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Optimal sizing and economic assessment of diesel and solar mills for cereal milling in rural areas of Senegal

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ABSTRACT

This paper aims at using life cycle costing (LCC) to assess the economic viability of solar and diesel mills for cereal milling, adopting several scenarios of village sizes in Senegal and time perspectives. This work is intended to provide decision-makers and stakeholders with valuable information for selecting optimal milling systems, taking into account both economic and village size considerations. The methodology adopted is based on system specifications and daily cereal consumption profiles. To determine the economic performance of systems, three types of villages are evaluated and analyzed in detail from short, medium, and long-term perspectives. The results indicate that solar mills are the most economical systems for milling cereals in remote villages in the long term, with a potential economic gain of 10%, 31%, and 41% for small, medium, and big villages respectively, compared to diesel mills. However, solar mills are less promising in the short term.

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1. INTRODUCTION

Pearl millet, maize and sorghum, are the staple food crops of rural households in Senegal, with an annual consumption of 64.8 kg per capita [1]-[3]. This high demand makes traditional cereal milling inefficient. With this trend, the mechanization of cereal milling with the use of hammer mills driven by induction motors due to their advantages has become a reliable alternative [4]-[6]. In this paper, we focus on cereal mills in Senegal's rural areas because, despite the efforts, the issue of cereal milling remains unresolved and needs to be addressed. On the one hand, many villages are not electrified, and on the other hand, cereal milling in Senegal mainly serves the domestic market and making an essential contribution to food security in rural areas. To achieve this, it is necessary to equip rural areas with mills that can only be powered by diesel or solar power.

Although both systems meet the requirements of cereal milling, there are significant differences in terms of cost, reliability and environmental impact. Thus, several works [7]-[9] have been carried out to highlight solar and diesel systems. For diesel systems, the steady diesel supply and maintenance are problematic, even if capital costs are low. In contrast, solar systems are highly appropriate due to the high solar potential in Senegal. However, the high capital costs are the main limits. Based on classic analyses, the high capital cost of solar systems is often daunting to donors and project implementers in rural areas on the one hand. On the other hand, with diesel systems, beneficiaries are often faced with the high running costs. Thus, it has become urgent to propose a solution through a detailed study, allowing them to select the most appropriate system.

Indeed, in previous studies comparing diesel and solar systems, the time and size criteria of the village are almost never taken into account at the same time. But, diesel and solar systems offer advantages, depending on specific needs of each village and government's short and medium-term rural electrification plans. Based on the analyses, the choice of systems in rural areas must take into account economic issues, but also the context and prospects, which consider the time and size of villages divided into small, medium, and large [10], [11].

The aim of this work is to compare solar and diesel mills through optimal sizing and economic assessments based on the life cycle costing (LCC) concept. This study was carried out on the basis of milling unit specifications, daily cereal requirements and economic parameters such as component costs, operating costs and economic rates for three scenarios based on criteria of time and of village size, which is set at 500, 900, and 1200 inhabitants for small, medium, and big villages. Within the context of the study, the short-term means a period shorter than 7 years, medium-term covers a range from 7 to 12 years and long-term is a period longer than 12 years.

The rest of this paper is organized as follows: The section 2 deals with sizing and assessment methodologies. In section 3, the results are presented and discussed. The conclusions are highlighted in section 4.

2. MATERIALS AND METHOD

The procedure for the assessment of mills, illustrated in Figure 1 and Figure 2, is as follows. By considering the milling unit model developed [5], [6] the hourly flow rate is calculated on the basis of rated power (P_n) and rotational speed (ω_n) as given in (1). Energy requirements are calculated taking into account input parameters such as the daily quantity of cereal required (M_c), the number of inhabitants per village (n_p), the daily cereal consumption per inhabitant (β_p), the daily operating time (t_{op}) and the efficiency of the milling unit (η_{mu}). These data, along with the power rating of the milling unit, are used to determine the size of solar and diesel mills. Once the systems have been sized, the economic assessment is carried out.

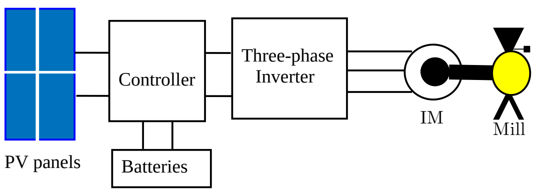

Figure 1. Schematic diagram of the solar mill

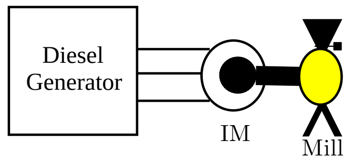

Figure 2. Schematic diagram of the diesel mill

The relationship between load torque (T_l) and flow rate (Q) in kg/min is given by (1).

$$\mathrm{T_l(Q) = 0.578 \cdot Q^2 + 7.621 \cdot Q + 0.047} \tag{1}$$

Hourly flow rate: Assuming that the load torque is equal to the rated motor torque at the operating point, the flow rate in kg per hours of the considered milling unit can be calculated from.

$$\mathrm{Q(P_n, \omega_n) = 60 \cdot 6.592 \left[\sqrt{0.9981 + 0.0398 \cdot P_n \cdot \omega_n^{-1}} - 1\right]} \tag{2}$$

Energy requirements: The variables t_{op}, M_c and the energy requirement (E_l) are calculated as (3).

$$\mathrm{t_{op} = \frac{M_c}{Q} = \frac{n_p \cdot \beta_p}{Q}} \tag{3}$$

$$\mathrm{E_l(n_p) = \frac{P_n}{\eta_{mu}} \cdot t_{op} = \left[\frac{P_n}{\eta_{mu}} \cdot \frac{\beta_p}{Q}\right] \cdot n_p} \tag{4}$$

2.1. Sizing of solar mill

PV panels: Based on [12]-[17], and according to (5), the power generated by PV panels ($\mathrm{P_{pv}}$) can be estimated based on solar irradiation $\mathrm{I_r}$(kW/m^2) and radiation G (kWh/m^2), and the PV system efficiency (η_s).

$$\mathrm{P_{pv}(n_p)} = \frac{\mathrm{I_r \cdot E_l}}{\mathrm{G} \cdot \eta_\mathrm{s}} = \left[\frac{\mathrm{I_r}}{\mathrm{G}} \cdot \frac{\mathrm{P_n}}{\eta_\mathrm{mu} \cdot \eta_\mathrm{s}} \cdot \frac{\beta_\mathrm{p}}{\mathrm{Q}}\right] \cdot \mathrm{n_p} \tag{5}$$

Given the inclusion of a battery, PV systems incur losses during the charging and discharging processes. In [18] and [19], the performances of the batteries were evaluated. Under optimum conditions, Li-ion batteries can achieve efficiencies of 99% efficiency. However, a reasonable estimate of efficiency is 95%. The charge controller and inverter have efficiencies of 95-97%. Based on results, system efficiency is set at 80%. Battery storage: The battery storage capacity is estimated according to the the daily energy required, the number of autonomous days (N_d) and the depth of discharge of the battery (DOD) [20].

$$\mathrm{C_{Wh}(n_p)} = \frac{\mathrm{E_l \cdot N_d}}{\mathrm{DOD} \cdot \eta_\mathrm{s}} = \left[\frac{\mathrm{N_d}}{\mathrm{DOD}} \cdot \frac{\mathrm{P_n}}{\eta_\mathrm{mu} \cdot \eta_\mathrm{s}} \cdot \frac{\beta_\mathrm{p}}{\mathrm{Q}}\right] \cdot \mathrm{n_p} \tag{6}$$

Inverter and charge controller: Ideally, the inverter size should be slightly larger than the peak AC load, and the charge controller should be sized to handle the maximum PV current and voltage, but also to be able to generate the required charging current. Thus, the inverter power and charge controller can be estimated using the (7) and (8), taking into account safety factors of 10% and 15% respectively.

$$\mathrm{P_{in}} = 1.1 \cdot \frac{\mathrm{P_n}}{\eta_\mathrm{mu}} \tag{7}$$

$$\mathrm{I_{ct}} = 1.15 \cdot \max\left(\frac{\mathrm{P_{in}}}{48}, \frac{\mathrm{P_{pv}}}{48}\right) \tag{8}$$

2.1.1. Sizing of diesel mill

The DG power should be equal to the power required by the milling unit. Therefore, it is obtained by:

$$\mathrm{P_G} = \frac{\mathrm{P_m}}{\eta_\mathrm{mu}} \tag{9}$$

previous studies [21]-[23] show that the diesel consumption $\mathrm{D_c}$ (l/h) can be calculated using (10).

$$\mathrm{D_c} = \mathrm{k_1 \cdot P_G + k_2 \cdot P_{Gt}} \tag{10}$$

$\mathrm{k_1}$ and $\mathrm{k_2}$ are coefficients of fuel consumption curve (l/kWh), given by 0.246 and 0.08145, respectively [24]. $\mathrm{P_G}$ is the rated power and $\mathrm{P_{Gt}}$ is the output power. For our case, it is assumed that the system operates at rated power. Therefore, the rated and the output power are equal. Thus, the daily consumption of diesel is:

$$\mathrm{V_d} = \mathrm{(k_1 + k_2) \cdot P_G \cdot t_{op}} \tag{11}$$

2.2. Economic assessment

The LCC method can be found in previous related works [25]-[28]. For this work, the remaining costs called are ignored but the discount factor is considered. Therefore, the LCC of each milling system is the sum of the capital cost ($\mathrm{C_c}$), the operating and maintenance costs (O&$\mathrm{M_c}$) and the replacement costs ($\mathrm{R_c}$). The LCC can be calculated using (12).

$$\mathrm{LCC} = \mathrm{C_c + O\&M_c + R_c} \tag{12}$$

According to [29], [30] the discount factor (γ) is estimated from the inflation (i) and discount (d) rates.

$$\gamma = \frac{1 + \mathrm{i}}{1 + \mathrm{d}} \tag{13}$$

2.2.1. LCC of solar mill

Capital cost: The $\mathrm{C_c}$ includes the component costs and the installation cost set at 10 % of components costs.

$$\mathrm{C_c^{SM}} = 1.1[\mathrm{C_{pv}} + \mathrm{C_{ct}} + \mathrm{C_{in}} + \mathrm{C_{bt}} + \mathrm{C_{mu}}] \tag{14}$$

$\mathrm{C_{mu}}$ is the milling unit cost. $\mathrm{C_{pv}}, \mathrm{C_{bt}}, \mathrm{C_{ct}}$ and $\mathrm{C_{in}}$ are total acquisition costs of PV panels, controller, inverter and battery, which can be described by the following:

$$\mathrm{C_{pv}}(\mathrm{n_p}, \alpha_{\mathrm{pv}}) = \left[\frac{\mathrm{I_r}}{\mathrm{G}} \cdot \frac{\mathrm{P_n}}{\eta_{\mathrm{mu}} \cdot \eta_{\mathrm{s}}} \cdot \frac{\beta_{\mathrm{p}}}{\mathrm{Q}}\right] \cdot \mathrm{n_p} \cdot \alpha_{\mathrm{pv}} \tag{15}$$

$$\mathrm{C_{bt}}(\mathrm{n_p}, \alpha_{\mathrm{bt}}) = \left[\frac{\mathrm{N_d}}{\mathrm{DOD}} \cdot \frac{\mathrm{P_n}}{\eta_{\mathrm{mu}} \cdot \eta_{\mathrm{s}}} \cdot \frac{\beta_{\mathrm{p}}}{\mathrm{Q}}\right] \cdot \mathrm{n_p} \cdot \alpha_{\mathrm{bt}} \tag{16}$$

$$\mathrm{C_{ct}}(\alpha_{\mathrm{ct}}) = 1.15 \cdot \max(\frac{\mathrm{P_{in}}}{48}, \frac{\mathrm{P_{pv}}}{48}) \cdot \alpha_{\mathrm{ct}} \tag{17}$$

$$\mathrm{C_{in}}(\alpha_{\mathrm{in}}) = \mathrm{P_{in}} \cdot \alpha_{\mathrm{in}} \tag{18}$$

where $\alpha_{\mathrm{pv}}(\$/\mathrm{W})$, $\alpha_{\mathrm{ct}}(\$/\mathrm{A})$, $\alpha_{\mathrm{in}}(\$/\mathrm{W})$ and $\alpha_{\mathrm{bt}}(\$/\mathrm{Wh})$ denote the acquisition cost per unit power of PV panels, controller, inverter and battery, respectively.

Operating and Maintenance cost: It is the sum of the operating and maintenance costs associated to PV panels ($\mathrm{OM_c^{pv}}$), controller ($\mathrm{OM_c^{ct}}$), inverter ($\mathrm{OM_c^{in}}$), battery ($\mathrm{OM_c^{bt}}$) and milling unit ($\mathrm{OM_c^{mu}}$).

$$\mathrm{OM_c^{pv}} = \sum_{\mathrm{y}=1}^{\mathrm{N_y}} \left[\frac{\mathrm{I_r}}{\mathrm{G}} \cdot \frac{\mathrm{P_n}}{\eta_{\mathrm{mu}} \cdot \eta_{\mathrm{s}}} \cdot \frac{\beta_{\mathrm{p}}}{\mathrm{Q}}\right] \cdot \mu_{\mathrm{pv}} \cdot \mathrm{n_p} \cdot \gamma^{\mathrm{y}} \tag{19}$$

$$\mathrm{OM_c^{bt}} = \sum_{\mathrm{y}=1}^{\mathrm{N_y}} \left[\frac{\mathrm{N_d}}{\mathrm{DOD}} \cdot \frac{\mathrm{P_n}}{\eta_{\mathrm{mu}} \cdot \eta_{\mathrm{s}}} \cdot \frac{\beta_{\mathrm{p}}}{\mathrm{Q}}\right] \cdot \mu_{\mathrm{mu}} \cdot \mathrm{n_p} \cdot \gamma^{\mathrm{y}} \tag{20}$$

$$\mathrm{OM_c^{ct}} = \sum_{\mathrm{y}=1}^{\mathrm{N_y}} 1.15 \cdot \max(\frac{\mathrm{P_{in}}}{48}, \frac{\mathrm{P_{pv}}}{48}) \cdot \mu_{\mathrm{ct}} \cdot \gamma^{\mathrm{y}} \tag{21}$$

$$\mathrm{OM_c^{in}} = \sum_{\mathrm{y}=1}^{\mathrm{N_y}} 1.1 \cdot \mathrm{P_{max}} \cdot \mu_{\mathrm{in}} \cdot \gamma^{\mathrm{y}} \tag{22}$$

$$\mathrm{OM_c^{mu}} = \sum_{\mathrm{y}=1}^{\mathrm{N_y}} \mathrm{C_{mu}} \cdot \mu_{\mathrm{mu}} \cdot \gamma^{\mathrm{y}} \tag{23}$$

$\mu_{\mathrm{pv}}(\$/\mathrm{W}), \mu_{\mathrm{ct}}(\$/\mathrm{A}), \mu_{\mathrm{in}}(\$/\mathrm{W}), \mu_{\mathrm{bt}}(\$/\mathrm{Wh})$ and $\mu_{mu}(\%)$ are the annual O&M costs of components.

Replacement cost: The replacement cost is calculated based on the acquisition cost, the lifetime and the number of replacement [31]. In our case, no replacement is needed for PV panels. Assuming that the lifetime of other components ranges between 10 and 15 years, one (1) replacement is needed for each of them. Thus, the replacement costs of batteries, inverter, controller and milling unit are calculated using the following:

$$\mathrm{R_c^{bt}} = \mathrm{C_{Wh}} \cdot \mathrm{n_p} \cdot \alpha_{\mathrm{bt}} \cdot \gamma^{\mathrm{N_{bt}}} \tag{24}$$

$$\mathrm{R_c^{ct}} = \mathrm{I_{ct}} \cdot \alpha_{\mathrm{ct}} \cdot \gamma^{\mathrm{N_{ct}}} \tag{25}$$

$$\mathrm{R_c^{in}} = \mathrm{P_{in}} \cdot \alpha_{\mathrm{in}} \cdot \gamma^{\mathrm{N_{in}}} \tag{26}$$

$$\mathrm{R_c^{mu}} = \mathrm{C_{mu}} \cdot \gamma^{\mathrm{N_{mu}}} \tag{27}$$

$\mathrm{N_{ct}}, \mathrm{N_{in}}, \mathrm{N_{bt}}$, and $\mathrm{N_{mu}}$ denote the lifetime of controller, inverter, battery, and milling unit.

2.3. LCC of diesel mill

Capital cost: The capital cost includes the milling unit, DG and installation costs. As introduces, the installation cost is set at 10% of investment cost. Thus, the capital cost of diesel mills can be calculated as:

$$\mathrm{C_c^{DM}} = 1.1 \cdot [\alpha_{\mathrm{gd}} \cdot \mathrm{P_G} + \mathrm{C_{mu}}] \tag{28}$$

where $\alpha_{\mathrm{g}}(\$/\mathrm{W})$ is the cost per unit power of the DG.

Operating and Maintenance: The O&M cost includes the cost to maintains the system components and the total cost associated to diesel consumption during the life cycle of the project. The O&M can be obtained by:

$$\mathrm{OM_c^{DM}} = \sum_{\mathrm{y=1}}^{\mathrm{N_y}} \left[\mathrm{C_{mu}} \cdot \mu_{\mathrm{mu}} + \sum_{\mathrm{i=1}}^{365} \mu_{\mathrm{g}} \cdot \frac{\beta_{\mathrm{p}}}{\mathrm{Q}} \cdot \mathrm{n_p} \right] \gamma^{\mathrm{y}} + \sum_{\mathrm{y=1}}^{\mathrm{N_y}} \left[\sum_{\mathrm{i=1}}^{365} \mathrm{C_d} \cdot \frac{(\mathrm{k_1} + \mathrm{k_2})\mathrm{P_m}}{\eta_{\mathrm{mu}}} \cdot \frac{\beta_{\mathrm{p}}}{\mathrm{Q}} \cdot \mathrm{n_p} \right] \gamma^{\mathrm{y}} \tag{29}$$

$\mu_{\mathrm{g}}(\$/\mathrm{h})$ is the hourly cost to maintains the DG. C_d corresponds to diesel cost per litter.

Replacement cost: The replacement cost for the DG can be calculated by:

$$\mathrm{R_c^g} = \sum_{\mathrm{k=1}}^{\mathrm{N_{rm}}} \alpha_{\mathrm{gd}} \cdot \mathrm{P_G} \cdot \gamma^{\frac{\mathrm{L_g}}{365 \cdot \mathrm{t_{op}}}} \tag{30}$$

$\mathrm{N_{rm}}$ is the number of replacement needed and $\mathrm{L_g}$ is the diesel generator lifetime in hours.

3. SIMULATION RESULTS AND DISCUSSIONS

3.1. Simulation program inputs

Economic rate: According to Central Bank of West African States and Media Center Statista, the inflation and discount rates are taken as 1.5% and 4.5%. The price of diesel is about \$1.12 per litter. Cereal consumption: The daily cereal consumption per hbts is estimated at 0.18 kg. Component costs and descriptions: Costs and descriptions of components are set out in Table 1.

Table 1. Input parameters for economic assessment

	PV panels	Controller	Inverter	Battery	Milling Unit	DG
Acquisition	\$ 1.1/Wp	\$ 8/A	\$ 0.4/W	\$ 0.2/Wh	\$ 689.66	\$ 0.37/W
O&M	\$ 3/kW/year	\$ 0.1/A/year	\$ 10/kW/year	\$ 5/kWh/year	\$ 7/year	\$ 0.01/h
Lifetime	25 years	12 years	12 years	10 years	15 years	12000/h

3.2. Results

3.2.1. Sizing results

The variations of the component sizes according to number of inhabitants are presented in Figure 3. In order to assess the economic viability of solar and diesel mills the following cases of study are selected: small village with 500 inhabitants, medium with 900 inhabitants, and big village with 1200 inhabitants (Table 2).

Table 2. Sizing results of the selected cases of study

		Daily requirements				Component sizes				
Village	People	Cereal	Time	Energy	Diesel	PV panels	Battery	Inverter	Controller	Generator
Small	500	90 kg	1.7 h	5123.3 Wh	1.68 l	1184.6 Wp	11994.4 Wh	3315 W	79.42	3014 W
Medium	900	162 kg	3.1 h	9221.9 Wh	3.02 l	2132.3 Wp	21589.9 Wh	3315 W	79.42	3014 W
Big	1200	216 kg	4.1 h	12296 Wh	4.03 l	2843.1 Wp	28786.5 Wh	3315 W	79.42	3014 W

The aim of the results is to validate the sizing model. From results, it is apparent that the sizes of DG, inverter and controller are independent to village size. In contrast, PV panels and battery sizes vary according to village size. Thus, 1184 Wp, 2132 Wp, and 2843 Wp with storage capacities of 11994 Wh, 21590 Wh, and 28786 Wh are required for small, medium, and large villages. For diesel mills, the diesel consumption varies according to the size of the village. Thus, 1.68, 3.02, and 4.03 liters per day are required for small, medium, and large villages. These results validate the sizing model and enable us to tackle the life cycle analysis.

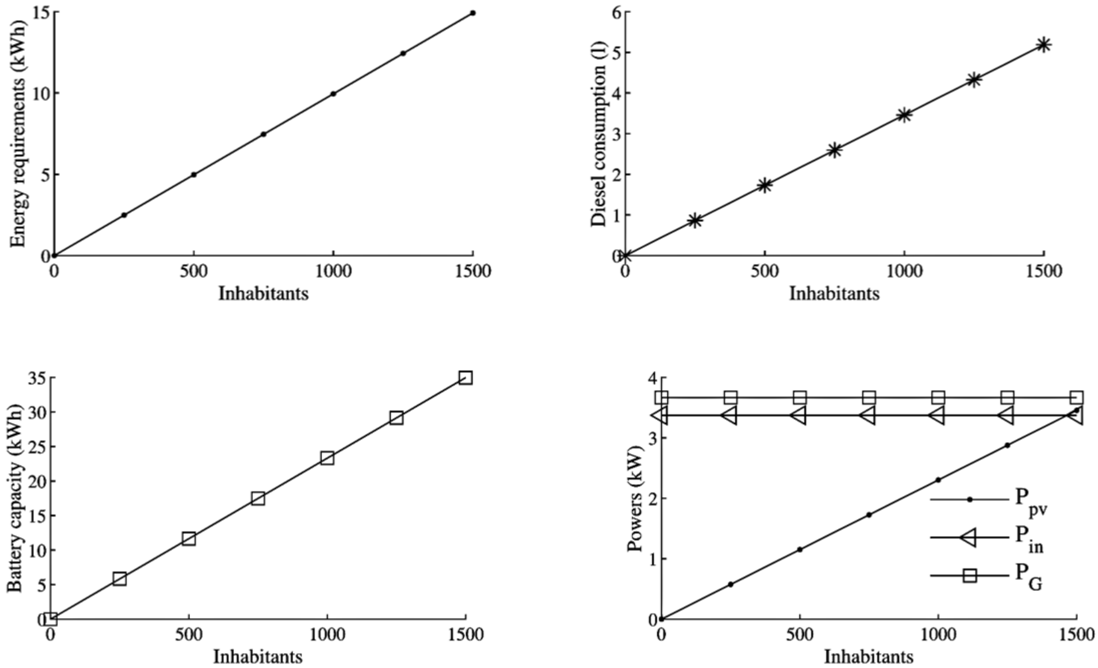

Figure 3. Variations of the component sizes versus number of inhabitants

3.2.2. LCC results

This section presents the LCC results for the solar and diesel mills. Table 3 and Figure 4 show a comparison for solar and diesel mills for three types of village. Life-cycle costs (LCC) were calculated over a 20-year period, taking into account capital costs, operating costs, maintenance costs, and replacement costs. The results show that solar mills are much cheaper on a LCC basis. The solar mills have a high capital cost, but very low operating and maintenance costs. Comparatively for diesel mills, the O&M costs required for small, medium and large villages are \$11162, \$20008, and \$26642 versus \$6988, \$10246, and \$12689.

Table 3. Life cycle costs of solar and diesel mills

	Solar mill				Diesel mill			
	Capital (\$)	O&M (\$)	Repl.(\$)	LCC (\$)	Capital (\$)	O&M (\$)	Repl.(\$)	LCC (\$)
Small village	6988.3	1667.4	3621.1	12276.8	1985.2	11161.9	445.5	13592.6
Medium village	10246.1	2426.6	5055.2	17727.8	1985.2	20007.7	1239.7	23232.6
Big village	12689.3	2996.1	6130.8	21816.2	1985.2	26642.1	2174.5	30801.7

This ratio, which varies from 6.69 to 9 depending on village size, explains the profitability of mills on life-cycle costs. However, although the solar mill is the most advantageous option in the long term prespective, the capital costs could justify the use of diesel mills in rural areas. But, economic lifetime can have a significant impact on the choice of diesel versus solar mills. This aspect is investigated by graphically comparing the LCC. Figure 4 shows the graphical comparison to analyze their economic viability in short, medium and long-term perspectives according to village sizes. Results show that the solar mill is the most economical option only in medium and long term, and diesel-powered mills are likely to be the best option in the short term due to their low capital cost. This result correlates with the capital costs, which are \$6988, \$10246, and \$12689 compared with only \$1985 for solar mills. However, for the medium and long-term perspectives, the overall comparison shows that solar mills are more competitive than diesel mills, even if some correspondence can be noted for small villages due to the fact that during this period some components need to be replaced.

3.3. Discussion

This paper compares solar and diesel mills for different scenarios relating to village sizes for short, medium and long-term perpectives. The results are discussed, while a comparison with the literature cannot be made, since there is hardly any work in the recent literature that provides a comparable in-depth analysis of milling systems. However, there are some closely related works that talk about pumping systems. In our work, we have come to same conclusions, but we have indicated that the choice should be based on technical and economic evaluations of each case. In fact, solar mills are economically viable for medium and long-term prospects, whatever the size of the village, as shown by the comparison between diesel and solar systems. These results can be explained by the considerable financial effort required to set up these systems, in contrast to diesel systems, which do not require as much financial effort. Inversely, for medium and long term prospects, the maintenance and operating costs of diesel systems will become very high, making them unprofitable. However, the use of diesel systems may be a viable option for relatively small villages, where demand is lower, making the payback period close to the replacement time of some PV components. So, choosing the diesel system in this case will not be absurd. The reliability of our results can be justified by the use of consumption and market data, but taking into account size and time parameters, which can influence system performances. However, the limits of this work lie in the lack of comparative work in the literature that would allow us to highlight results.

As a recommendation, we have provided evidence that solar mill is the most reliable and cost-effective option for cereal milling in remote areas of developing countries, where access to energy is often problematic. Indeed, rising diesel prices obviously change economic calculations, and these increases have a considerable impact on LCC and a reduction in the number of years it takes to break even on PV systems compared with diesel systems. Added to this is the decline price in PV systems, making solar systems more attractive.

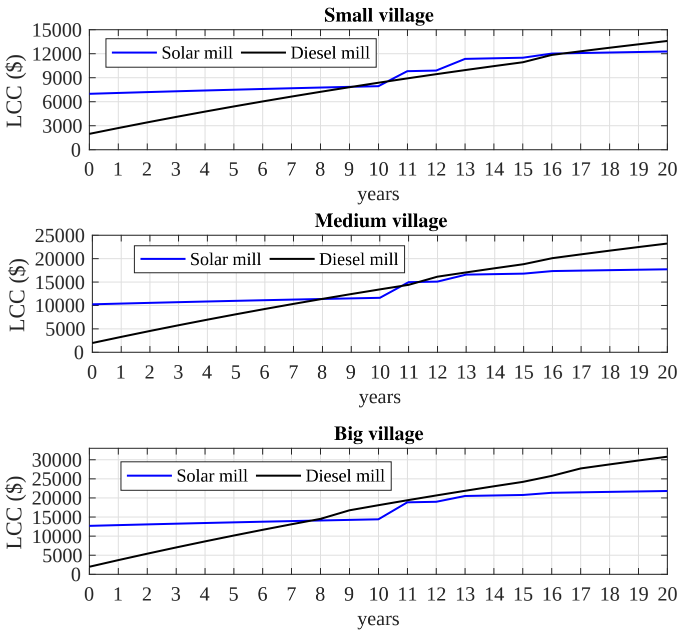

Figure 4. LCCs of solar and diesel mills according the village categories

4. CONCLUSION

This paper comparatively assesses the economic aspects of solar and diesel mills for three different village sizes using the LCC concept. Based on the comparative analysis for a 20-year life cycle, the solar mill is more economical. But for a shorter life cycle, the diesel mill becomes more affordable due to the very high capital cost of solar mills. In the medium and long terms, the overall comparison shows that, for remote villages, the solar mill seems more competitive if we take into account the decrease in the price of PV systems and the fluctuating price of diesel. The financial results determined through an economic analysis can help decision-makers in strategic choices aimed at supporting the development of the milling systems in rural areas.

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