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Research Article

Design and Development of Solar-Powered Structures for Agricultural Machinery

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Abstract

The structural configuration and preliminary energy sizing of solar-powered low-capacity agricultural machinery are examined. A stationary 5 kWp photovoltaic (PV) charging canopy is integrated with a detachable 24 kWh lithium iron phosphate (LiFePO4) battery, maximum power point tracking (MPPT), a battery management system (BMS), a power electronic inverter, and an electric traction/implement drive. A transparent design scenario is formulated for a 4.0 kW mechanical load, a 0.65 load factor, and five daily operating hours. The calculated mechanical demand is 13.00 kWh/day; the corresponding battery output is 15.20 kWh/day, and the minimum nominal battery capacity is 20.01 kWh. Under 4.6 equivalent peak-sun hours and explicitly assumed conversion efficiencies, the proposed PV system yields 15.77 kWh/day of usable energy. A diesel reference system is assessed on an equal useful-work basis. All numerical findings are model-based design estimates rather than field-validated measurements.

Keywords

Agricultural machinery; photovoltaic energy; solar charging canopy; electric drive; MPPT; LiFePO4 battery; power balance; battery sizing; fuel displacement.

1. Introduction

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Agricultural mechanization improves field productivity but typically relies on diesel engines for traction, spraying, light cultivation, and on-farm transport. Electrification can provide flexible torque control, reduce some mechanical transmission requirements, and permit renewable electricity to be integrated at the farm level. However, unlike a continuously supplied grid-connected machine, a mobile agricultural platform must carry sufficient energy to meet the variable demands of field operations. A structurally feasible design therefore requires coordinated selection of the motor, transmission, battery, charging power, and protective equipment.

Published research has described high-voltage tractor electrification, electric powertrain architectures, and the use of photovoltaics in modern agricultural machinery [1–4]. Experimental investigations of electric tractors further demonstrate that traction and implement loads differ substantially across working conditions; usable battery time consequently depends on the duty cycle rather than rated power alone [5–8]. The integration of solar charging with electric mobility introduces additional constraints, particularly seasonal irradiation, dust accumulation, charging time, and available farm area [1].

The objective is to develop a conceptual configuration for a compact electric agricultural platform intended for spraying, light inter-row cultivation, and local goods transport, and to establish reproducible energy-balance calculations for selecting its major components. The study is limited to a hypothetical engineering design and does not report construction, commissioning, or laboratory validation of a prototype.

2. Structural arrangement and operating requirements

The proposed architecture comprises five functional groups: (i) a stationary PV canopy installed at the farm; (ii) an MPPT charge controller with DC protection; (iii) an exchangeable LiFePO4 traction battery and its BMS; (iv) an inverter, electrical disconnects, and supervisory controller; and (v) the electric motor, reduction gear, and wheels or agricultural implement. The PV panels remain at the charging station, while the battery is carried by the mobile machine. This separation avoids imposing the structural and aerodynamic loads of a full-sized PV array on the moving platform.

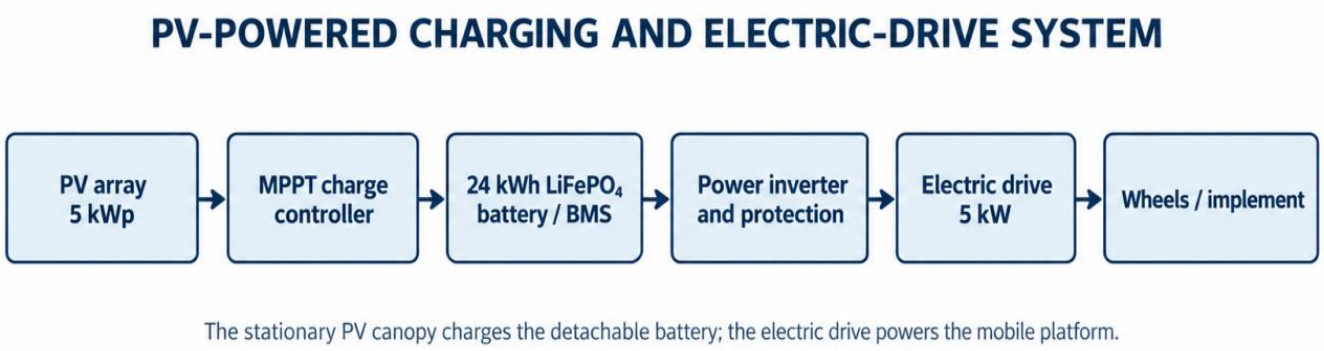


Figure 1. Functional architecture of a PV-powered charging and electric-drive system for compact agricultural machinery.

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The mechanical layout must tolerate vibration, impact loading, dust, water ingress, and repeated maintenance operations. The battery is placed in a protected enclosure with secure retention and appropriate thermal management. Cables require abrasion-resistant routing and suitable ingress protection; the inverter and BMS must remain service-accessible without exposing live conductors. Emergency isolation, fusing, insulation monitoring where applicable, and safe maintenance procedures are integral design constraints rather than optional accessories.

Three operational constraints govern field reliability. First, sudden contact between implements and stones or compacted soil can create torque peaks that must be resisted by the frame and motor mounting structure. Second, the electrical assembly is exposed to wet soil, irrigation water, fertilizers, and metallic debris; equipment selection therefore depends on applicable environmental and electrical safety requirements. Third, thermal conditions affect motor winding temperature, inverter derating, and allowable battery charge or discharge power. Charging cables and connectors should be rated for the maximum charging current under realistic thermal conditions. Excessive separation between the PV canopy and charging location increases cable I^2R losses and may require larger conductor cross-sections. The station layout should minimize DC cable lengths and allow safe vehicle positioning, ventilation, and charging access. Protection coordination should cover reverse polarity, ground faults, overcurrent, and connector disconnection under load.

3. Mathematical model and component sizing

3.1. Mechanical work and battery demand. The useful mechanical energy delivered to traction or implement shafts is determined by integration of the time-dependent power demand. For preliminary sizing, the duty cycle may be approximated using an average load factor:

$$E_m = \int^{0} {}^{t} P_{m(\tau)d\tau} \approx P_n \cdot k_u \cdot t, \quad \text{kWh.} \qquad (1)$$

Here, P_n is the assumed mechanical rated load (kW), k_u is the average utilization factor, and t is daily operating time (h). The energy extracted at the battery terminals is calculated with the motor and inverter efficiencies:

$$E_b, \text{out} = \frac{E_m}{\eta_m \cdot \eta_i}, \quad \text{kWh.} \qquad (2)$$

The parameters η_m and η_i denote electric-motor and inverter efficiencies, respectively. Allowing for the usable depth of discharge (DoD) and battery discharge efficiency η_d gives the minimum nominal stored energy:

$$C_{b,min} = E_{b,out}/(DoD \cdot \eta_d), \quad \text{kWh.} \qquad (3)$$

A commercial battery rating must satisfy $C_{b,nom} \geq C_{b,min}$. Additional design margins may be necessary for ageing, low-temperature operation, peak-current capability, reserve operation, and permissible state-of-charge limits. Therefore, the calculated theoretical minimum must not be treated as a complete battery procurement specification. Duty-cycle-based battery selection

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is strongly supported by recent agricultural workload studies [5–7].

3.2. Photovoltaic production and charging balance. Daily PV generation is approximated using equivalent peak-sun hours and a performance ratio (PR) representing array-level losses:

$$E_{PV} = P_{PV} \cdot H_s \cdot PR, \quad \text{kWh/day.} \qquad (4)$$

In Eq. (4), P_{PV} is the installed PV capacity (kWp), H_s is the daily plane-of-array irradiation expressed as equivalent full-sun hours (h/day), and PR accounts for temperature effects, soiling, wiring, shading, and associated array-level losses. To prevent double counting, the adopted PR does not include the separately modelled MPPT, charging, or battery discharge losses. Since no measured irradiance series is available for this design exercise, H_s represents a selected sunny-day scenario rather than a verified annual mean [1,4].

$$E_{PV,usable} = E_{PV} \cdot \eta_{MPPT} \cdot \eta_{ch} \cdot \eta_d, \quad \text{kWh/day.} \qquad (5)$$

A nominally solar-sufficient day requires $E_{PV,usable} \geq E_{b,out}$. Whenever this condition fails, the demand must be met by stored electricity from previous days, a grid connection, an auxiliary renewable source, or curtailed field operations. Daily energy equality is not equivalent to uninterrupted autonomy; battery state of charge and power limits should also be simulated at hourly or sub-hourly resolution.

3.3. Comparison with a diesel-powered reference machine. The reference diesel machine is assumed to perform exactly the same useful mechanical work. If the lower heating value of diesel fuel is q_d (kWh/L) and the combined diesel engine–transmission efficiency is η_D, the fuel demand is estimated as:

$$V_D = E_m/(q_d \cdot \eta_D), \quad \text{L}; \qquad \Delta V_D = V_D - V_{D,e}, \quad \text{L}. \qquad (6)$$

For a fully battery-electric machine, direct on-board diesel use can be zero ($V_{D,e} = 0$). This does not establish zero life-cycle emissions, because electricity generation, battery production, PV manufacturing, auxiliary generator operation, and machinery construction are excluded from the boundary. A complete environmental comparison therefore requires separate life-cycle assessment, as illustrated by previous tractor studies [12].

4. Design scenario and input assumptions

A small mobile platform for spraying, shallow inter-row cultivation, and material transport is considered as the calculation object. The numerical values are hypothetical component-sizing assumptions, not field observations or calibrated performance data. Five operating hours per day and a moderate load factor represent a relatively light agricultural duty cycle; they are not applicable without modification to deep ploughing or high-power rotary tillage. All efficiencies are held constant for transparent hand calculations.

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Table 1. Assumed design parameters of the compact agricultural platform

Parameter	Symbol	Adopted value	Comment
Useful mechanical load	P_n	4.0 kW	Light-duty scenario
Daily operating time	t	5 h	One working day
Mean load factor	k_u	0.65	Assumed duty cycle
Motor / inverter efficiency	η_m / η_i	0.90 / 0.95	Design assumption
Battery DoD / discharge efficiency	DoD / η_d	0.80 / 0.95	Design assumption
Nominal battery capacity	$C_{b,nom}$	24 kWh	Selected design size
PV nominal capacity	P_{PV}	5.0 kWp	Stationary canopy
Peak-sun hours / PR	H_s / PR	4.6 h / 0.80	Sunny-day assumption
MPPT / charging efficiency	η_{MPPT} / η_{ch}	0.96 / 0.94	Design assumption
Diesel q_D / drivetrain efficiency	q_D / η_D	9.8 kWh/L / 0.25	Reference assumption

5. Model-based results and discussion

Using Eq. (1), the daily mechanical work equals $E_m = 4.0 \times 0.65 \times 5 = 13.00$ kWh. With the assumed 0.90 motor efficiency and 0.95 inverter efficiency, battery output is $E_{b,out} = 13.00/(0.90 \times 0.95) = 15.20$ kWh. Equation (3) gives $C_{b,min} = 15.20/(0.80 \times 0.95) = 20.01$ kWh. The selected 24 kWh battery provides a nominal sizing margin of approximately 20%; this margin does not independently verify its thermal, mass, ageing, or peak-power adequacy.

Daily PV generation is $E_{PV} = 5.0 \times 4.6 \times 0.80 = 18.40$ kWh. After the assumed MPPT, charging, and battery discharge efficiencies, the usable electrical energy is $E_{PV,usable} = 18.40 \times 0.96 \times 0.94 \times 0.95 = 15.77$ kWh. The difference between solar supply and battery demand is about 0.57 kWh for this representative day. The margin is small; a reduction in insolation or an increase in average traction power would remove the nominal solar balance.

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Table 2. Calculated energy quantities for the assumed operating day

Energy metric	Calculated value
Useful mechanical work	13.00 kWh/day
Battery-output electricity demand	15.20 kWh/day
Minimum nominal battery capacity	20.01 kWh
Proposed battery rating	24.00 kWh
PV electricity before storage losses	18.40 kWh/day
Usable PV energy after charging losses	15.77 kWh/day
Nominal PV energy balance margin	0.57 kWh/day
Reference diesel fuel demand	5.31 L/day

Solar sufficiency is sensitive to daily insolation. Figure 2 illustrates the available energy for 2.5–6.0 equivalent peak-sun hours with all other parameters unchanged. The estimated balance threshold is approximately 4.43 h/day. Below that value, the daily operating requirement cannot be fully replenished without supplemental energy. A practical project must therefore assess seasonal weather series, the calendar of field operations, and a dynamic battery state-of-charge model rather than relying on a single sunny-day estimate.

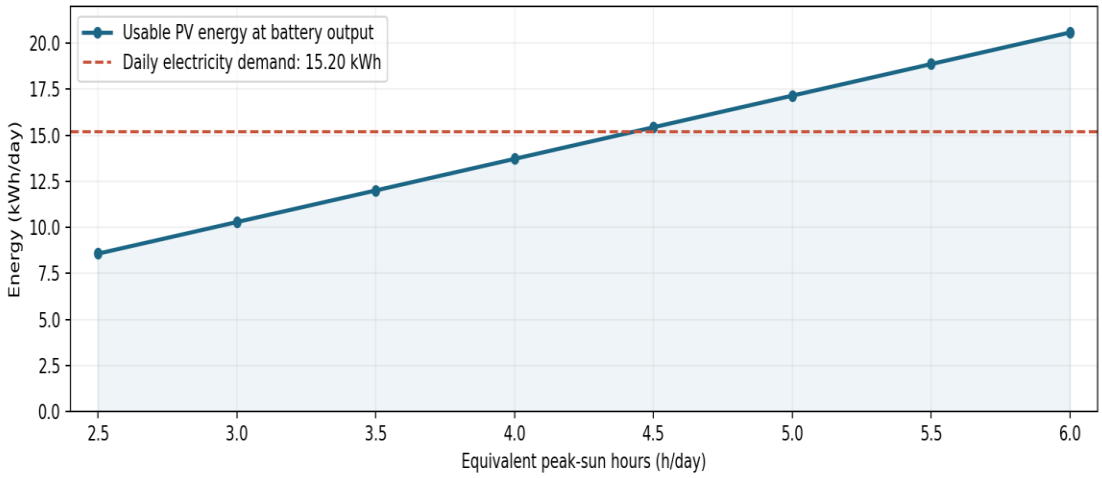


Figure 2. Sensitivity of usable daily PV energy to equivalent peak-sun hours (calculated scenario).

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Table 3. PV energy sensitivity under different irradiation scenarios

Peak-sun hours, h/day	Usable PV energy, kWh/day	Daily demand supplied	Meets demand?
2.5	8.57	56%	No
3.5	12.00	79%	No
4.0	13.72	90%	No
4.6	15.77	100%	Yes
5.0	17.15	100%	Yes
6.0	20.57	100%	Yes

For an equivalent diesel machine delivering the same 13.00 kWh of mechanical work, q_d = 9.8 kWh/L and η_D = 0.25 give $V_D = 13/(9.8 \times 0.25)$ = 5.31 L/day. If the electric platform is charged without diesel-generated electricity, its direct on-board diesel use is eliminated for the same task. At 150 operating days, the notional displacement reaches 795.9 L; this is an illustrative upper-bound fuel comparison, not a measured annual saving. The environmental significance must be evaluated using an explicitly defined electricity-supply and life-cycle boundary [12].

For brief peak-load conditions, the selected 5 kW motor requires additional checks of maximum torque, continuous current, cooling, and gearbox rating. The assumed 4 kW load is intended for light tasks and cannot be extended to heavy drawbar applications. Measurements of axle torque, power take-off demand, and hydraulic load in existing tractors demonstrate why sizing must follow the operation-specific load envelope [6,7].

5.1. Sensitivity of structural design parameters.

A battery capacity derived from nominal motor power alone does not establish reliable operation. Real motor efficiency changes with torque, rotational speed, temperature, and inverter control conditions. A cultivator may exhibit short-duration overloads when tools encounter compacted soil, while a sprayer pump can have a steadier load profile. Even at equal daily energy demand, the corresponding current ratings, thermal constraints, and motor torque reserves may be substantially different.

Table 4. Battery sizing sensitivity to motor and inverter efficiency

Motor efficiency	Inverter efficiency	Electricity demand, kWh	Minimum battery, kWh
0.80	0.92	17.66	23.24
0.85	0.93	16.45	21.64
0.90	0.95	15.20	20.01
0.93	0.97	14.41	18.96

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Table 4 shows that a motor efficiency of 0.80 combined with an inverter efficiency of 0.92 requires more than 23 kWh of minimum nominal battery energy under the assumed DoD and discharge efficiency. The proposed 24 kWh pack would then have little spare capacity. A two-dimensional motor efficiency map over torque and speed, rather than a single nominal efficiency, is needed for detailed design. Peak power should also be checked against cell current limits and BMS trip settings.

PV module area is another structural consideration. With an illustrative standard-test-condition module efficiency of 20%, 5 kWp requires an active module area of approximately $A_{PV} = 5000/(1000 \times 0.20) = 25\ m^2$. The physical canopy footprint will generally be larger owing to module mounting, access paths, wind-load design, and shading clearance. Panel cleaning is especially relevant for dusty agricultural sites, and realistic array yield must be recalculated once tilt, orientation, and site-specific weather are available [1].

6. Operating control and experimental verification

Three operating states are defined for the charging controller. During PV surplus and allowable battery state of charge, MPPT operation transfers energy to the battery. At the upper SOC or temperature limit, charging current is reduced or surplus PV power is redirected to farm loads. During agricultural operation, the BMS permits inverter output only within predefined cell-voltage, temperature, and current limits. Forecast energy shortages may trigger charging prioritization, delayed nonessential operations, or charging from an external electrical source.

Field verification requires continuous measurements of plane-of-array irradiance G (W/m^2), PV current and voltage, MPPT output, battery SOC and state of health, inverter input and output power, motor torque and speed, ground speed, implement load, and reference diesel consumption. Measured energy balances should be reconciled with model predictions, while the root mean square error and relative deviations should be reported for independent validation periods. The system must also be checked for electrical protection and thermal behaviour under transient duty cycles.

Initial field experiments should include at least two contrasting tasks: spraying with an approximately continuous load and cultivation with fluctuating mechanical resistance. Seasonal tests would quantify declining winter irradiation and cold-temperature charging limitations. Financial evaluation should include capital cost, battery replacement, PV maintenance, downtime, charging infrastructure, local diesel prices, electricity tariffs, and the number of operating days [9–11].

7. Economic assessment and implementation requirements

Technical adequacy does not automatically imply economic advantage. PV modules, batteries, the motor, the inverter, protective systems, and associated installation require initial investment. Comparisons with diesel machinery should use an equivalent functional unit, such as hectares treated, tonnes transported, or useful shaft energy delivered. The influence of operating hours and charging infrastructure on tractor economics has been emphasized in previous studies [9–11].

The equivalent annual cost can be expressed through the capital-recovery factor (CRF), investment cost K, discount rate r, service life n, annual service cost C_s, and purchased-electricity cost C_e:

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$$CRF = r(1+r)^n/[(1+r)^n - 1]; \quad C_y = K \cdot CRF + C_s + C_e. \qquad (7)$$

For the diesel reference, an analogous annual cost is $C_{y,D} = K_D \cdot CRF + C_{s,D} + V_{D,y} \cdot c_D$, where c_D is the price of diesel per litre. No defensible payback period can be calculated without verified component prices, annual machine utilization, discount rate, battery degradation, and local energy tariffs. Accordingly, the illustrative 5.31 L/day is reported only as a fuel-consumption comparator, not a monetary saving.

Before a physical prototype is built, the mechanical load limits, battery positioning and centre of gravity, vehicle stability, ingress protection, electrical isolation, cooling, and emergency stopping arrangement must be defined. A monitored pilot farm can supply the radiation and duty-cycle data needed to determine a site-specific PV capacity and battery replacement strategy. This evidence is essential before design assumptions are generalized to larger agricultural equipment.

8. Conclusions

A conceptual solar-powered architecture for low-capacity agricultural machinery is established by combining a stationary PV charging canopy, a detachable battery, and an inverter-controlled electric drive. In the transparent design scenario, 13.00 kWh/day of useful mechanical energy requires 15.20 kWh/day of electricity at the battery output. A 24 kWh battery and 5 kWp PV station can nominally meet this demand on a day with 4.6 equivalent peak-sun hours, producing 15.77 kWh/day of usable electrical energy. The estimated diesel comparator consumes 5.31 L for the same useful work. The feasibility result is conditional on assumed efficiencies, irradiance and light-duty operation; field validation, long-term energy balance, structural assessment and life-cycle costing remain necessary.

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