sum_{t=0}^{i} Tp_{k-1,t} - \frac{Tp_{k,t}}{Eff_k} \quad (6)$$

where $S_{k,i}$ (kg) is the material from the operation k-1 stored before operation k, a time step i.

The model simulates each minute of the operation as shown in **Figure 3**.

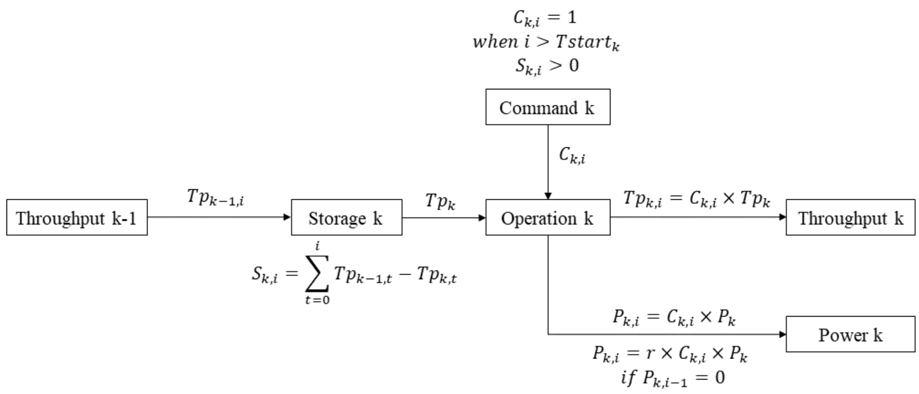


Figure 3. Operation block mathematical model

where $Tstart_k$ is the time at which operation k can start.

The energy consumption E is given by:

$$E = \frac{1}{60} \sum_{i=0}^{T} \left(\sum_{k} P_{k,i} \right) \tag{7}$$

where E (Wh) is the total energy consumption of the SME and T (min) is the duration of the simulation. The simulation monitored the electrical load of individual operation $P_{k,i}$, the total load $\Sigma P_{k,i}$, and the productivity on a one-minute basis for a duration of one year. The details of the content of the simulation blocks are included in **Appendix A.**

2.2.3. Sensitivity analysis

A Monte Carlo simulation was carried out in order to determine the influence of the parameters affecting the raw material on the production and energy consumption of the SME. The considered variables in the analysis are shown in **Table 2**. The results of the study were used to determine the parameters corresponding to the 4 tons of processed in-shell peanuts per day at 67 kWh per day. An optimization algorithm minimizing the root mean square error was used on the MATLAB Simulink parameter estimator. The **Figure 4** shows the parameters adjusted in the optimization to obtain the targeted productivity and energy consumption.

Table 2. Parameters for sensitivity analysis on load profile

Parameter	**Unit**	**Lower value**	**Upper value**
End time of customer acceptance, T_{max}	hh:mm	10:00	20:00
Customer arrival probability, p_c		0	1
Maximum order size per customer, n_{max}	50-kg-bag	1	10

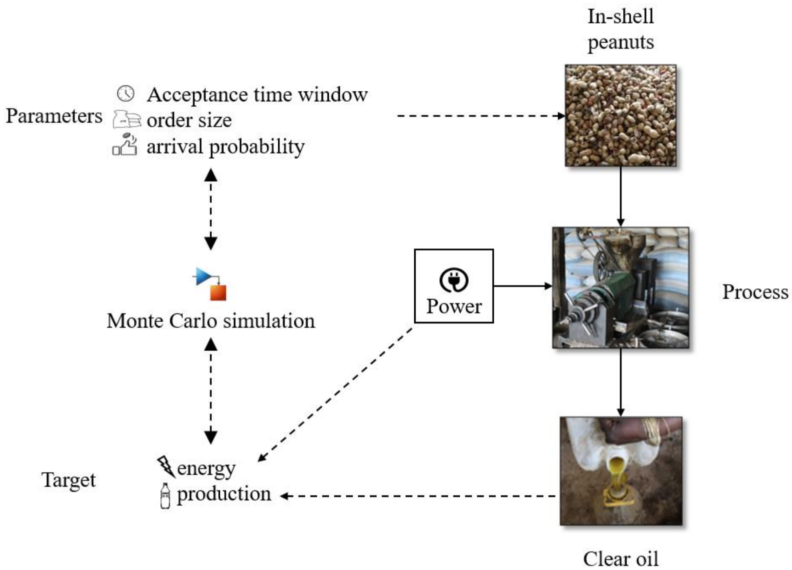


Figure 4. Peanut oil process simulated in Simulink and optimization approach

2.2.4. PV sizing

HOMER Pro 3.14.2 (UL Solutions, Boulder Colorado, USA) was used to determine the optimal size and combination of a hybrid system, as depicted in **Figure 5**. The microgrid components considered were based on generic components provided by the HOMER Pro library, but were modified to match the available components in Senegal. The energy sources were the grid, a diesel generator, and PV panels. The monthly average solar global horizontal irradiance (GHI) was determined based on the SME location and data from NASA Prediction of Worldwide Energy Resource (Jul 1983 – Jun 2005)[36]. All hybrid scenarios combining one or more of these energy sources, with or without a battery, were evaluated. Thus, a renewable solution is made up solely of PV panels, with or without battery storage. A grid-connected solution includes the grid, while an off-grid solution excludes it. The scenarios are represented by codes including their energy sources such as PV/battery/grid/diesel. Out of 14 possible combinations, four were excluded: the PV-only option was not technically feasible and the diesel-only, PV/diesel and battery/diesel scenarios were extremely expensive.

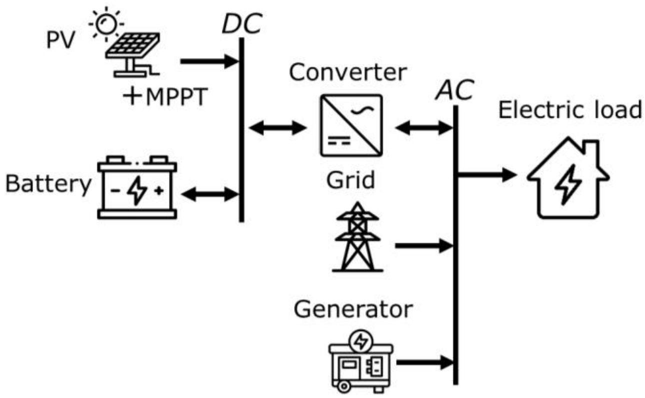


Figure 5. Configuration of hybrid system combinations using HOMER Pro

Randomized grid outages were considered in the simulation. For Senegal a mean outage frequency of 19 days per year with a mean repair time of one hour was considered based on data from the World Bank [37].

For all scenarios, a project lifetime of 25 years, a discount rate of 4.5%, and an inflation rate of 2.5% were used. The individual costs of solar component, replacement, and operation and maintenance costs were based on an interview with a solar company (ENERGECO, Dakar, Senegal). The economic parameters included in HOMER Pro are shown in **Table 3**.

Table 3. Economic parameters included in HOMER Pro

Component	Capacity	Installation (€)	Replacement (€)	O&M[1]	
PV	1 kW_p	533.6	457.3	1.52	€/a
MPPT	1 kW_p	76.2	76.2		
Battery	1 kWh	297.9	206.4	0.76	€/a
Inverter	1 kW	457.3	152.4	1.52	€/a
Grid	1 kWh			0.29	€/kWh
Diesel generator	1 kW	167.7	167.7	1.00 ; 0.53	€/L[2] ; €/h

[1] O&M: Operation and Maintenance cost; [2] Diesel price

During the simulation, various constraints were imposed in the optimization process. The maximum capacity shortage refers to a deficit in required operating capacity and the actual operating capacity the system can deliver. For the current operation of the SME powered solely by the grid the maximum capacity shortage was set to 4%. A lower value would require combining the grid with another energy source to meet the energy needs, while a higher capacity shortage could result in using a less reliable renewable energy source. No limit was set on the amount of renewable energy that can be used. The primary objective is to identify the most cost-effective solution that results in the least net present cost (NPC) over the project lifetime. To ensure adequate operating reserves, a surcharge of 10% was set on the load profile, and one of 30% on the solar power output.

3. Results

3.1. Diagnosis results

The diagnosis allowed to identify the parameters presented in **Table 4**, which were then used as inputs for the simulation model. The sensitivity analysis on the operation strategy parameters was conducted to match the daily production capacity of 4 tons.

Table 4. Peanut oil production operation parameters

Process	Device No.	Throughput (kg/min)	Operation yield (kg/kg)	Start time (hh:mm)	Power (W)
Shelling	1	7.9	0.6	06:00	1,700
	2				1,100
Steaming	1-4	1.5	1.1	06:00	
	5+6	0.9	1.1		
Pressing	1	1.8	0.4	06:00	2,000
	2	1.8	0.4		1,500
	3	3.3	0.4		4,000
Filtration	1	4.5	0.9	06:00	900

The mass balance for producing one ton of clear oil is illustrated in **Figure 6** using a Sankey diagram. The diagram shows that the operation requires 4.4 tons of in-shell peanuts, out of which 1.7 tons of shells are used as fuel during the steaming process and mixed with the steamed peanuts. To steam the shelled peanuts, 156 kg of water is added, which increases the moisture content from 3.7 to 6.9% d.b. Analysis shows a significant difference between the moisture content of shelled peanut, steamed peanut and press cake. After pressing, 1,058 kg of crude oil is obtained, resulting in an operation yield of 37%. The press cake produced has an oil content of 10.7% d.b, and is significantly different from the oil content of the shelled and steamed peanut (49.0 and 48.6%). It corresponds to an oil recovery of 87.3%.

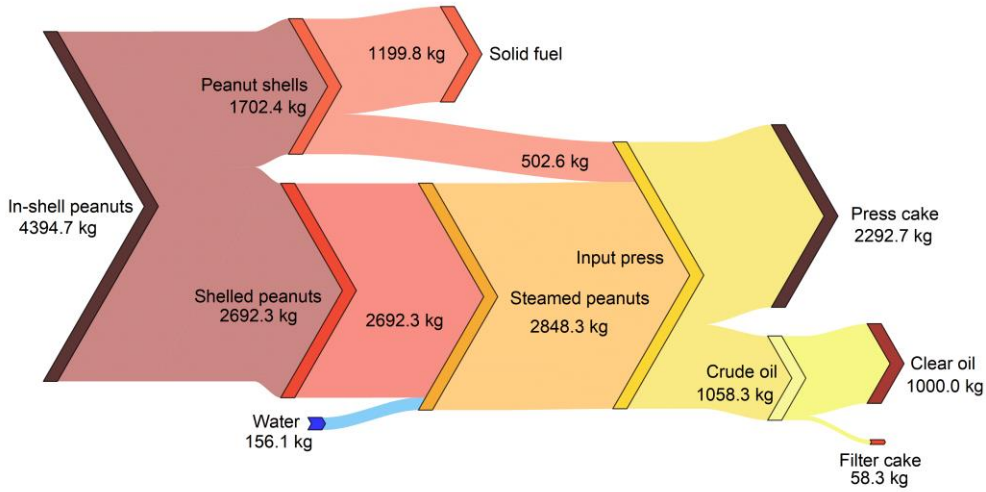


Figure 6. Mass balance for the production of 1 ton of clear oil

3.2. Estimation of electric power consumption

3.2.1. Simulated load profile

Figure 7 displays the load profiles for a typical day of production, including the power usage of individual equipment and the total power consumption of the SME.

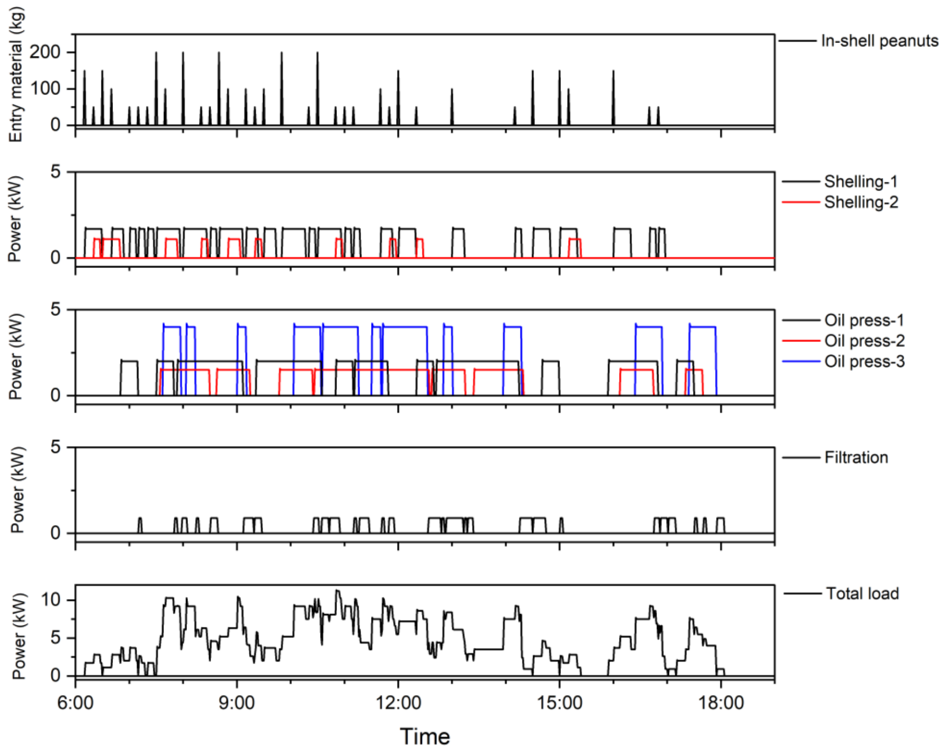


Figure 7. Simulated daily load profile

Figure 8 depict the simulated load profiles for a standard week and a standard year, respectively. These profiles vary from day to day due to the random effect of raw material arrival in the model. The period from May to September is considered as off-season.

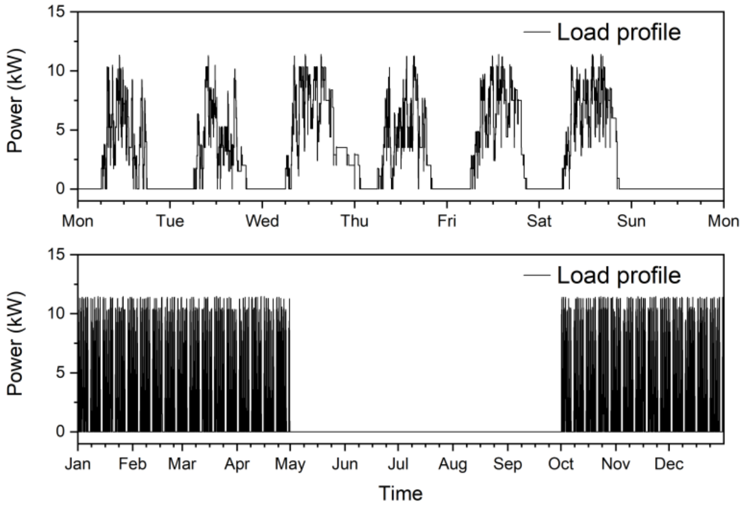


Figure 8. Simulated week (top) and year (bottom) load profile

3.2.2. Validation

Based on the simulation results, the following parameter values were identified: the customer acceptance window from 06:00 to 16:20, the maximum order size of 5 50-kg-bags, and the customer arrival probability of 0.69. **Figure 9** compares the simulated load profile of the three presses with the load profile measured on-site during 9 h of operation. The comparison was made by considering the total power consumption of the three oil presses present on-site. The different levels of operation, whether 1 press, 2 presses, or 3 presses are being used can be distinguished in the on-site measurement and the simulated load profile. The peak loads during start-up were instantaneous and could hardly be captured by the measuring device.

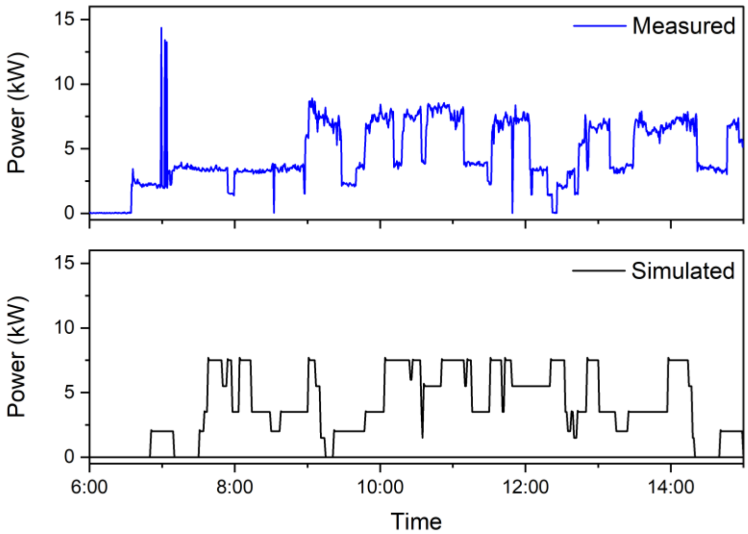


Figure 9. Cumulated load profile of the oil presses, measured (top) and simulated (bottom)

The histograms in **Figure 10** show the different operating powers that correspond to the power of the three oil presses (P1), (P2) and (P3) and the combinations, when oil presses are used simultaneously because of high capacity demand. The simulation shows high counts at a power of 7,500 W (P1-3) and 3,500 W (P1+2) when respectively all of the three oil presses or when (P1) and (P2) are operated simultaneously. Medium counts at a power of 1,500 W (P1) and 2,000 W (P2) are also noticable. Due to variabilities of the instant power of machineries during the on-site measurements, normal distributions of power counts are noticeable, however centered around the operating points in the simulation. High counts in the measured power indicate the operation with two presses (P1+2), and all three presses (P1-3) similarely to the simulation.

Due to the variability of the results between the on-site measurements and the simulation, statistical comparisons were made on both profiles. Although the confidence interval of the on-site measurements is wider than that of the simulation, the average power shows a similarity and the range of the on-site measurements includes the range of the simulations (**Figure 10**).

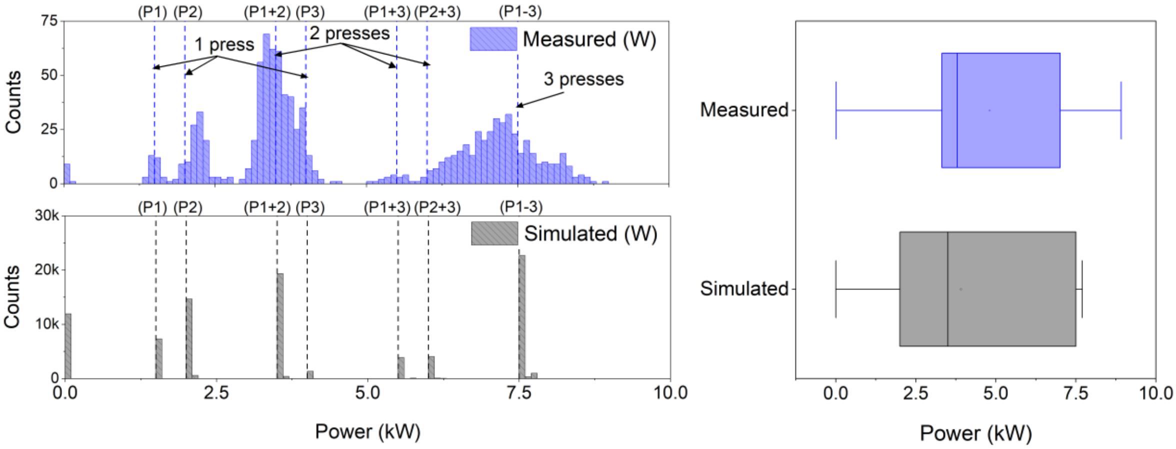


Figure 10. Power profiles of on-site measurements and simulation (left) and box plot of average power demand (right)

3.2.3. Sensitivity analysis

The points considered as input in the sensitivity analysis are displayed in **Figure 11**. It presents the effect of customer randomness on the daily productivity. The figure displays the total amount of in-shell peanut processed per day and the daily energy consumption, average power, and peak power. The histograms show the output of the simulation as frequency of occurrence of the response values simulation. The results show that the customer arrival probability is the most influential parameter on in-shell peanut processed, the energy consumed, and the peak power. A probability of at least 0.25 is necessary for the processing of four tons per day and energy consumption of 67 kWh. The maximum order size has a limiting impact on production, with at least four bags of 50 kg per customer to achieve the daily production of four tons.

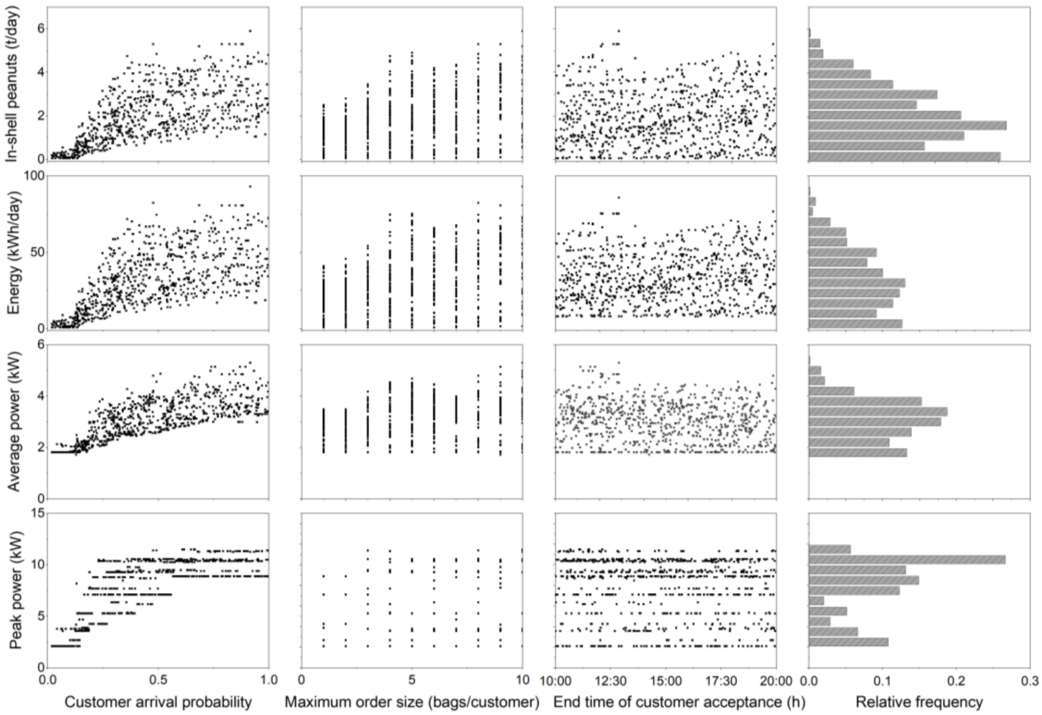


Figure 11. Monte Carlo simulation results for sensitivity analysis

3.4. Composition and sizing of power supply scenarios

Five main scenarios are presented in the following. Those are the base case scenario, and the best scenarios for a fully renewable system, a hybrid system, an off-grid system and a system without battery storage.

3.4.0. Grid-scenario

The grid-scenario is the current situation in the SME and represents the baseline scenario. It does not require an investment and operates solely with electricity from the grid. The cost of energy (COE) is set to 0.29 €/kWh, which is the actual price the SME is currently paying. The energy consumption of the SME operating with this scenario is 12,504 kWh/a, with a NPC of 72,163 €, representing 3,675 €/a of energy cost. Due to grid outages, an unmet demand of 0.41% is assumed in this scenario.

3.4.1. PV/battery-scenario

The PV/battery-scenario is a 100% renewable energy system powered exclusively by PV. Since power is also needed after sunset, a storage system is needed, which is provided by a battery. The optimal configuration would consist of 46.6 kW_p of PV and a battery storage of 40 kWh. **Figure 12** illustrates one week of production for the PV/battery-scenario. It can be seen that on a sunny day, peak PV production could reach almost four times the demand. The daytime demand can be fulfilled while charging the battery even during cloudy days (Thursday and Friday in the example). The battery is also regularly called upon early in the morning when the SME start to operate at 6:00, and at sunset.

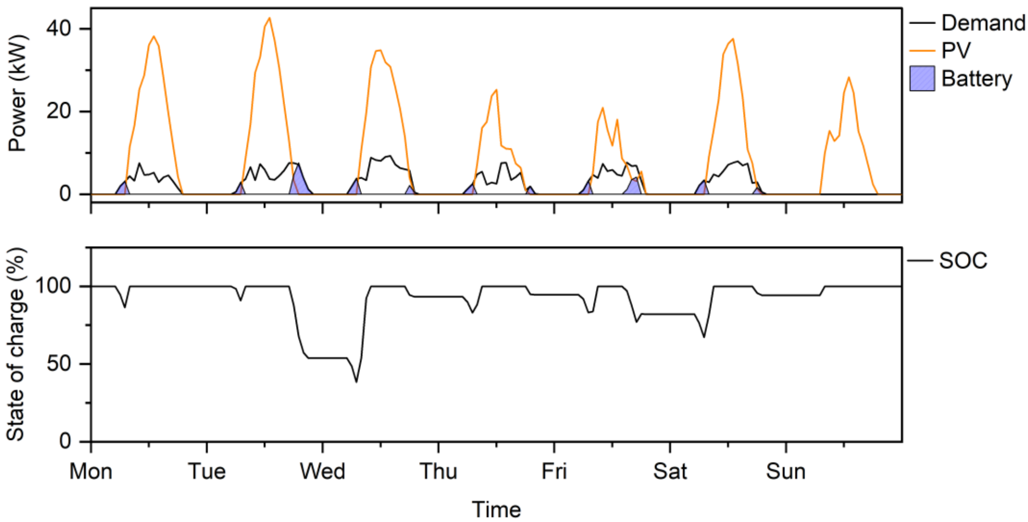


Figure 12. Power profile of the PV/battery-scenario during one-week of peanut oil production; demand, PV-, and battery power (top), state of charge (SOC) of the battery (bottom)

The NPC of the PV/battery -scenario would be 54,958 €, with an initial investment of 45,323 €, where 24,843 € is for PV and 11,916 € for the battery. The cost of energy (COE) would be 0.22 €/kWh. The energy surplus would be very high with 62,961 kWh/a (82.5%), since the system has to be oversized to provide enough energy during unfavourable weather condition.

3.4.2. PV/battery/diesel-scenario

The PV/battery/diesel-scenario is a PV/battery system combined with a diesel generator in order to avoid the oversizing that would be necessary for operation in days of low solar radiation. It corresponds to the best off-grid scenario. The system would consist of 24.5 kW_p of PV with a storage capacity of 40 kWh combined with a diesel generator supporting only 4.1% of the energy demand. **Figure 13** illustrates one week of production for the PV/battery/diesel-scenario. On sunny days, PV power is double the demand (Tuesday, Wednesday and Saturday). This allows to charge the battery while covering the daytime demand. The battery is used in the morning and at sunset. On cloudy days, diesel is used to fulfil the demand and quickly charge the battery (Monday, Thursday and Friday). It should be noted, that the generator produces more than necessary, as it is sized to cover the SME's maximum requirements unlike the battery, which only supplies the actual demand.

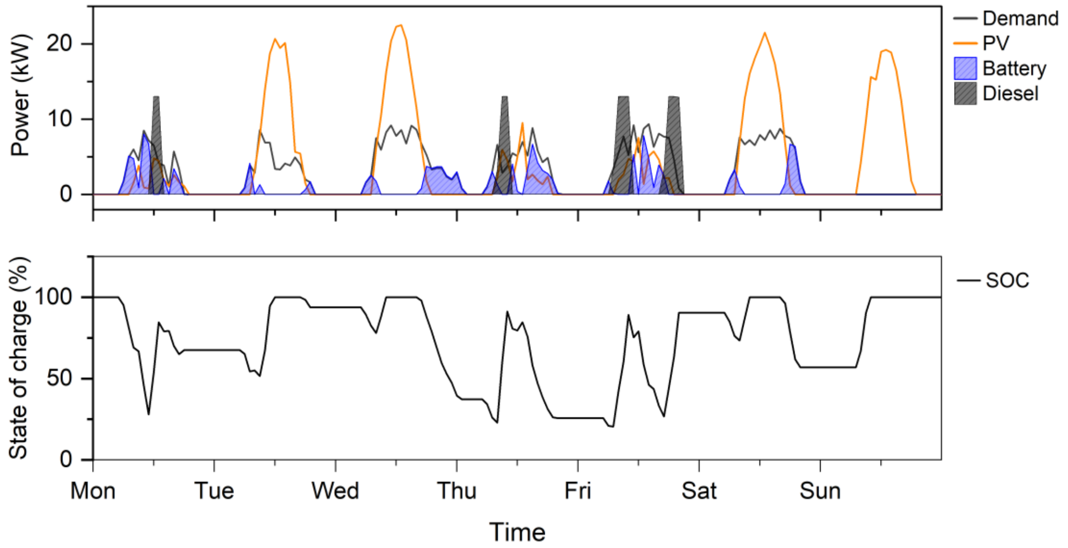


Figure 13. Power profile of the PV/battery/diesel-scenario during one-week of peanut oil production; demand, PV-, battery- and diesel power (top), state of charge (SOC) of the battery (bottom)

The NPC would be 50,746 €, with an initial investment of 34,268 € where 13,054 € is for PV and 11,916 € for the battery. The COE would be 0.21 €/kWh, and the energy surplus would be 27,135 kWh/a (66.8%).

3.4.3. PV/grid-scenario

The PV/grid-scenario is a PV system connected to the grid without battery storage. It runs on solar energy, with all PV production being consumed by the SME and supported by the grid when being required. It consists of 20.0 kW_p of PV fulfilling 77.3% of the demand. The unmet demand of this scenario would be 0.03%. **Figure 14** displays a typical week of production under this scenario. In the middle of the day, the PV is able to meet the demand, however a surplus is not exploited. The grid is always called upon at the beginning and end of the day, and on cloudy days when there is insufficient solar radiation (Tuesday to Friday). This scenario is only realistic if the grid is stable, as no alternative is available in the event of an outage. The NPC would be 34,930 € with an initial investment of 16,091 € and an operating cost of 959 €/a, resulting in a COE of 0.14 €/kWh.

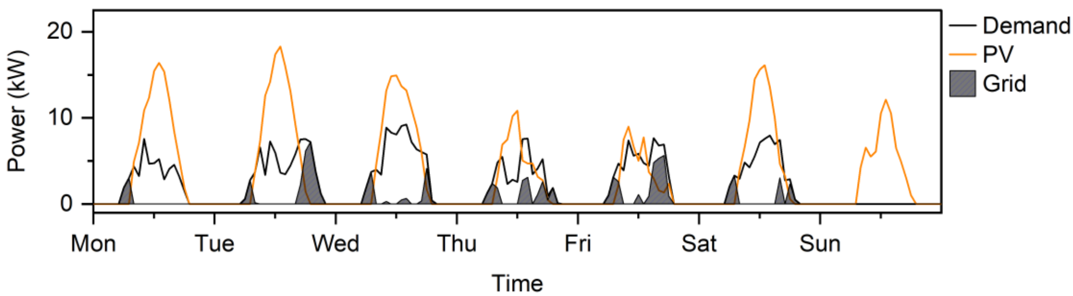


Figure 14. Power profile of the PV/grid-scenario during one-week of peanut oil production; demand, PV-, grid power

3.4.4. PV/battery/grid-scenario

The PV/battery/grid-scenario is a PV/battery system connected to the grid. It operates primarily on solar-generated energy and, if necessary, draws additional power from the grid. The best hybrid solution resulting from the simulation is a 18.6 kW_p grid connected PV system with 16 kWh battery storage. The renewable fraction of this system would be 90.0%, with an unmet demand of 0.01%. **Figure 15** displays a typical week of production under this scenario, demonstrating how the grid compensates for low solar radiation. The NPC would be 31,603 € and the initial investment 20,019 € with 9,926 € for PV and 4,767 € for the battery. The operation cost would be 590 €/a with 370 €/a for grid energy, and the COE of 0.13 €/kWh. The system would produce a surplus of 18,400 kWh/a (58.0%).

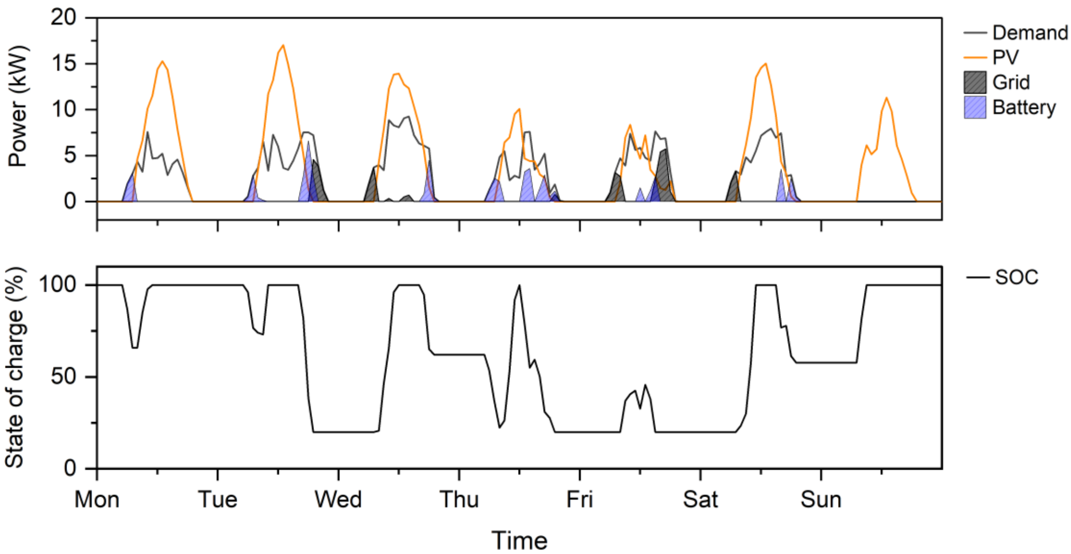


Figure 15. Power profile of the PV/battery/grid-scenario during one-week of peanut oil production; demand, PV-, battery- and grid power (top), state of charge (SOC) of the battery (bottom)

3.4.5. System classification

The optimization results and characteristics of the scenarios presented above are summarized in the **Table 5** with the grid only scenario as baseline scenario. The best hybrid scenario proposed is the PV/battery/grid-scenario. It would reduce the NPC from 72,163 € to 31,603 € compared to the baseline scenario. The operating cost would be reduced from 3,675 € to 590 €/a, resulting in a COE decrease from 0.29 to 0.13 €/kWh. Under this scenario, the renewable fraction would increase from 0% to 90.0%, while the unmet demand would decrease from 0.41% to 0.01%. The expected payback period for this scenario is 6.2 years.

For the best off-grid scenario (PV/battery/diesel), allowing to be independent from grid, an initial investment of 34,268 €, would be required, which is 77% more expensive than the investment of the PV/battery/grid-scenario. This option, as well as the PV/battery-scenario, is not as cost effective as the PV/battery/grid-scenario, but is still more profitable than the grid-scenario.

Table 5. Parameters of the investigated scenarios, ranked according net present cost (NPC)

Scenarios	PV	Battery capacity	NPC	Initial cost	COE	Ren. fraction	Unmet demand	Total energy produced	Total energy consumption	Excess electricity
	(kW_p)	(kWh)	(€)	(€)	(€)	(%)	(%)	(kWh/a)	(kWh/a)	(kWh/a)
Grid	-	-	72,163	0	0.29	0	0.41	12,504	12,504	0
PV/battery	46.6	40	54,958	45,323	0.22	100	0.36	76,298	12,510	62,961
PV/battery/diesel	24.5	40	50,746	34,268	0.21	95.9	0	40,603	12,555	27,135
PV/grid	20.0	-	34,930	16,091	0.14	77.3	0.31	35,548	12,551	22,486
PV/battery/grid	18.6	16	31,603	20,019	0.13	90.0	0.01	31,742	12,554	18,400

In **Figure 16** 10 out of 14 possible combinations of power sources were ranked according their NPC. The scenario PV-only was not technically feasible and the scenarios diesel-only, PV/diesel, or PV battery/diesel, were exclude from the analysis due to their high NPC, reaching up to 180,000 €. The figure indicates that the PV/battery/grid-scenario is located in position 1. In position 2, the PV/battery/grid/diesel-scenario is similar to the first scenario, since the generator would be rarely used. Scenarios 3 and 4 are PV/grid-scenarios with optional diesel generator (still rarely used). These are options without storage, which means lower initial cost. However, the absence of battery creates a reliability problem with an unstable grid. The optional generator, on the other hand, allows a more stable system. The presented off grid scenarios are the PV/battery/diesel-scenario and the PV/battery -scenario respectively in position 5 and 6 and the grid-scenario is located in position 7. Scenarios 8, 9 and 10 are non-renewable grid systems, with or without diesel and battery. But they remain similar to the baseline, and operate mainly on the grid.

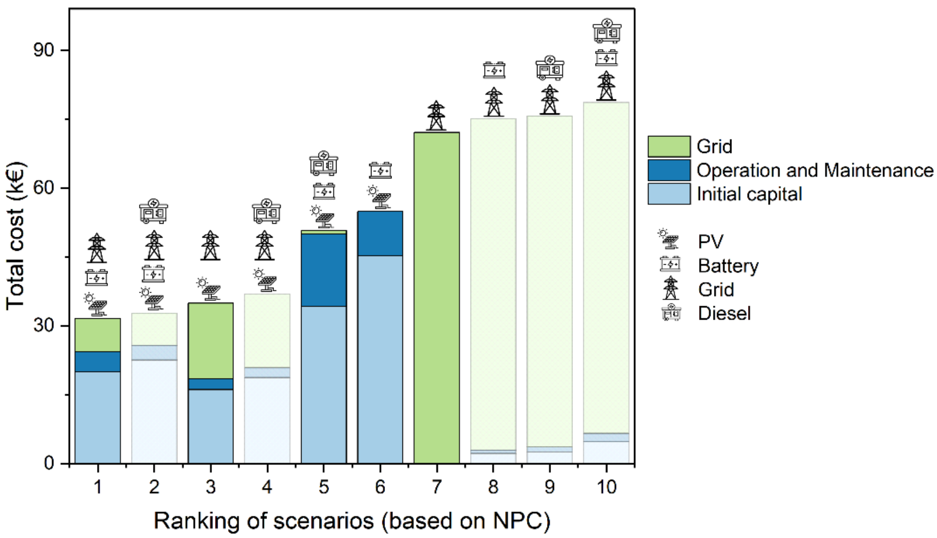


Figure 16. Classification of power supply scenarios ranked according to total cost for 25 years of operation

4. Discussion

The results demonstrate the feasibility of using a production plant diagnosis to create a load profile for sizing a PV system. During the diagnosis, four operations were identified that correspond to a simplified model of the industrial extraction process of peanut oil by cold pressing. The operating parameters differ slightly from the optimal parameters found in the literature. The steamed peanuts are mixed with 15% of shell while a mixing of 5 to 10% of shell is recommended [38]. However, it should be noted that a worn screw in the oil press or a poor destoning after shelling may cause clogging in the oil press, requiring more shells to be added. Additionally, the steaming time in this SME goes up to 90 minutes, whereas the optimum properties reported in the literature suggest a range of 10 to 25 minutes [38]–[40]. During the steaming in this SME the shells are used as fuel, which makes the operation cost and energy efficient.

The service-oriented mode of operation of the SME led to the definition of parameters to simulate the variability of activities. These parameters have similarities with the bottom-up approach used in household simulations to predict the behaviour of individual households and their interactions with the larger system. In the present case study, the parameters considered are used to build a more comprehensive picture of the interactions of the SME and the customers.

Similarities were found between peak and average power consumption obtained from simulation and on-site measurements. This validates the model used. The PV/battery/grid-scenario was found to be the most economic solution. It shows a 90.0% renewable energy coverage at a low storage requirement (20% of the daily consumption), based on the fact that the activities are mostly performed during the day, with power demands early in the morning from 06:00 and at early night to finish the processing of already started batches. The optimization shows that no new customers should be accepted close to sunset and the end time of customer acceptance was at 16:20.

An alternative conventional sizing approach could be made by considering the typical "commercial load profile" available on HOMER Pro, scaled to the daily energy consumption of the SME. The result would be again a PV/battery/grid-scenario with 35.4 kW_p of PV, 40 kWh battery storage. However, this system based on standard load profiles would be larger than for a real load profile and the investment would be 37,858 €. The proposed approach, therefore, allows a reduction in the investment cost of 47%, in particular thanks to a reduced storage capacity of 60%.

Nevertheless, a large amount of energy remains unused in the hybrid solutions. Alternatives should be found to exploit this extra energy. Since Senegal, for the time being, does not allow a feed-in to the grid, an additional economic activity for using the excess energy should be developed.

5. Conclusions

In this study, a novel process simulation model has been developed to obtain load profiles for PV sizing. The model focuses on capturing the complex peanut oil production system of SME and service-based operation, where various machines operate at different times throughout the day based on the operation strategy and the customers demand. An implementation in MATLAB Simulink was carried out and the operating parameters of the model were adjusted to match the real on-site conditions.

The load profiles were used in HOMER Pro to find the optimal configurations from an economic point of view. All the hybrid configurations combining grid, PV, battery and diesel generator were evaluated. The results showed that the most economical solution is a PV/battery/grid-system with 18.6 kW_p of PV and 16 kWh of battery storage. The NPC would be 31,603 € with initial costs of 20,019 € and the COE would be 0.13 €/kWh. The renewable fraction of the suggested PV system is 90.0% with an unmet load of 0.01%. The payback period of the system would be 6.2 years. For an off-grid solution, the simulations showed that although the solutions are more cost-effective than the grid, the benefits are lower than that of the hybrid solution and the investment cost are very high. The COE of the fully renewable PV/battery-system would be 0.22 €/kWh, which is still lower than the COE of energy from the grid at 0.29 €/kWh. However, this scenario would be not affected by rising electricity prices and could be applied in remote areas without grid connection.

Beyond the load profiles established and used for the simulations, it should be noted that the SME may have other parallel activities, such as rice husking. Excess energy may be used for those activities. An analysis of the whole activity of the SME could show how much of the parallel activities can be covered by the PV system.

Author contributions

Wiomou Joévin Bonzi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization, **Sebastian Romuli:** Conceptualization, Methodology, Investigation, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition, **Djicknoum Diouf:** Conceptualization, Investigation, Resources, Writing - Review & Editing, Supervision, **Bruno Piriou:** Conceptualization, Investigation, Writing - Review & Editing, **Klaus Meissner:** Writing - Review & Editing, Supervision, Project administration, Funding acquisition and **Joachim Müller:** Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

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Declaration of interests

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Appendix A