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DESIGN AND ANALYSIS OF A SOLAR ENERGY SYSTEM FOR A FRUIT HARVESTING ROBOT IN PAKISTAN

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In order to meet the growing agricultural demands, modern machinery needs to be deployed and cheaper energy supply needs to be ensured. With advancements in artificial intelligence, fruit harvesting robots can improve both the quality and productivity of fruit picking and increase orange fruit exports. However, to ensure effective working of the fruit harvesting robot, an energy source that is both efficient and cost-effective is necessary. This paper aims at designing of a solar energy system for a lightweight fruit harvesting robot for orange orchards in Pakistan and conducting a feasibility study for the deployment of the robot for remote agricultural land. The site for fruit harvesting robot employment is decided by irradiance using random forest regression. Solar system sizing is done based on the design and energy requirements of the fruit harvesting robot. The Homer Pro software is used for simulation of the system to analyse the potential of using solar system for fruit harvesting robot in Sargodha, Pakistan. The results show that compared to hybrid system, a stand-alone system is a more cost effective, reliable, and efficient option with a payback time of 3.36 years and levelized cost of energy being $0.085 per unit kWh. This study proves that solar energy is a viable and cheaper solution for using modern agricultural machineries, like fruit harvesting robot, in remote areas in developing countries, like Pakistan, to enhance productivity and improving quality of the produce.

Keywords: orange harvesting; random forest regression; Homer Pro; solar potential; fruit harvesting robot

In recent years, developing countries like Pakistan have experienced a huge rise in electricity prices. The energy supply shortage has not only made the availability of existing energy resources like electric power and natural gas very expensive, but the continuous availability of electricity and natural gas has also not been possible in many areas. Improved agricultural machinery can be a huge step in order to meet the growing demands as well as to keep the quality of produce better and consistent. However, to use modern agricultural machinery and methods, a consistent and affordable energy supply is also a must requirement. Hence, efforts must be made to design machinery and study the feasibility of other renewable resources like solar energy for agricultural applications.

Pakistan is an agricultural country. Modern technology and machinery can play a vital role in exploring the full agricultural potential of the country. Pakistan is known for its export of delicious fruits to many countries. Top exported fruits of Pakistan include mangoes, Kinnows (fragrant mandarin), other citruses, tomatoes, and bananas. The use of fruit harvesting robots equipped with deep learning techniques can enhance the productivity and value of export by quality pickup. However, this can only be achievable with the availability of a consistent low-cost energy supply. Solar energy has huge potential in a tropical country like Pakistan. Figure 1 shows the solar potential of Pakistan. An efficient solar setup not only reduces its dependency on electricity, but continuous power supply can be made available that can help the machinery to function without interruption.

Solar energy can play a significant role in the agricultural sector of developing countries by providing a reliable and cost-effective source of power for agricultural machinery, lighting, irrigation systems, and other farm equipment. Solar energy can play a crucial role in powering fruit harvesting robots. Machine learning algorithms can assist in determining feasible areas for use of fruit harvesting robots based on irradiance. These robots are equipped with a variety of sensors, cameras, and other technologies that allow them to identify and pick ripe fruits. They also use advanced algorithms to navigate the orchard and avoid obstacles. By using solar energy to power these robots, farmers can reduce their reliance on fossil fuels and decrease their operating costs. The robots can be equipped with solar modules that convert sunlight into electricity, which can be used to power the motors, sensors, and other electronic components. Solar energy can also be used to charge batteries that can store electricity for use during the periods of low sunlight, such as on cloudy days. This can help to ensure that robots can continue to operate even when there is little sunlight available.

Several factors need to be taken in account before installing the solar system in the agricultural sector. It is important to conduct a thorough site assessment to determine the best location for solar modules, taking into account the factors such as sunlight availability, shading, and the orientation of the land. The power needs of the specific agricultural equipment and operations that the solar energy system will be powering should be taken into account. This will help to ensure that the system is appropriately sized

and can meet the energy demands of agricultural machines. The cost of the solar energy system should be taken into account, and it should be designed to be cost-effective over long term, with a good return on investment and a reasonable payback time. Last but not the least, government incentives and funding programmes can help to make solar energy more affordable for farmers.

Solar energy has a great potential in the agricultural sector. Several recent studies have been conducted to assess the design and utilization of solar technology in the agricultural sector. Gorjian et al. (2021) provided a sustainable solar energy solution by the design of agricultural machine operation. Similarly, the design of solar energy power has been attempted in agricultural sector by other researchers for agricultural machinery for irrigation (Tariq et al., 2021), multi-purpose agricultural machines (Chadalavada et al., 2021), agricultural pumps (Zyoud et al., 2020), and portable IOT-enabled irrigation system (Ramli and Jabbar, 2022). Jamroen et al. (2022) dried banana products using solar energy with the energy consumption per day of only 0.323 kWh and a payback period of only 0.76 months. Gebremicheal et al. (2021) designed a solar collector for a solar dryer unit for perishable food items. Similarly, Madhankumar et al. (2021) designed a solar dryer with a payback time of 1.42 years. Many farms around the world now use solar energy for irrigation purposes. Ghosal et al. (2020) used solar power for a drip irrigation system for aerobic rice cultivation with a ayback period of 4 years.

Techno-economic analysis and feasibility study is an important aspect of solar system design. In the agricultural sector, techno-economic studies can be used to evaluate potential cost savings. In addition, techno-economic studies can also help to determine the feasibility of using solar systems to power precision agriculture technologies, such as sensors, drones, robots, and autonomous vehicles. These technologies can help farmers to optimize crop yields and reduce costs, but they often require significant amounts of power. By evaluating the costs and benefits of different solar power systems, techno-economic studies can help farmers to determine the most cost-effective and practical way to power these technologies. Shahzad et al. (2017) conducted a techno-economic feasibility analysis of solar renewable system in rural areas of Pakistan with a payback time of 9.5 years. Similarly, other feasibility studies were conducted for solar-based systems in buildings (Singh et al., 2017) with a payback of 13.6 years, and a desalination process (Elmaadawy et al., 2020), which concluded the hybrid power of solar and wind combined being low cost with 451 solar modules and 25 wind turbines. Elkadeem et al. (2019) also did a techno-economic analysis on agricultural area in Sudan with positive returns of 39.64% and 95% carbon reduction. Similarly, other studies have been conducted for feasibility analysis of solar system for various applications.

This study proposes the design of a fruit harvesting robot operated via solar energy. This study is novel in the following aspects:

- The study designs a unique light-weight hollow orange harvesting robot with a three-finger soft gripper that can be easily deployed in remote farms with minimal cost, as opposed to conventional large bulky industrial robots.
- The dataset used for the study is unique and collected for orange growing areas of Pakistan only. No prior dataset exists for determining solar potential for orange growing areas for the design of a model to be used by fruit harvesting robot.
- Another novel aspect of the study is that the parameters of the machine learning model, random forest regression, are fine-tuned to make it specific for this application only.
- Lastly, the techno-economic study for conventional, standalone, and hybrid system for installation of agricultural robot in Pakistan has never been done for this area and application. This study can be used to determine the feasibility of use of the robot in the agricultural sector and help boost the economy of the country.

Hence, this study is significant in assessing the performance and economic viability of solar-operated fruit harvesting robot as well as pave way for the design and use of further solar-operated modern agricultural machines in the region.

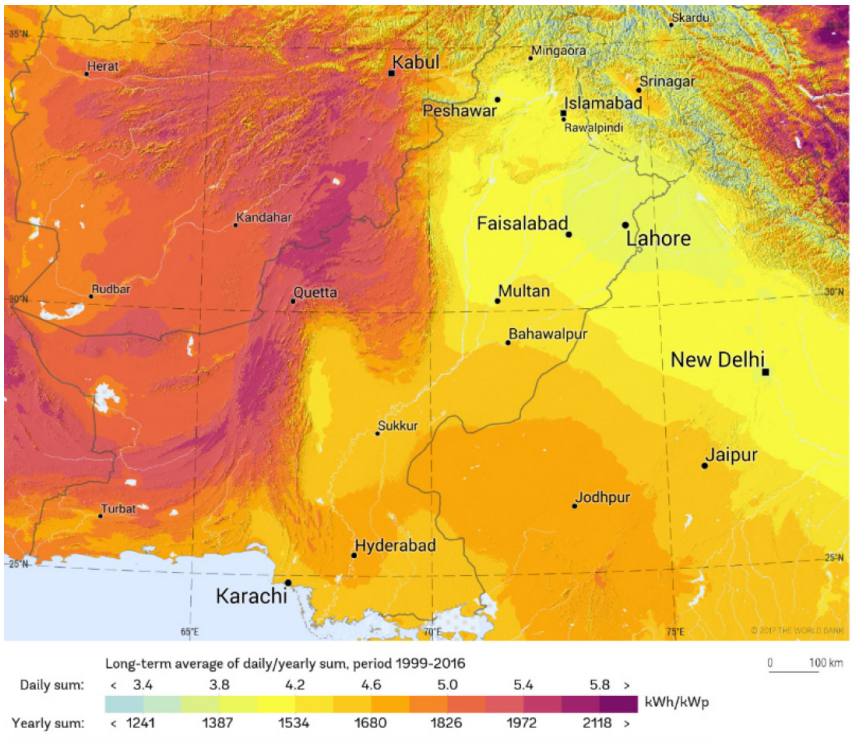


Fig. 1 Solar potential of Pakistan
Source: Global Solar Atlas

This paper designs the solar setup for an orange harvesting robot. It compares the energy and cost feasibility of electric energy supply, solar energy supply, and hybrid energy supply. The material and methods section explains the method for the design of solar setup for the fruit harvesting robot. Detailed calculations and the sizing of various components of solar setup are discussed. The feasibility study compares the electric system, solar system, and hybrid system. The results and discussion section discusses with reasoning the energy design that is better to be used for fruit harvesting application in remote areas of Pakistan. Finally, the paper concludes the designs and findings in the conclusion section.

Material and methods

A solar setup is studied for the designed light-weight fruit harvesting robot in the remote orange growing area of Sargodha, Pakistan. The methodology is illustrated in the flowchart as shown in Fig. 3. Torque is calculated for the robotic arm that determines the motor selection for the movement of the robot. The energy requirement of all the energy consuming devices of the fruit harvesting robot is noted and losses are added. Based on the location of areas, solar irradiance is determined using a random forest regression model. Solar module sizing, battery sizing, and controller sizing is computed based on energy requirement. Figure 2 shows the process diagram of the solar stand-alone energy system and the hybrid energy system. Next, the feasibility analysis is done. Electric energy supply from the grid, solar stand-alone setup, and hybrid energy setup are compared for cost feasibility to determine which setup is better for the energy supply of the fruit harvesting robot. The Homer Pro software is used for the verification of feasibility study.

The solar system is designed for a 5 DOF articulated robotic arm. The end effector is a three-finger silicon-based

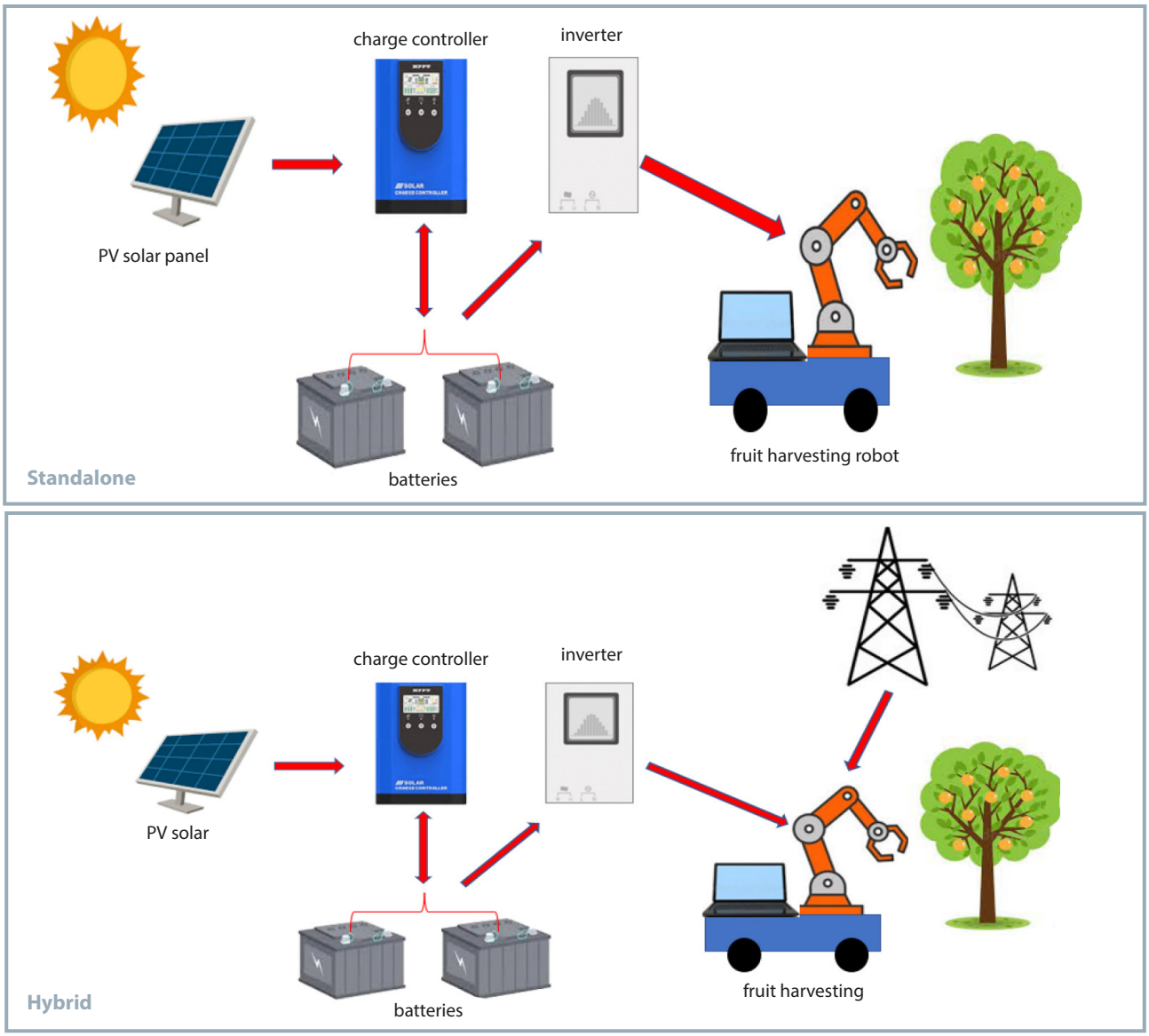


Fig. 2 Process diagram of the solar stand-alone system vs hybrid system for the fruit harvesting robot

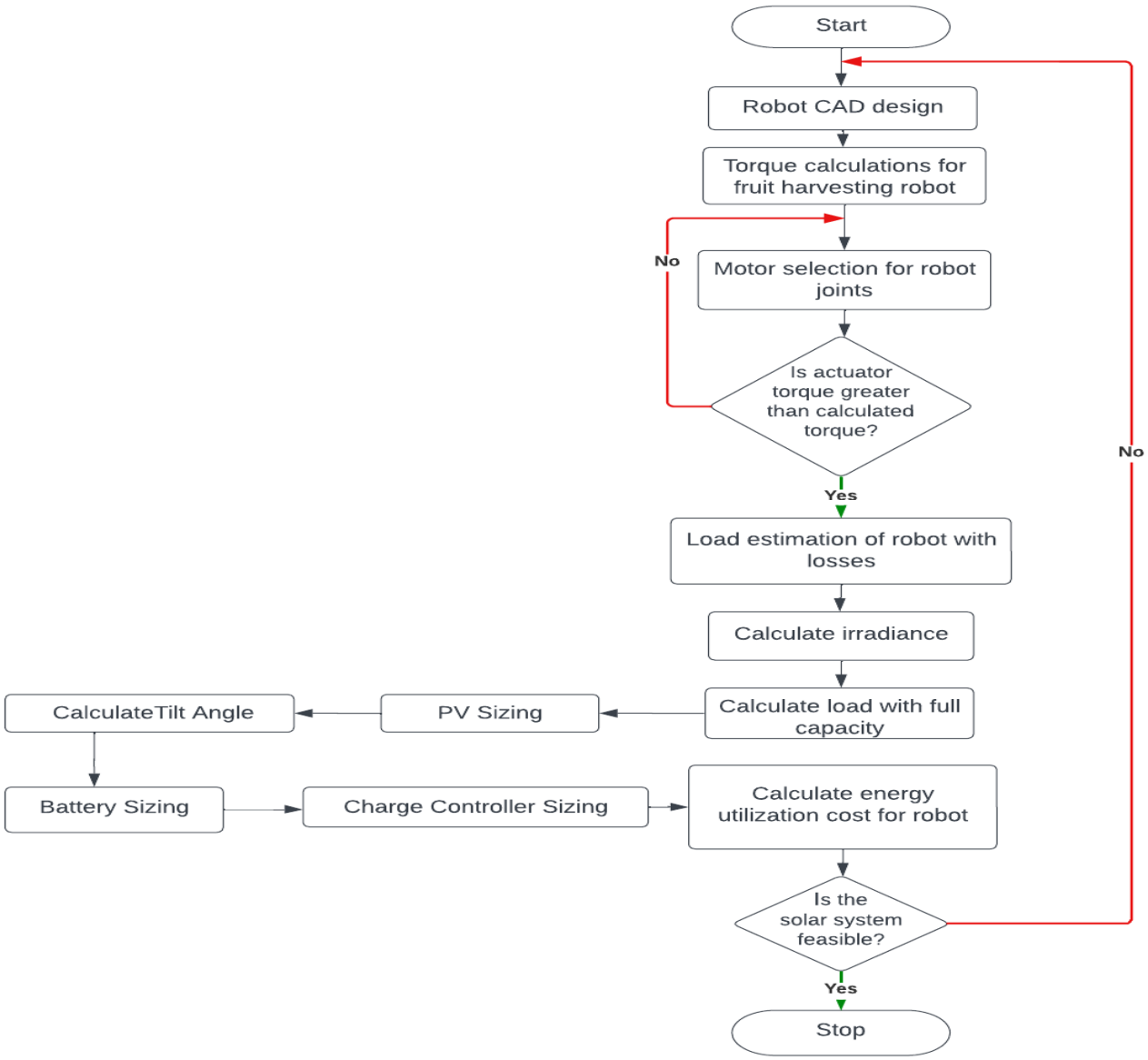


Fig. 3 Flowchart for the design of the solar system for the orange harvesting robot

electric gripper to prevent fruit damage while picking the fruit. Robot design is a lightweight hollow aluminium structure to make it more efficient, as shown in Fig. 4 below. The Kinect RGB_D camera is connected to a laptop for the fruit detection process. The load calculation of all devices is to be considered while designing of the solar system for the fruit harvesting robot in remote farms.

Two kinds of torques are acting on the robotic arm. Furthermore, pay load effect and the weight of motors is also added. Torque due to weight for a rectangular arm is calculated according to Eq. (1):

$$T = m \times g \times r \tag{1}$$

where: m – the mass of the rod; r – the distance from the centre of the rod to the pivot

The second torque is angular acceleration given by:

$$T_a = I \times \alpha \tag{2}$$

where: I – the moment of inertia; α – angular acceleration

Torque calculation is started from the base joint (joint 1) where the maximum torque acts, followed by joints 2, 3 4, and 5. Torques due to weight, angular torques, and additional payloads like the weight of fruit, are all added to calculate the torque for each joint. Total torque is calculated

Table 1 Torques for the joints of the robotic arm

	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5
Torque (N·m)	2.14	2.20	0.7	0.29	0.18

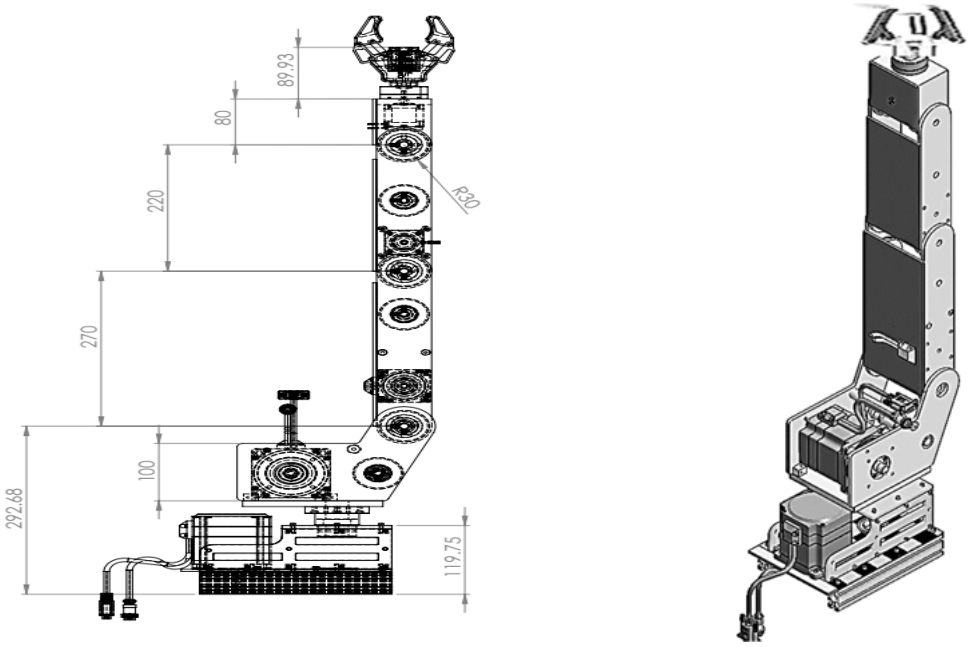


Fig. 4 CAD model of the fruit harvesting robot

using the formulas above and are also verified using the SolidWorks software.

Based on torque, actuators are selected for the fruit harvesting robotic arm joints.

The total load of the fruit harvesting robot per day is calculated. It is assumed the robot works for 6 hours a day. The estimated load of the fruit harvesting robot is shown in Table 3.

Table 2 Actuator selection based on torque calculated

Joints	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	End-effector joint
Actuator	Nema 34HE46-60004D-E1000	Nema 34E1K-120	Nema 23E1K-12	Nema 17HS15-104-ME1k	Nema 17HS15-104-ME1k	Nema 17HS15-104-ME1k
Power	360 W	360 W	192 W	41 W	41 W	41 W
Voltage	48 V	48 V	48 V	24 V	24 V	24 V
Rated current	6.0 A	6.0 A	4.0 A	1.5 A	1.5 A	1.5 A
Number of phases	2	2	2	2	2	2
Selected speed	120 rpm	150 rpm	300 rpm	300 rpm	300 rpm	300 rpm
Selected torque (N·m)	6.3 N·m	8.3 N·m	1 N·m	0.4 N·m	0.4 N·m	0.4 N·m
Peak torque (N·m)	9 N·m	12 N·m	1.2 N·m	0.45 N·m	0.45 N·m	0.45 N·m
Weight	4.5 kg	5 kg	0.72 kg	0.3 kg	0.3 kg	0.3 kg

Table 3 Estimated load of the fruit harvesting robot

Device	No. of devices	Total load (W)	Hours ($hr \cdot day^{-1}$)	Total load per day ($kWh \cdot day^{-1}$)
Stepper Nema Motors	6	1035	6	6.210
Dell Intel i5 core laptop	1	125	6	0.750
Kinect RGB-D camera	1	2.5	6	0.015
Encoder	6	36	6	0.216
Controller	6	36	6	0.216
Inverter driver	6	36	6	0.216
				7.623

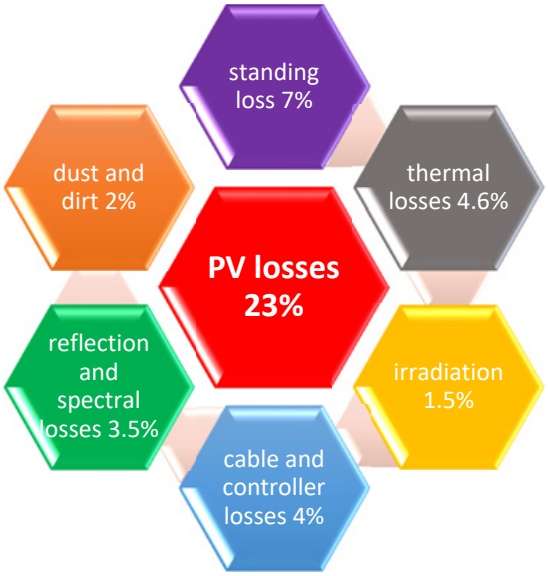


Fig. 5 Solar PV system losses for the designed system

Hence, it is a total load per day is 7.623 kWh without adding losses per day. After 23% losses, the total load requirement of the robot per day is as follows (Fig. 5): total load estimation (with 25% losses) per day = 9.376 kWh.

The amount of energy generated also depends on irradiance. Random forest regression is used to predict irradiance. Actual and predicted values are used to calculate the root mean square error that is 0.205 kWh·m^{-2}. The dataset of all fruit growing areas from northern, central, and southern Punjab of 237 entries are studied. The data is used to train and validate the model using an 80 : 20 ratio. The hyperparameters for this study include a total of 100 trees, with a maximum depth of 10. The initial node is set to 10, and the minimum sample split is 5. The minimum sample leaf is kept 2, with a random-state value of 42.

The mean daily irradiance of orange growing areas in Pakistan is 4.8 kWh·m^{-2} in winters. The orange growing areas of Pakistan like Sargodha, Chiniot, Sahiwal, and Bhalwal are the most favourable for the study. Figure 6 below shows the irradiance of Sargodha, where specific photovoltaic power output refers to solar output from the solar system per unit area, and global horizontal irradiation is the total solar radiation reaching the earth surface at a selected location.

$$\textit{solar system size}\ (\text{kW}) = \textit{required load per day}\ (\text{kWh})/\ /\textit{irradiance}\ (\text{kWh}\cdot\text{m}^{-2}) \quad (3)$$

$$\textit{solar system size} = 9.376/4.8 = 1.953\ \text{kW}$$

$$\textit{number of modules} = \textit{calculated solar system size}/\ /\textit{available module size} \quad (4)$$

$$\textit{number of modules} = 1{,}953/330 = 5.9$$

To get the maximum benefit from solar energy, the panel should be placed at an angle which captures the maximum power output of the array. The tilt angle for the orange harvesting location is computed as shown in figure 7 below.

$$\textit{battery sizing}\ (\text{Ah}) = \textit{solar power required} \times \textit{backup hours}/\ /\textit{battery efficiency} \times \textit{battery volts} \quad (5)$$

$$\textit{battery sizing} = 1{,}953 \times 4/0.85 \times 12 = 765.88\ \text{Ah}$$

Hence, three batteries of 300 Ah, 12 V each is suggested for the proposed design.

$$\textit{battery capacity}\ (\text{kWh}) = \textit{daily energy consumption} \times \textit{autonomy days/depth of discharge} \times \textit{battery cycle} \quad (6)$$

$$\textit{battery capacity} = 1{,}953 \times 3/0.85 \times 2{,}400 = 2.87\ \text{kWh}$$

$$\textit{charge controller sizing} = \textit{number of modules} \times \textit{short circuit current} \times \textit{safety factor} \quad (7)$$

$$\textit{charge controller sizing} = 6 \times 9.74 \times 1.2 = 70.128\ \text{A}$$

Hence, 80A MPPT solar charge controller is recommended for the design.

The feasibility study of the solar system determines whether the system is technically and financially suitable to be used. The solar system designed is proposed to be used in orange growing agricultural orchards in Pakistan. The economic crisis has caused the electricity price to hike up to more than 150%. In the current scenario, opting for an alternative source of energy seems like a viable option. This study compares the electric grid system, the solar stand-alone system, and the hybrid system with both electric and solar energy usage. The feasibility of solar stand-alone and hybrid energy using both solar energy and grid electricity are compared using performance indicators like payback period and the cost of energy. Payback period determines the time duration required to yield the profitability of the solar project. Payback period is given by:

$$\textit{payback time} = \textit{investment cost/net annual cash flow} \quad (8)$$

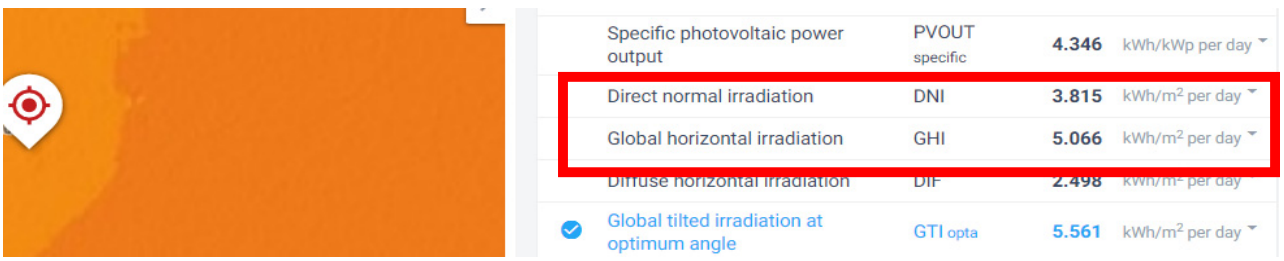


Fig. 6 Irradiance computation of a major orange growing area in December for Sargodha, Pakistan

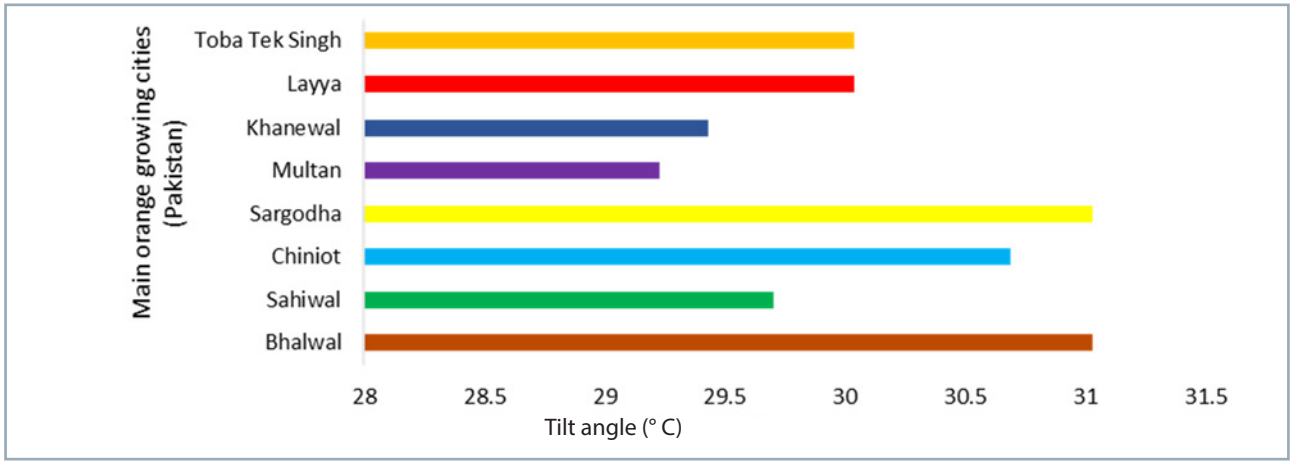


Fig. 7 Tilt angles for solar panels in orange growing regions of Pakistan

Table 4 Comparison of set-up cost for electric grid, solar stand-alone, and hybrid system

Electric grid energy setup	Solar stand-alone setup	Hybrid system set up
the cost of electricity is calculated based on the energy unit price in September 2022 – unit price of electricity = Rs 55 = $ 0.252 – electricity consumed per day = 7.623 × 0.252= $ 1.921 – electricity bill per month = $60 – included tax percentage = 45% – total cost after tax = $99	– solar panel cost: $ 75 × 6 = 450 – battery cost: $ 998 × 3 = 2,994 – controller cost: $ 278 – installation charges and wiring = $ 278 – total cost = $ 4,000 – yearly saving = $ 1,188 – payback time = 4,000/1,188 = 3.36 years	Solar setup cost: – solar sizing for 4 kW – total load estimation (with 25% losses) = 5 kW – solar system size = 5/4.8 = 1.04 kW – number of modules = 1,041/330 = 3.15 – battery sizing = 4,898.8 AH – 2,300 AH battery 12 V – charge controller sizing = 46.75 A – 60 A MPPT charge controller – solar panel cost: $ 75 × 4 = $ 300 – battery cost: $ 998 × 2 = $ 1,996 – controller cost: $ 100 – installation charges and wiring = $ 278 – total cost = $ 2,674 per day Electric grid cost: – unit price of electricity = Rs 55 = $ 0.252 – electricity consumed per day = $ 0.913 – electricity bill per month = $ 28.3 – tax percentage = 45% – total cost = $ 41.035 per month

The cost of energy refers to the financial expense associated with providing solar power over a specified period of time.

$$\textit{cost of energy for unit}\ (\text{kWh}) = \textit{total system cost} / \textit{total energy produced by the system} \quad (9)$$

Results and discussion

This study uses the HOMER Pro tool for the simulation and analysis of solar potential for a fruit harvesting robot. Figure 8 shows the schematic diagrams for simulations for the solar stand-alone and hybrid system in HOMER.

The study uses the following assumptions and input to determine the financial metrics for the study, as shown in Table 5.

Table 5 Assumptions and inputs for the study

Parameters	Values
Exchange rate	275 Rs·$^{-1}$
Discount rate	7%
Inflation rate	8%
Location	Sargodha, Pakistan
Maintenance cost	2.5% of PV cost
Project life	25 years

Table 6 Comparison on financial metrics for the stand-alone solar vs hybrid system

	Solar stand-alone	Hybrid system
Payback period	3.36	3.85
Cost of energy	$ 0.085 per kWh	$ 0.082 per kWh

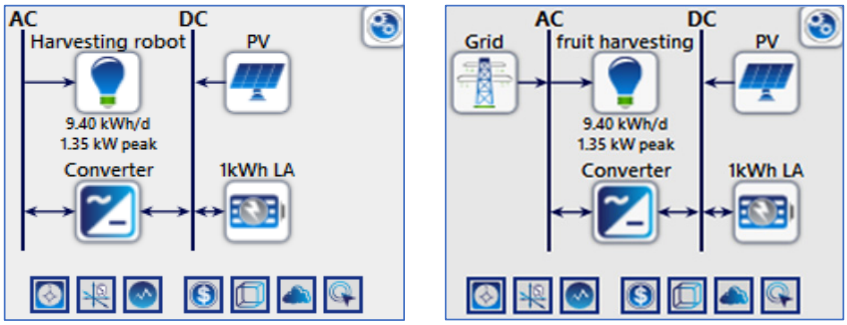


Fig. 8 Simulation of the solar stand-alone system vs hybrid system in HOMER

Figure 9 above compares the setup cost and payback time of the electric grid system, stand-alone solar system, and hybrid system and reveals that compared to the electric grid system, the solar stand-alone system and hybrid system has a payback of 3.36 and 3.85 years.

With increasing electricity cost as well as the shortage of electric supply, an alternate energy supply can be a feasible option for agricultural machinery. The solar system designed for operating a fruit harvesting machine is assessed for feasibility in terms of cost. It is found that for long-term usage, solar proves to be a viable option. Study shows that the solar stand-alone system proves to be beneficial after 3.36 years, while the hybrid system has a payback period of 3.85 years. Further, the cost of energy of the solar stand-alone system is $ 0.085 per unit kWh, while for the hybrid system, the cost of energy is $ 0.082 per unit kWh. With the economic conditions of the country, it is very likely that the cost of electricity shall rise further at a much higher cost than suggested. Hence, it can be deduced that the solar stand-alone system shall be beneficial in the long run.

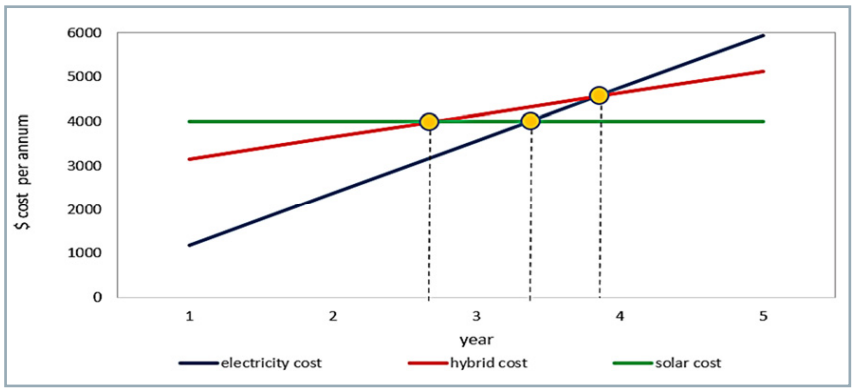


Fig. 9 Comparison of payback time for electric, solar, and hybrid energy system setup

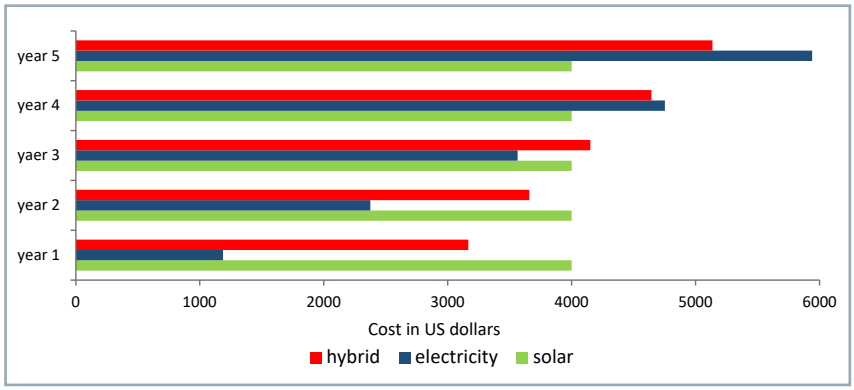


Fig. 10 Cost analysis of electric, solar, and hybrid energy system setup over 5 years

Furthermore, currently due to shortage of energy, long electricity load shedding is experienced in remote areas up to 10 hours. The solar system provides a continuous uninterrupted supply and, hence, it is preferred over the uncertain electric supply from the grid.

For the first two years, grid electricity cost is cheaper. However, after the third year, solar system design proves to be more beneficial, as shown in Fig. 10. The hybrid system is also better than the grid system in the long run, however, due to increasing electricity cost, the stand-alone solar system proves to be much cheaper than the hybrid system. Hence, for agricultural applications using modern machinery, it is recommended to design stand-alone solar systems for running machines like fruit harvesting machine rather than unreliable grid electric supply or the hybrid system comprising of both grid supply and the solar system. This shall ensure an uninterrupted energy supply and a clean and efficient energy source for agricultural applications. With improvement in solar energy systems, government incentives and immense increase in electricity prices, there is an increased scope of solar energy in important sector like agriculture. For many countries, economy is greatly dependent on the production and quality of agricultural goods. Many agricultural machineries are now shifting to solar energy for better reliability and payback. With improved agricultural technology, robots, drones, and intelligent machines are being used for many agricultural applications. Hence, it is only reasonable to power modern agricultural machines with renewable sources to get the maximum benefit. The use of solar energy in farms can not only increase efficiency, reduce cost but also support sustainable energy practices.

Conclusion

Pakistan is an agricultural country whose agricultural produce directly affects the economy of the country. With recent immense increase in electricity prices and prolonged electricity shortage in remote areas,

the use of modern machinery in the agricultural sector becomes very expensive. Further, inconsistent energy supply also adversely affects productivity. Hence, a more reliable and cheaper energy supply is suggested to be used for modern agricultural machinery like fruit harvesting robots. Fruit harvesting robots helps in enhancing the quality of fruit picked up as well as aids in improving productivity. Designing a solar energy system provides the solution for the existing problem for a cheaper and more reliable energy source for remote village areas of orange growing farms in Pakistan. Pakistan is well known for its flavourful fruits and unique odour of Kinnow (mandarin) and is one of the top fruits exported to many countries. The novel aspect of the study is that the research aims at designing a lightweight orange fruit harvesting robot powered by solar energy that can aid in picking quality fruits from the orchard in Pakistan. Solar potential is determined using a unique fine-tuned random forest regression model, and the area for installing the fruit harvesting robot is selected. Furthermore, a techno-economic analysis is done where the solar system design is analysed for its cost feasibility. Current electric grid system, solar stand-alone system, and hybrid system are compared. It is found that after 3.36 years, the solar energy system proves to be a better and more reliable solution with the cost of energy of $0.085 per unit kWh. With prolonged load shedding in remote areas of Pakistan of up to 10 hours, the stand-alone PV system is a better option than the hybrid or electric grid system. For future study, research can be conducted to design a solar energy system for other agricultural machineries to be used in remote areas. Further, studies can also highlight better ways of improving the cost of solar setup for better and improved implementation.

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