Design and Calculation of Solar Power Operated Sugarcane Loading Machine

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Abstract— Amid growing environmental and economic challenges, solar energy has emerged as a promising renewable energy source, offering significant economic and environmental benefits. The agricultural sector, which heavily depends on fossil fuels for activities such as irrigation, harvesting, and transportation, stands to gain substantially from integrating solar energy technologies. These technologies help reduce costs, enhance efficiency, and mitigate environmental impacts. Sugarcane farming, in particular, is a resource-intensive and labor-dependent activity that can benefit significantly from adopting modern solar-powered mechanization technologies. This study focuses on the development and application of a solar-powered sugarcane loader designed to improve loading efficiency while minimizing operational costs and environmental impacts. The proposed system comprises key components, including solar panels, batteries, an electric motor, and hydraulic components, tailored to meet the energy demands of a loader weighing 1500 kg with a loading capacity of 250 kg and an operating speed of 2 m/s. Energy calculations indicate a daily requirement of 24,000 Wh, supported by 710 W solar panels and battery storage. Despite an initial investment of 500,000 EGP, the solar-powered loader benefits from negligible operational costs (50 EGP per acre), making it a sustainable and cost-effective alternative to traditional manual and mechanical methods. The results highlight that manual loading, while requiring no initial investment, is labor-intensive and time-consuming (1-2 days per acre) with high operational costs (2,250 - 3,000 EGP per acre). In contrast, mechanical loaders, such as tractor-mounted and bell loaders, improve efficiency but come with varying cost implications. The solar-powered loader demonstrates competitive performance, with a loading time of 5-8 hours per acre, positioning it as a viable alternative to conventional loading methods. Additionally, its adoption significantly reduces dependence on fossil fuels and lowers carbon emissions, aligning with global sustainability goals. The study recommends adopting solar energy technologies, particularly in regions with abundant sunlight, as a long-term solution for sustainable agricultural mechanization. Further research is encouraged to assess the large-scale feasibility of solar-powered systems in sugarcane farming.

Keywords: Solar-powered; sugar cane; loading machine; solar energy; sustainability; efficiency; energy; environmental; cost and not as an independent document. Please do not revise any of the current designations.

I. Introduction

In the face of increasing environmental and economic challenges, solar energy has emerged as one of the most promising renewable energy sources to meet global energy demands sustainably. This growing attention is attributed to its, environmental benefits, such as reducing carbon emissions, as well as its economic advantages, being a free and sustainable energy source compared to fossil fuels, which face rising costs and resource depletion. ([1], [2], [7]) The agricultural sector is among the primary industries heavily dependent on energy for operating machinery and systems, from irrigation to harvesting and transportation. Traditionally, these processes rely significantly on fossil fuels, leading to higher financial costs and negative environmental impacts. Solar energy, therefore, provides a sustainable solution that can meet the sector's energy needs, enhancing agricultural operations' efficiency while reducing costs and environmental burdens ([3], [4], [5], [10]). Powering irrigation pumps, providing heating and lighting for greenhouses, and supporting precision farming systems that rely on automation and clean energy. Furthermore, solar energy can reduce operational costs by up to 70%, minimize carbon emissions, and promote resource sustainability, thus easing financial burdens on farmers. ([2], [5], [12], [14])

Sugarcane cultivation is one of the agricultural fields that significantly benefits from these modern technologies. Globally, sugarcane is considered a strategic crop used for sugar and ethanol production, as well as animal feed. However, sugarcane farming is characterized by its high resource consumption and labor-intensive operations, making agricultural mechanization essential for improving efficiency and reducing costs. ([3], [6], [8], [14])

In Egypt, sugarcane is a vital crop that plays a central role in the national economy. The largest sugarcane cultivation areas are in Upper Egypt, particularly in governorates such as Sohag, Qena, Asyut, and Luxor. The cultivated area is estimated at approximately 320,000 hectares annually, producing around 10 million tons of sugarcane. With the growing global demand for sugarcane products, adopting modern technologies, including solar energy, has become essential for resource sustainability and productivity improvement. ([6], [7], [11], [13]). Research indicates that introducing agricultural machinery in sugarcane farming can increase productivity by over 40%, especially in major producing countries such as India and Brazil. These machines reduce the time required for planting and transportation, lower labor costs, and minimize crop losses during harvesting and transport. ([3], [4], [11])

The integration of solar energy into agricultural machinery, such as harvesters and loaders, represents a crucial step toward sustainable sugarcane farming. This technology reduces fossil fuel consumption, mitigates environmental pressures, and increases farmers' profitability. With advancements in solar energy research and the development of innovative solar-powered systems, the opportunities to apply these technologies in the agricultural sector are expanding rapidly. ([1], [2], [5], [9], [14]).

II. METHODS OF LOADING

A. *Manual Method*

Fig. 1. Manual Loading Method

In manual loading, 8-10 workers are required to load one acre of sugarcane Figure1, which takes about one to two days. Approximately 45-60 tons of sugarcane are produced per acre. Workers are paid 50 EGP per ton loaded. Consequently, the total cost of manual loading per acre ranges between 2,250-3,000EGP.

B. *Mechanized Method*

Fig. 2. Mechanized Loading Method

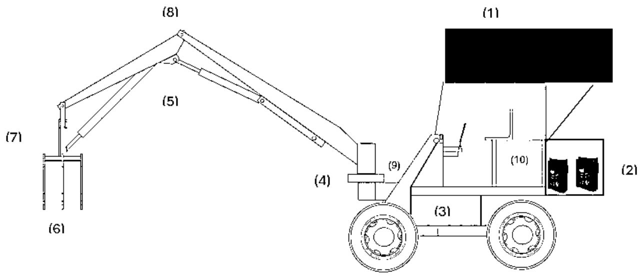
Currently, loading is done using loaders, and although there are several types, they all share the same hourly operating cost, which is 40 EGP. It takes 6 to 7 hours to load one acre of sugarcane, with an average production of 45-60 tons. Therefore, the total loading cost ranges between 240 and 280 EGP per acre. As for the available loader prices, the price of a loader mounted on a tractor ranges from approximately 45,000 to 60,000 EGP, while the price of a bell loader ranges between 900,000 and 1,100,000 EGP Figure2.

III. OBJECTIVE

The main and basic objective is to load the sugarcane stems onto the agricultural trailer or the Decauvelle There are a number of factors that must be taken into consideration to improve the sugarcane loading process. These include the following:

- The loading should be done quickly and efficiently. The cane must be loaded swiftly and with precision.
- The machine should not damage the crops near the cane being loaded. Its design and size should account for this.
- The cost of the machine satisfying these objectives should be optimal. It should be affordable for a middle-class farmer.
- The machine should not occupy a large space. It should be compact enough to fit within the land.
- The machine should not have excessive weight. It should be lightweight enough for a single person to operate it with ease.

IV. METHODOLOGY AND CALCUTATIONS



1.Solar Panels | 2. Batteries | 3. Electrical Hydraulic Pump | 4. 180° Rotating Component | 5. Hydraulic Cylinders for boom | 6. Grab |7. Hydraulic Cylinders for grab | 8. Boom | 9. Hydraulic Cylinders for rotating part |

Fig. 3. Proposed Solar-Powered Loader Design

The proposed system in this research is a solar-powered loader with the following specifications:

- Weight of the loader: 1500 kg
- Maximum load capacity: 250 kg
- Speed of the loader: 2 m/s
- Rated power of the electric motor: 3000 Wh

A. *System Component*

The main components of the system include:

- Solar Panels: Capacity of 710 watts (W), used to convert solar energy into electrical energy.
- Battery Bank: Each battery has a capacity of 300 ampere-hours (Ah) at 48 volts (V). The batteries store energy for use when solar power is unavailable.

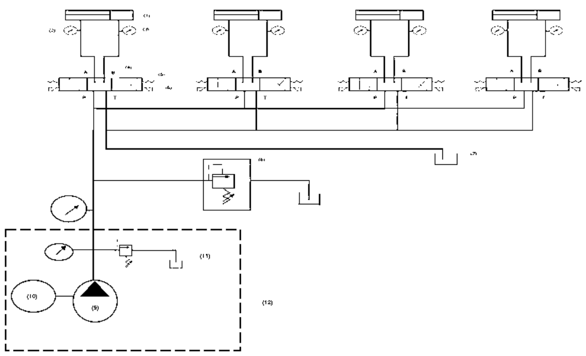
- Charge Controller: Regulates the voltage and current from the solar panels to prevent battery overcharging.
- Hydraulic System: Includes hydraulic pumps, cylinders, control valves, and piping to control the movement of the loader.
- Electric Motor: Rated at 3 kW, operates the loader to move and position it for loading sugarcane stems.

Fig.4. Electric motor (3KW)

TABLE 1:- MOTOR SPECIFICATIONS (ELECTRIC MOTOR)

Specification	Value
Nominal Power	3kw
Operating Voltage	48V
Speed (rpm)	2800 rpm
Type	DC Motor
Armature Current	79A

B. Hydraulic System Design



1.Cylinder | 2. Pressure gauge | 3. Pressure gauge | 4. Solenoid valve | 5. Return spring | 6. Solenoid | 7. Tank | 8. External relief valve | 9. Pump | 10. Motor | 11. Pump unit internal relief valve | 12. Hydraulic pump / motor unit

Fig. 5. Hydraulic Circuit Diagram

C. Energy Storage and Solar Power System Design

- System Load Calculation

The system is designed to power an electric motor with a rated power of 3 kW operating from 8:00 AM to 2:00 PM, which corresponds to 6 hours of daily operation.

$$E_{load} = P\times t \quad (1)$$

$$E_{load} = 3000\times 6 = 18000 \text{ Wh}$$

Where:

- ❖ E_{load} = Total daily energy consumption (Wh)
- ❖ P = Motor power (W)
- ❖ t = Operating hours per day (h)

- Energy Storage System Sizing

The required battery storage capacity was calculated by considering the efficiency of the charging and discharging cycle (η_p) and the depth of discharge (DOD). In this analysis, the battery efficiency was assumed to be $\eta_p = 0.85$.

$$E_{storage} = \frac{E_{load}}{\eta_p} \quad (2)$$

- ❖ $E_{storage}$ = 18000/0.85 =21176 Wh
- ❖ $E_{Storage}$ = Required energy storage capacity (Wh)
- ❖ η_p = Battery efficiency

The system utilizes two lithium-ion batteries, each with a voltage of 48V and a capacity of 300Ah, providing an individual energy storage capacity of:

$$E_{battery} = v \times c \quad (3)$$

$$E_{battery} = 48 \times 300 = 14400 \text{ Wh}$$

Where:

- ❖ $E_{battery}$ = Energy storage per battery (Wh)
- ❖ V= Battery voltage (V)
- ❖ C = Battery capacity (Ah)

Since one battery does not meet the required storage, two batteries are used, giving a total storage capacity of:

$E_{total} = 2\times E_{battery} = 28800$Wh

Solar Panel Sizing

The photovoltaic (PV) system is designed to generate sufficient energy to charge the batteries and power the motor. The required solar power is estimated using the following equation:

$$P_{solar} = \frac{E_{storage}}{H_{sun}\times\eta_{system}} \quad (4)$$

Where:

- ❖ P_{solar} = Required solar power (W)
- ❖ H_{sun} = Peak sun hours (h)
- ❖ η_{system} = Overall system efficiency

Three solar panels with a rated power of 710W each are selected, giving a total power capacity of:

$$P_{total} = 3 \times 710 = 2130 \text{ W}$$

Each panel operates at 48V with a short circuit current of Isc =18A. The total system current is:

$$I_{total} = 3 \times 18 = 54 \text{ A}$$

Where:

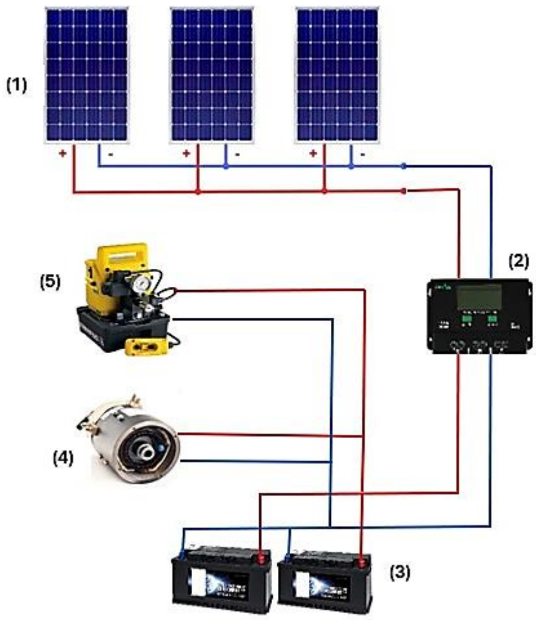
- ❖ P_{total} = Total solar power capacity (W)
- ❖ I_{total} =Total current from solar panels (A)
- ❖ I_{sc} = Short-circuit current per panel (A)

The system is designed to ensure compatibility between components, considering voltage, current, and efficiency factors to optimize performance and reliability.

TABLE 2:- DISPLAYS THE KEY COMPONENTS OF THE SOLAR-POWERED LOADER SYSTEM AND THEIR ESTIMATED PRICES

Part	Cost / EGP
Loader Frame	180,000
Hydraulic System	50,000

Electric Motor	18,000
Solar Panel (710 w)	6,000
2 Batteries	166,047.42
Charge Controller	2,000
Control Tools and Wiring	20,000
Arm and Grab	40,000
4 wheels	20,000
Accessories	4,000
Total Estimated Cost	500,000



1.Solar Panels | 2. Solar Charge Controller | 3. Batteries | 4. Electric Motor | 5. Electric Pump
Fig. 6. Hydraulic Circuit Diagram

V. RESULTS AND DISCUSSION

The study results revealed that manual loading remains the most widely used method for loading sugarcane, requiring 8 to 10 workers to load between 45 and 60 tons per acre over a period of one to two days. This method is characterized by its low initial investment cost, ranging from 0 to 3,000 EGP per acre, making it the least expensive in terms of infrastructure requirements. However, the heavy reliance on manual labor presents an ongoing challenge, particularly due to fluctuations in the availability of seasonal workers, which increases the likelihood of loading delays and indirectly raises operational costs.

Regarding mechanical loading methods, the findings indicate that using a tractor-mounted loader provides higher operational efficiency compared to manual loading, requiring approximately 6 to 7 hours to load one acre. The initial investment cost of this system ranges between 45,000 and 60,000 EGP, while operational costs per acre are estimated between 550 and 825 EGP. This system offers a balanced trade-off between operational efficiency and economic feasibility, making it a practical option for many farms.

In contrast, the bell loader demonstrated a superior performance compared to the tractor-mounted loader in terms of loading time per acre, requiring only 4 to 6 hours. However, its initial investment cost is significantly higher, ranging between 900,000 and 1,100,000 EGP, posing a major obstacle to its widespread adoption. Although its operational costs remain lower than those of the tractor-mounted loader (300-350 EGP per acre), the high initial investment makes it less economically viable in many cases.

Regarding the proposed solar-powered loader, the results indicate that its loading time per acre ranges between 5 and 8 hours, making it competitive with conventional mechanical systems. Its initial investment cost is estimated at approximately 500,000 EGP, but it benefits from significantly lower operational costs of around 50 EGP per acre due to its complete reliance on solar energy. The prices of the system components are based on current market estimates, and actual costs may vary depending on suppliers (see Table 3). Each component has been carefully selected to ensure efficient performance and a long system lifespan. The system includes key components such as the DC motor, solar panels, batteries, charge controller, and hydraulic components to provide the necessary force to carry the load. This system represents a sustainable and efficient alternative, particularly given the increasing shift toward reducing dependence on fossil fuels and adopting environmentally friendly technologies.

Based on these findings, it is evident that each loading method has its own advantages and limitations, necessitating a detailed analysis of factors such as long-term costs, labor availability, and the economic feasibility of each system under different operational conditions. Furthermore, these results highlight the need for further research to explore the viability of adopting sustainable systems, such as the solar-powered loader, as a cost-effective and environmentally friendly alternative in the sugarcane farming sector.

The shift towards using solar-powered loaders presents a potential reduction in reliance on traditional diesel-powered loaders, which in turn decreases fossil fuel consumption in sugarcane loading and transportation operations. As a result, the environmental impact associated with fuel combustion, such as greenhouse gas emissions and harmful pollutants, is minimized. Therefore, adopting this technology contributes to environmental preservation by reducing pollution and improving air quality in production areas, while also enhancing the sustainability of the sugarcane supply chain. This impact is further illustrated in the comparative cost analysis presented in Table 3 and the graphical representation in Figure7.

TABLE 3:- COMPARISON OF THE COSTS OF LOADING AN ACRE USING DIFFERENT SUGARCANE LOADING METHODS

System	Initial Cost (EGP)	Loading Time (per acre)	Operating Cost per Acre (EGP)
Manual Loading	No initial cost	1-2 days	2,250 - 3,000
Tractor-mounted Loader	45,000 - 60,000	6-7hours	550-825
Bell- Loader	900,000 - 1,100,000	4-6 hours	300-350
Solar-powered Loader	500,000	5-8 hours	50

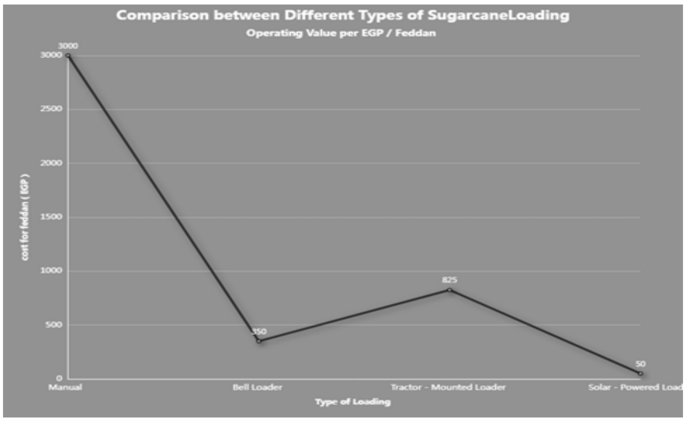


Fig. 7. Chart illustrates a comparison between different sugarcane loading methods in terms of operating costs per acre.

VI. CONCLUSION

- Manual Loading: It is preferable to use it in cases where labor is readily available at affordable prices. However, if labor availability becomes difficult, mechanized options should be considered.
- Tractor-mounted Loader: It is a good option for many farmers due to its acceptable initial cost and efficiency in terms of time.
- Wheel Loader: Although it is effective in saving time, its high initial cost could be a barrier for small farms.
- Solar-powered Loader: It is recommended as a sustainable option for farmers looking to reduce operational costs in the long run, especially in areas with abundant solar energy.

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