

Article

Hybrid Battery–Laser Wireless Power Transfer System for Range-Extended Disaster-Relief UAVs: A Coupled Thermal–Electrical Battery Sizing Optimization

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Abstract

Extending flight endurance is critical for unmanned aerial vehicles (UAVs) deployed in post-disaster surveillance missions. This study proposes a hybrid battery–laser power system in which a ground-based laser source continuously tracks and charges a photovoltaic (PV) array mounted on a UAV, and develops an integrated optical–thermal–electrical model coupled with a battery-sizing optimization framework. Using a realistic trajectory derived from experimentally measured UAV flight data, the results show that the proposed hybrid system reduces the required battery capacity by up to 23.8% compared with a laser-off configuration. Alternatively, for the same battery capacity, laser-assisted operation extends the achievable mission duration by approximately 23%, enabling longer disaster-relief missions without increasing the UAV payload. These findings provide practical design guidance for developing laser-powered UAV systems for extended disaster-relief operations.

Keywords: unmanned aerial vehicle (UAV); laser wireless power transfer (LWPT); photovoltaic receiver; battery sizing; disaster reconnaissance

1. Introduction

Natural disasters such as earthquakes, floods, and hurricanes claim on the order of 150,000 lives and cause more than US\$130 billion in economic losses worldwide every year [1]. In the immediate aftermath of such events, the effectiveness of search-and-rescue and relief operations depends critically on rapid and continuous situational awareness, yet collapsed roads, debris, and damaged critical infrastructure frequently render ground-based access unreliable or impossible. Therefore, unmanned aerial vehicles (UAVs) have become indispensable tools of disaster management: they can bypass interrupted ground networks and perform post-disaster inspection, damage assessment, victim search, and relief support. Rotary-wing UAVs are particularly well-suited for reconnaissance missions in disaster zones because their vertical takeoff and landing and hovering capabilities allow for continuous close-range monitoring of collapsed structures and confined urban areas [2].

The principal obstacle to such persistent operation is the onboard energy source. Small multirotor UAVs are almost exclusively powered by lithium-based batteries whose



Received: 30 July 2026

Revised: 21 August 2026

Accepted: 27 August 2026

Published: 21 September 2026

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limited specific energy restricts typical flight times to roughly 20–40 min, and to as little as 5–15 min for micro-class platforms [3]. Because a multirotor must continuously work, its hover power scales unfavorably with takeoff mass; enlarging the battery therefore yields strongly diminishing returns in endurance, as propulsion-system sizing analyses and empirical flight-energy datasets consistently show [4]. In a disaster scenario this limitation is operationally severe. The reconnaissance mission must be interrupted every few tens of minutes so that the vehicle can return to a depot for recharging or battery swapping, and mission-planning frameworks developed for post-disaster drone operations must explicitly embed recharging stations and battery state-of-charge constraints into their routing formulations [2]. The resulting downtime and detours directly reduce the area that can be monitored and delay time-critical information exactly when it is needed most.

A substantial body of research has sought to relax this endurance bottleneck by harvesting or hybridizing energy on board. Solar-powered UAVs have been studied extensively through flight-strategy optimization [5], intelligent energy management [6,7], power-balance and parameter analyses [8], multidisciplinary airframe design [9], and comprehensive reviews of photovoltaic (PV), storage, and power-management technologies [10,11]. However, solar flight fundamentally favors large-aspect-ratio fixed wings with generous PV area, and its energy income collapses at night and varies strongly with latitude, season, and cloud cover [12]. Hybrid PV/fuel-cell/battery architectures extend the endurance of fixed-wing platforms [13], but add mass, complexity, and refueling logistics that are difficult to justify on a small reconnaissance multirotor. Tethered supply confines the drone to a fixed operating radius, while battery swapping still forces the mission to be suspended [14]. None of these options provides uninterrupted operation over a disaster area.

Laser wireless power transfer (LWPT) has emerged as the most promising far-field alternative for exactly this class of mission. A ground-based laser can deliver watt-to-kilowatt power levels over distances of hundreds of meters to kilometers onto a compact PV receiver, independently of sunlight, with negligible electromagnetic interference [14,15]. Zhang et al. [16] established a multi-module DLC system model and derived the maximum power-transmission efficiency in closed form as a function of laser wavelength, atmospheric attenuation, and PV-cell temperature. Mohammadnia et al. [14] demonstrated theoretically that a drone equipped with a GaAs receiver can obtain a net power of about 73.5 W at a 500 m range from a 600 W laser module, provided that the receiver is actively cooled. The practical feasibility of LWPT for UAV applications has been validated through a series of experimental studies. Early demonstrations achieved continuous indoor flight of a 1 kg quadcopter for 12 h 27 min using laser power beaming [17]. Subsequently, a laboratory-scale LWPT prototype incorporating a 976 nm laser, a PV receiver, and a LiPo battery was shown to significantly extend UAV hovering time [18]. More recently, a battery-less micro-UAV successfully performed vertical flight powered exclusively by an optical beam [3]. Furthermore, industrial-scale demonstrations have delivered more than 400 W of electrical power over a transmission distance of 325 m, enabling UAV operation for durations well beyond the limitations of battery-only systems [19].

However, research on laser-powered UAVs has been conducted almost exclusively from the perspective of wireless communications and networking. Existing studies have investigated laser-powered UAV relays by maximizing charging efficiency [20] and optimizing the energy allocation of hovering relays in optical backhaul networks [21]. Other works have focused on the large-scale deployment of laser-powered aerial base stations using stochastic geometry [19], the integration of laser-powered UAVs with RF-powered ground sensor networks [22], and the optimal placement of laser chargers in WPT-enabled IoT systems [23]. More recently, drone-borne laser resonators have also been proposed as

airborne power sources [24]. Despite these advances, the primary objective of all existing studies remains the provision of communication services.

Another important line of research focuses on the receiver-side physics of LWPT, independently of specific UAV missions. Li et al. developed a coupled transmitter-beam–PV model and demonstrated that beam-spot/array mismatch together with attitude-induced non-uniform irradiation can produce mismatch losses of up to 32% and efficiency reductions approaching 48% under pointing errors [25]. Their analysis further indicated that the overall system efficiency currently remains below approximately 20%. Meng et al. reported that optimizing the PV array configuration under a Gaussian laser spot increases the maximum output power by at least 24.6% [26].

Thermal effects have also been identified as a key factor limiting LWPT performance. As the laser irradiance increases, the PV temperature rises nearly linearly, reducing conversion efficiency and potentially causing permanent cell damage. Consequently, previous studies have investigated dynamic thermal models for laser-illuminated PV cells [27], experimentally characterized crystalline silicon (c-Si) receivers for laser power beaming [28], developed receiver-positioning and beam-steering strategies [29], and optimized the trajectories of fixed-wing UAVs operating under atmospheric turbulence [30]. Although these studies provide valuable insights into the optical and thermal behavior of LWPT receivers, they rarely extend their analyses to the vehicle level, where battery sizing, energy management, and mission duration must be considered simultaneously.

The battery itself—the element that ultimately determines whether a laser-fed drone can complete its mission—has received remarkably little attention. To the best of our knowledge, the only study that places the battery at the centre of a laser-charged UAV analysis is that of Jaafar and Yanikomeroglu [31], who combined a kinetic battery model (KiBaM) with a sub-kilowatt laser source and showed that battery-aware path planning substantially outperforms conventional energy-based planning. Their scenario, however, is an urban IoT data-collection use case in which the UAV lands on rooftops to charge, the battery capacity is a fixed input rather than a design variable, and no disaster-related reconnaissance requirements (area coverage, persistence, degraded infrastructure) are considered.

The literature review summarized in Table 1 highlights several significant research gaps. Existing studies on laser-powered UAVs primarily focus on communication and IoT applications, while disaster-area reconnaissance missions have received little attention despite their stringent endurance requirements and limited infrastructure availability. Moreover, receiver-level optical and thermal analyses are rarely integrated with vehicle-level battery dynamics and mission planning, leaving the system-level impact of laser power transfer largely unexplored.

To address these gaps, this study investigates a laser-powered UAV designed for long-endurance disaster-area reconnaissance. Unlike previous studies, the proposed framework is driven by power-consumption data measured from an actual UAV flight, enabling the reconstruction of a realistic mission profile. The integrated optical–thermal–electrical model is then employed to optimize battery sizing under laser-assisted operation. In addition, the proposed framework quantifies the improvement in mission endurance achieved through laser power transfer while maintaining the same battery capacity, thereby providing a practical assessment of the endurance benefits offered by LWPT in realistic operating conditions. The main contributions of this study are as follows:

- An integrated optical–thermal–electrical model is developed for a laser-powered UAV by coupling laser transmission, PV conversion, thermal behavior, battery dynamics, and UAV power consumption.

- A realistic disaster-area reconnaissance mission is modeled using experimentally measured UAV power-consumption data, enabling mission-level performance evaluation under laser-assisted operation.
- The battery-sizing problem is formulated as an optimization model to determine the minimum battery capacity required under different laser power levels and operating conditions.
- The improvement in mission endurance achieved through laser power transfer is quantified for a fixed battery capacity, and the potential for battery downsizing is systematically evaluated.

Table 1. Taxonomy of related studies and positioning of the present work in terms of power-link modeling, receiver thermal behavior, battery modeling, and mission-level analysis.

Study	Primary Focus	Dynamic Power-Link/ Flight Coupling	PV Thermal Model	Battery Dynamics	Battery Sizing Optimization	Mission/ Endurance	Measured UAV Power Profile	Disaster Context	Key Distinction/Result
[14]	Drone LWPT feasibility	~	✓	×	×	×	×	×	73.5 W net power at 500 m using GaAs; receiver cooling identified as critical.
[17]	Indoor endurance demonstration	~	×	×	×	✓	×	×	12 h 27 min continuous flight demonstrated experimentally; no battery or receiver optimization.
[18]	Laser-PV-LiPo prototype	~	~	✓	×	✓	×	×	Experimental laser charging increased hover time from 630 to 675 s (+7.14%); battery size remained fixed.
[3]	Battery-less OWPT micro-drone	~	×	×	×	~	×	×	Battery-less vertical flight demonstrated at 35 W optical output; focused on proof of concept.
[25]	UAV LWPT receiver multiphysics	✓	✓	×	×	×	×	×	Models distance, attitude, pointing error, and non-uniform irradiation; mismatch loss up to 32% and efficiency reduction up to 48%.
[26]	PV array under Gaussian laser spot	~	✓	×	×	×	×	×	Receiver-side array reconfiguration improves maximum PV output power by at least 24.6%.
[30]	Fixed-wing trajectory optimization	✓	×	×	×	~	×	×	Trajectory velocity and radius optimized to maximize net harvested laser power under atmospheric turbulence.
[20]	UAV relay with laser charging	✓	×	~	×	~	×	×	Joint trajectory–power optimization with energy-causality constraints; objective driven by communication and WPT efficiency.
[21]	SLIPT hovering UAV relay	~	×	~	×	✓	×	×	UAV uptime is maximized subject to communication QoS using a fixed stored-energy representation.
[19]	Large-scale aerial communication coverage	~	×	×	×	×	×	×	Stochastic-geometry framework analyzes communication/energy coverage and optical turbulence; battery retained only as backup.
[22]	WRSN charging and data backhauling	~	×	~	×	~	×	×	3-D hovering points and trajectory are optimized to maximize sensor-network service under UAV energy constraints.
[31]	Battery-aware path planning	~	×	✓	×	✓	×	×	KiBaM-based battery dynamics and mission-time optimization; battery capacity is prescribed rather than optimized.
[2]	Post-disaster inspection routing	×	×	~	×	✓	×	✓	Disaster-oriented routing with battery-level tracking and station-based recharging; battery capacity is a fixed parameter.
[6]	Solar-UAV energy management	✓	✓	✓	×	✓	×	×	Integrated solar, PV-thermal, battery, propulsion, and trajectory model; focuses on energy management rather than battery sizing.
This study	LWPT-assisted disaster reconnaissance	✓	✓	✓	✓	✓	✓	✓	Measured UAV power profile integrated with optical–thermal–electrical optimization; battery requirement reduced from 42 to 32 cells (23.8%), or mission endurance increased by approximately 23.4% for equal battery capacity.

✓: Explicitly addressed; ~: partially or indirectly addressed; ×: not addressed.

The remainder of this paper is organized as follows. Section 2 describes the system architecture and the mathematical models of the laser link, PV receiver, battery, and drone power demand. Section 3 presents and discusses the results on battery capacity and mission duration. While Section 4 discusses the general findings, Section 5 concludes the paper and highlights areas for future research

2. System Description and Methodology

2.1. Overview of the System

Figure 1 illustrates the LWPT system for the long-endurance UAV investigated in this study. Figure 1a presents a side-view illustration of a disaster-relief deployment scenario,

in which a ground-based laser source operating at 976 nm transmits optical power to a PV array mounted on the underside of the UAV. Figure 1b shows the top view of the closed patrol trajectory, including local triangular survey maneuvers, flown around the laser ground station located at the origin (0,0,0), which also serves as the UAV launch and landing point. The dashed line represents the laser beam continuously tracking the UAV throughout the mission.

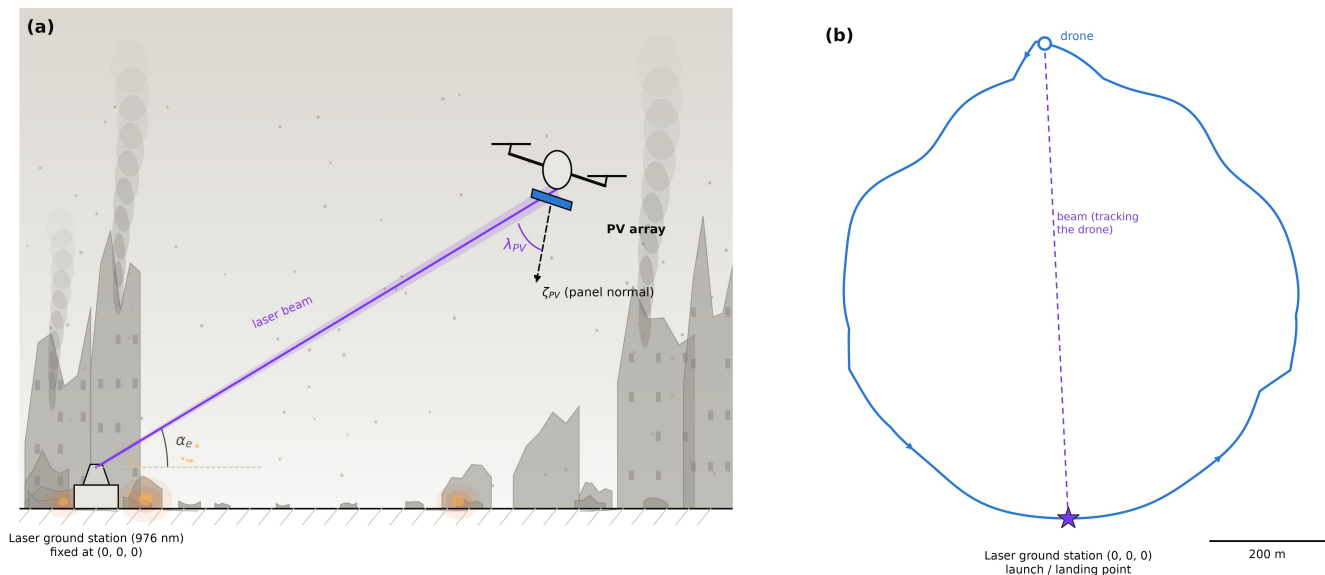


Figure 1. Schematic of the hybrid battery-laser wireless power transfer system for a disaster-relief UAV: (a) Side-view beam-PV incidence geometry; (b) top-view closed route.

Based on this mission profile, the proposed framework first reconstructs a realistic UAV flight trajectory from experimentally measured power-consumption data and determines the corresponding time-varying laser-PV incidence angle. A thermal model is then established in which the convective heat-transfer coefficient is expressed as a function of wind speed and ambient temperature, enabling accurate prediction of the PV panel temperature and the resulting efficiency degradation. Finally, the coupled optical-thermal-electrical model is formulated as a nonconvex mixed-integer quadratically constrained programming (MIQCP) optimization problem to minimize the number of battery cells required for the hybrid battery-laser-powered UAV system.

2.2. Mathematical Modeling

The instantaneous incidence angle λ_{PV} between the laser beam and the PV array is obtained by projecting the earth-fixed unit vector pointing from the UAV toward the ground laser source onto the array's body-fixed normal, following the same rotation-matrix formulation used for solar-facing PV panels but adapted to a fixed ground beam source and to an underside-mounted, downward-facing panel. Here α_e and α_a denote the elevation and azimuth angles of the source as seen from the UAV, while φ , θ , and ψ are the roll, pitch, and yaw angles of the UAV body. The expanded closed-form expression is given by [13]

$$\begin{aligned} \cos \lambda_{PV}(t) = & \cos(\alpha_e) \cos(\alpha_a) [\sin \varphi \sin \psi + \cos \varphi \sin \theta \cos \psi] \\ & + \cos(\alpha_e) \sin(\alpha_a) [\cos \varphi \sin \theta \sin \psi - \sin \varphi \cos \psi] \\ & - \sin(\alpha_e) \cos \varphi \cos \theta. \end{aligned} \quad (1)$$

The transmission efficiency of the laser beam through the atmosphere, η_t , is obtained from the Kruse atmospheric attenuation model, which expresses the Beer-Lambert extinc-

tion coefficient as a function of the meteorological visibility κ and the ratio between the laser wavelength λ and a reference wavelength χ [14]:

$$\eta_t(t) = \exp\left(-\left[\frac{\sigma}{\kappa}\left(\frac{\lambda}{\chi}\right)^{-\rho}\right]dis(t)\right) \quad (2)$$

where σ is the visibility-based extinction constant, ρ is the particle-size-distribution exponent, and dis is the instantaneous slant distance between the UAV and the fixed ground laser source. Clear-sky conditions are assumed throughout this study, corresponding to $\kappa = 23$ km and $\rho = 1.3$. Since the ground station is fixed while the UAV follows the derived patrol trajectory, dis is computed at each time step from the instantaneous UAV position, so that η_t decreases as the UAV moves away from the source and recovers as it returns. Although a visibility of 23 km is adopted as the clear-sky reference condition, additional atmospheric transmission conditions were also evaluated. Within the investigated range, the corresponding reduction in transmission efficiency did not alter the optimal battery-cell count. This is primarily because the PV receiver thermal constraint becomes dominant under favorable transmission conditions; reduced atmospheric transmission simultaneously decreases the received optical power and relieves the thermal loading of the receiver. Therefore, the resulting change in harvested electrical energy was insufficient to shift the discrete battery-sizing optimum for the cases considered.

The convective heat-transfer coefficient due to airflow, h_w , is calculated using the empirical McAdams correlation, as adopted by Hassanian and Riedel for forced convection over photovoltaic modules [32]:

$$h_w(t) = 5.7 + 3.8 V_f(t) \quad (3)$$

where $V_f(t)$ is the effective air velocity acting on the PV receiver surface, calculated from the relative airspeed between the UAV and the ambient wind together with the rotor-induced downwash. The resulting $h_w(t)$ is expressed in $\text{W}/(\text{m}^2 \text{K})$ and represents only the convective heat-transfer contribution in the present model. Radiative heat transfer is accounted for separately through the Stefan–Boltzmann term in the thermal energy balance; therefore, no radiative contribution is included in $h_w(t)$.

The three relations presented above—the incidence-angle cosine $\cos \lambda_{PV}$, the convective heat-transfer coefficient h , and the atmospheric transmission efficiency η_t —constitute the preparatory stage of the proposed framework: they are evaluated once along the derived UAV trajectory and supplied as time-series inputs to the optimization model. The equations presented in the remainder of this section define the general formulation of the battery-capacity optimization problem itself, which determines the minimum number of battery cells n_b required by the hybrid battery–laser UAV system subject to the coupled optical, thermal, and electrical constraints of the system.

The instantaneous optical output power of the laser source, $P_{laser}(t)$, is bounded by the maximum rated power of the laser module:

$$P_{laser}(t) \leq P_{max,laser} \quad (4)$$

The optical power actually received at the UAV, $P_{rec}(t)$, is obtained by attenuating the transmitted power with the atmospheric transmission efficiency $\eta_t(t)$ and the incidence-angle cosine $\cos \lambda_{PV}(t)$:

$$P_{rec}(t) = P_{laser}(t) \eta_t(t) \cos \lambda_{PV}(t) \quad (5)$$

For the considered mission geometry, the active PV receiver surface remains oriented toward the tracked ground-based laser source; therefore, $\cos \lambda_{PV}(t)$ remains non-negative throughout the analyzed trajectory.

The PV power at the reference irradiance G_{ref} , corrected for the actual cell temperature $T_{pv}(t)$, is given by a linear temperature-derating relation:

$$P_{PV,ref}(t) = \frac{(T_{pv}(t) - T_{ref}) \beta + 100}{100} P_{PV,298} \quad (6)$$

where $\beta = -0.3 \text{ \%}/\text{K}$ is the temperature coefficient of maximum power and $P_{PV,298}$ is the rated PV power at the reference temperature and irradiance. Note that all temperatures are expressed in Kelvin in this study, so the reference temperature is taken as $T_{ref} = 298.15 \text{ K}$, consistent with the standard test condition implicit in $P_{PV,298}$.

The PV power at the actual irradiance $G(t)$ is then scaled proportionally from the reference-irradiance value:

$$P_{PV}(t) = \frac{G(t)}{G_{ref}} P_{PV,ref}(t) \quad (7)$$

where the actual irradiance on the panel is obtained from the received optical power and the PV active area A :

$$G(t) = \frac{P_{rec}(t)}{A} \quad (8)$$

The fraction of received optical power not converted to electricity is dissipated as heat:

$$Q_{loss}(t) = P_{rec}(t) - P_{PV}(t) \quad (9)$$

The thermal balance of the PV array accounts for convective and radiative heat losses to the ambient, together with the transient thermal storage associated with the panel's finite thermal mass:

$$Q_{loss}(t) = h(t) A_{th} (T_{pv}(t) - T_{\infty}(t)) + \varepsilon \sigma A_{th} (T_{pv}^4(t) - T_{\infty}^4(t)) + C_{th} \frac{T_{pv}(t) - T_{pv}(t-1)}{\Delta t} \quad (10)$$

where C_{th} is the lumped thermal capacitance of the PV array. The initial condition $T_{pv}(1) = T_{\infty}$ is imposed, analogous to the battery initial-state condition of Equation (19). The PV-surface emissivity is taken as $\varepsilon = 0.88$, while the equivalent lumped thermal capacitance of the PV receiver assembly is $C_{th} = 406 \text{ J/K}$. The thermal surface area used in the convection and radiation terms is $A_{th} = 0.0484 \text{ m}^2$. For the considered mission, $V_f(t)$ varies between 0.72 and 23.13 m/s, resulting in $h_w(t)$ values between 8.43 and 93.61 W/(m² K).

For numerical implementation, the fourth-order temperature term in Equation (10) is reformulated using a normalized temperature variable. The PV temperature is defined as

$$\tau(t) = \frac{T_{pv}(t)}{300} \quad (11)$$

and an auxiliary variable is introduced as

$$w(t) = \tau^2(t) \quad (12)$$

Accordingly, the fourth-order radiation term can be expressed as

$$T_{pv}^4(t) = 300^4 w^2(t) \quad (13)$$

Thus, the original fourth-order temperature dependence in Equation (10) is represented through quadratic equality constraints, allowing the thermal model to be incorpo-

rated into the nonconvex MIQCP formulation without altering the underlying physical energy-balance equation.

The panel temperature is constrained not to exceed the maximum allowable operating temperature:

$$T_{pv}(t) \leq T_{pv,max} \quad (14)$$

At every time step, the PV output together with the battery discharge power must meet the UAV power demand $P_{load}(t)$, with any surplus routed to battery charging:

$$P_{PV}(t) + P_{b,dis}(t) = P_{b,ch}(t) + P_{load}(t) \quad (15)$$

The battery charge and discharge power are limited by the per-cell charge and discharge rates, scaled by the number of battery cells n_b :

$$P_{b,ch}(t) \leq CR_{bat} n_b \quad (16)$$

$$P_{b,dis}(t) \leq DR_{bat} n_b \quad (17)$$

For $t > 1$, the battery state of energy evolves according to the charging and discharging power, weighted by the corresponding efficiencies:

$$SoE_{BAT}(t) = SoE_{BAT}(t-1) + P_{b,ch}(t) CE_{bat} \frac{\Delta t}{3600} - \frac{P_{b,dis}(t)}{DE_{bat}} \frac{\Delta t}{3600}, \quad t > 1 \quad (18)$$

At $t = 1$ the battery is initialized at a prescribed state of energy per cell:

$$SoE_{BAT}(1) = SoE_{bat}^{ini} n_b \quad (19)$$

The state of energy is bounded between the minimum and maximum admissible levels, scaled by the number of cells:

$$SoE_{BAT,min} n_b \leq SoE_{BAT}(t) \leq SoE_{BAT,max} n_b \quad (20)$$

A binary variable $u(t)$ enforces that the battery cannot charge and discharge simultaneously, using a sufficiently large constant N :

$$P_{b,dis}(t) \leq N u(t) \quad (21)$$

$$P_{b,ch}(t) \leq N (1 - u(t)) \quad (22)$$

The objective of the resulting optimization problem is to minimize the required number of battery cells while satisfying the coupled optical, thermal, and electrical constraints of the hybrid battery–laser UAV system throughout the entire mission. To reduce degeneracy among solutions with the same battery-cell count, the cumulative battery discharge energy is included as a secondary term in the objective function. Accordingly, the optimization problem is formulated as

$$\min \left[1000n_b + \sum_{t=2}^N P_{b,dis}(t) \frac{\Delta t}{3600} \right]. \quad (23)$$

The weighting factor is selected such that minimization of n_b remains the primary design objective, while the secondary term favors solutions with lower cumulative battery discharge energy. Consequently, the reported time-dependent laser-power and thermal trajectories correspond to the optimizer-selected solution under the stated objective and are not necessarily unique.

3. Test and Results

All optimization scenarios reported in this section were solved on a workstation equipped with an Intel® Core™ i7 processor and 32 GB of RAM, using Python 3.13 interfaced with the Gurobi Optimizer 12.0.3 (Gurobi Optimization, LLC, Beaverton, OR, USA). A time step of approximately 1 s was used throughout the numerical analysis. The Non-Convex=2 option was enabled to solve the nonconvex quadratic constraints, the relative MIP-gap tolerance was set to 10^{-4} , and the maximum computation time was limited to 900 s. For the representative 298 K case comprising 7480 time steps, the optimization was completed in 685.37 s, with an "OPTIMAL" solver status and a final relative optimality gap of 0.0035%.

For clarity and reproducibility, the domains of the decision and auxiliary variables used in the optimization model are summarized in Table 2. The corresponding bounds are defined according to the physical operating limits of the laser source, PV receiver, battery system, and thermal model.

Table 2. Domains of the optimization variables.

Variable	Type	Domain
$P_o(t)$	Continuous	$0 \leq P_o(t) \leq P_{o,\max}$
$P_{\text{rec}}(t)$	Continuous	$0 \leq P_{\text{rec}}(t) \leq P_{o,\max}$
$G(t)$	Continuous	$0 \leq G(t) \leq P_{o,\max} / A_{\text{opt}}$
$P_{\text{PV}}(t)$	Continuous	$P_{\text{PV}}(t) \geq 0$
$Q_{\text{loss}}(t)$	Continuous	$0 \leq Q_{\text{loss}}(t) \leq P_{o,\max}$
$T_{\text{pv}}(t)$	Continuous	$T_{\infty} \leq T_{\text{pv}}(t) \leq 373 \text{ K}$
$\tau(t)$	Continuous	$T_{\infty}/300 \leq \tau(t) \leq 373/300$
$w(t)$	Continuous	$(T_{\infty}/300)^2 \leq w(t) \leq (373/300)^2$
$P_{b,\text{ch}}(t)$	Continuous	$0 \leq P_{b,\text{ch}}(t) \leq 48n_b$
$P_{b,\text{dis}}(t)$	Continuous	$0 \leq P_{b,\text{dis}}(t) \leq 240n_b$
$\text{SoE}_{\text{BAT}}(t)$	Continuous	$3n_b \leq \text{SoE}_{\text{BAT}}(t) \leq 12n_b$
$u(t)$	Binary	$u(t) \in \{0, 1\}$

The specifications of the battery cell adopted in the optimization model are summarized in Table 3.

The ground-based laser source operates at a wavelength of 976 nm, matched to the absorption band of the vertical multi-junction (VMJ) PV cells employed in this study. The optical output power of the laser, $P_{\text{max,laser}}$, was treated as a design parameter and investigated up to a maximum value of 900 W in order to assess its effect on the required battery capacity. The photovoltaic array is based on the commercially available MIH® VMJ Cell-Array module [33], whose specifications are summarized in Table 4. In total, 16 modules have been designed in a 4×4 grid.

Table 3. Battery cell specifications used in the optimization model.

Parameter	Symbol	Value
Charge rate per cell	CR_{bat}	48 W
Discharge rate per cell	DR_{bat}	240 W
Charging efficiency	CE_{bat}	99%
Discharging efficiency	DE_{bat}	95%
Initial state of energy per cell	SoE_{bat}^{ini}	12 Wh
Minimum state of energy per cell	$\text{SoE}_{BAT,min}$	3 Wh
Maximum state of energy per cell	$\text{SoE}_{BAT,max}$	12 Wh

Table 4. Photovoltaic array specifications used in the optimization model.

Parameter	Symbol	Value
Module dimensions	—	$55 \times 55 \times 1.5$ mm
Active area per module	—	26.35 cm ²
Reference PV power (per module)	$P_{PV,298}$	12.3 W
Reference irradiance	G_{ref}	1.5 W/cm ²
Reference temperature	T_{ref}	298.15 K
Temperature coefficient of power	β	$-0.3\%/K$
Maximum allowable cell temperature	$T_{pv,max}$	373 K
Optimal wavelength range	—	$900\text{--}1000$ nm

Figure 2 presents the time-dependent power consumption profile of the UAV, derived from the measured power data of an actual UAV flight and extended to about 1 h. As shown in Figure 2a, the power demand fluctuates periodically throughout the 3739.5 s mission, reflecting the repeated cruise, turning, and local-survey maneuvers performed along each lap; a representative single-lap segment is shown in greater detail in Figure 2b. Over the entire mission, the UAV draws an average power of approximately 343 W, with the instantaneous power demand ranging from a minimum of about 3 W during the ground idle phases to a maximum of approximately 507 W during the most power-intensive flight maneuvers. This substantial variability in instantaneous power demand illustrates the dynamic loading conditions that the battery–laser hybrid power system must accommodate throughout the mission.

Table 5 summarizes the battery sizing results obtained for the 3739.5 s mission under the laser-off condition and under laser-assisted operation at three ambient temperatures. Without laser support, the UAV requires $n_b = 42$ battery cells to complete the mission, ending with a final energy state of 128.70 Wh, compared to a lower bound of 126 Wh. When laser-assisted power transfer is enabled, the required number of battery cells drops to 33, 32, and 32 at ambient temperatures of 298 K, 288 K, and 278 K, respectively; this corresponds to a reduction of up to 23.8% compared to when the laser is off. The last two columns of Table 5 quantify this benefit from a complementary, time-based perspective: if the laser-off UAV were equipped with the same (smaller) battery capacity as its laser-assisted counterpart, it would deplete its battery after 2944.0 s at 298 K and after 2863.5 s at 288 K and 278 K, i.e., 795.5 s (21.3%) and 876.0 s (23.4%) before the 3739.5 s mission could be completed. These results indicate that laser-assisted power transfer allows the hybrid battery–laser UAV system either to carry a smaller battery for the same mission, or, equivalently, to sustain a mission that is up to 23% longer with an identical battery, with the benefit becoming slightly more pronounced at lower ambient temperatures due to improved convective cooling of the PV array.

Table 5. Simulation results for the 3739.5 s mission (laser-off and three laser-on ambient-temperature cases).

Scenario	n_b	Final SoE (Wh)	SoE Lower Bound (Wh)	Time-to-Depletion at Equal n_b (s)	Mission Shortfall at Equal n_b	Max. η_{sys} (%)	Avg. η_{sys} (%)
Laser-off	42	128.70	126	—	—	—	—
Laser-on, 298 K	33	105.00	99	2944.0	795.5 s (21.3%)	9.45	5.56
Laser-on, 288 K	32	103.34	96	2863.5	876.0 s (23.4%)	12.54	6.68
Laser-on, 278 K	32	101.05	96	2863.5	876.0 s (23.4%)	11.10	6.59

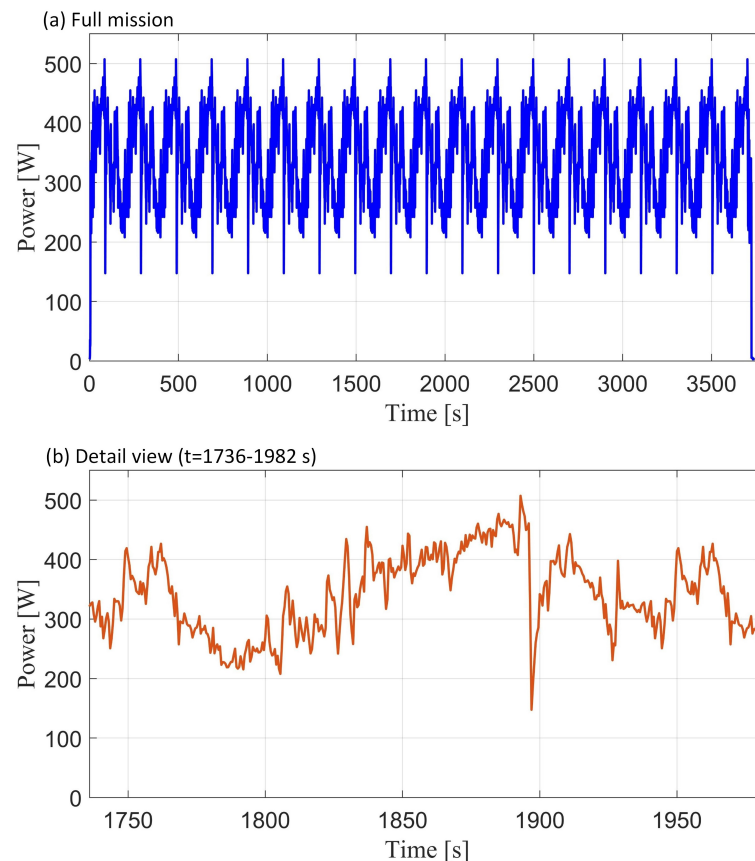


Figure 2. Time-dependent drone electrical power consumption curve: (a) Over the entire duration (b) in the range of 1736–1982 s.

The end-to-end LWPT system efficiency is strongly influenced by the ambient temperature and the resulting thermal operating condition of the PV receiver. At 298 K, the ground-based laser system consumes a cumulative electrical energy of 1426.05 Wh, while the onboard PV receiver generates 79.24 Wh of electrical energy, corresponding to a mission-level end-to-end efficiency of 5.56%. The maximum instantaneous efficiency reaches 9.45%. When the ambient temperature is reduced to 288 K, the cumulative laser-input energy decreases to 1346.33 Wh, whereas the harvested PV electrical energy increases to 89.91 Wh. Consequently, the mission-level efficiency increases to 6.68%, with a maximum instantaneous value of 12.54%. At 278 K, the cumulative laser-input and PV-output energies are 1330.93 Wh and 87.74 Wh, respectively, yielding a mission-level efficiency of 6.59% and a maximum instantaneous efficiency of 11.10%. The improvement observed at lower ambient temperatures is primarily associated with the increased thermal margin of the PV receiver, which reduces temperature-induced power degradation and permits more effective utilization of the transferred laser energy. At 298 K, the receiver remains at the imposed maximum temperature of 373 K for approximately 31% of the mission, thereby constraining further utilization of the available laser power. Although the efficiencies at 278 K are slightly lower than those obtained at 288 K, they remain substantially higher than in the 298 K case. This non-monotonic variation can be attributed to the different optimizer-selected laser-power trajectories and operating points, since the optimization objective minimizes the required battery capacity rather than maximizing LWPT efficiency.

Figure 3 presents, for comparison, the battery discharge power and state of energy (SoE) for the laser-off baseline scenario, plotted together on a common time axis. In the absence of PV support, the discharge power directly mirrors the UAV's raw power demand, fluctuating between 0 W and 507.2 W with a higher mission-averaged value of 343.2 W. The

corresponding state of energy, initialized at 504 Wh for the $n_b = 42$ battery pack required in this scenario, declines to 128.7 Wh by the end of the mission—illustrating both the larger battery capacity required without laser assistance and the steeper depletion rate resulting from the absence of any PV offset.

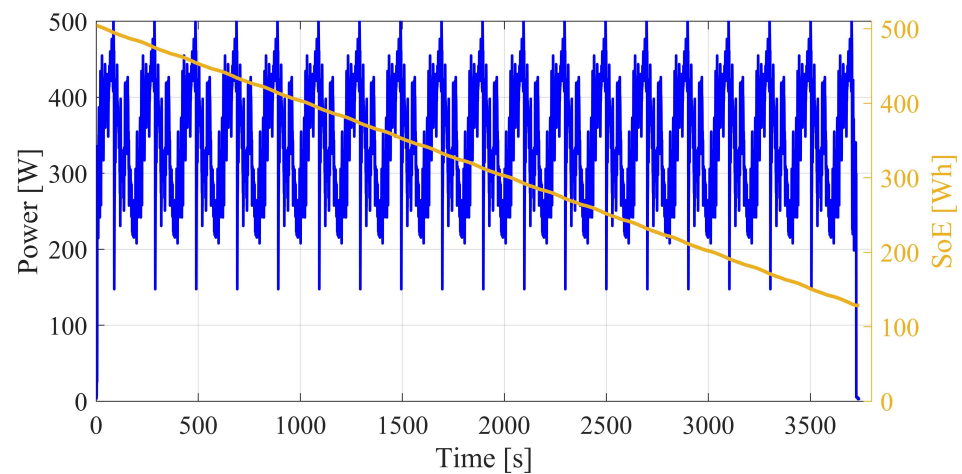


Figure 3. Time-dependent battery discharge power and state-of-energy (SoE) curves for the laser-off (baseline) scenario.

Figure 4 presents the corresponding PV power output, P_{PV} , which fluctuates sharply between 0 W and a peak of 217.3 W as the laser is switched on and off in response to the time-varying incidence angle and the thermal ceiling constraint. Despite these rapid oscillations, the array delivers a time-averaged power of 77.1 W, yielding a cumulative PV energy contribution of 80.1 Wh over the course of the mission—energy that would otherwise have to be supplied entirely by the battery.

Figure 5 shows the time evolution of the PV array temperature, T_{pv} , for the 15-lap mission under the 298 K ambient-temperature scenario. Starting from the ambient temperature at the beginning of the flight, the panel heats up rapidly once the laser beam is engaged and reaches the imposed upper bound of $T_{pv,max} = 373$ K within approximately 15 s. For the remainder of the mission, the panel temperature oscillates between this ceiling and local minima of approximately 358–363 K, corresponding to the periods in which the incidence angle $\cos \lambda_{PV}$ decreases and the panel cools via convective and radiative losses; the array remains at the 373 K ceiling for approximately 31% of the total mission duration.

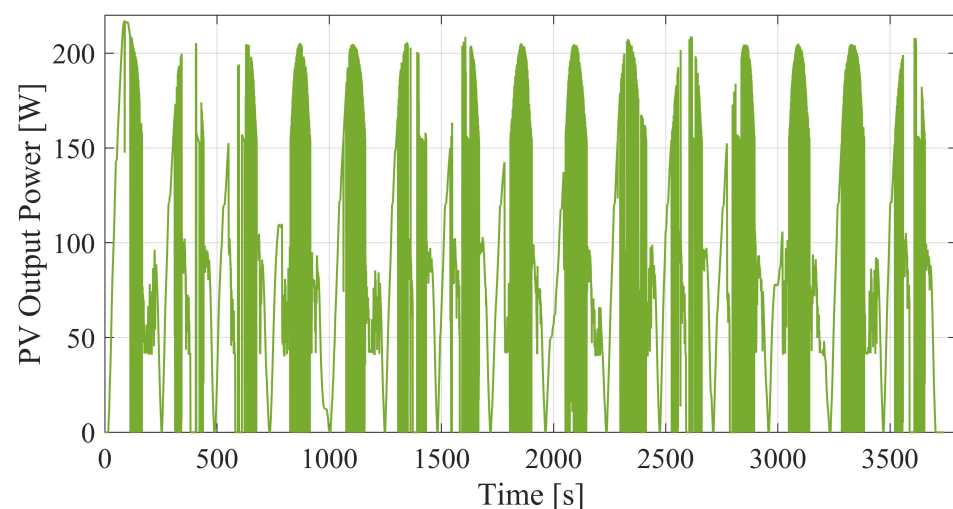


Figure 4. Time-dependent PV array power output curve.

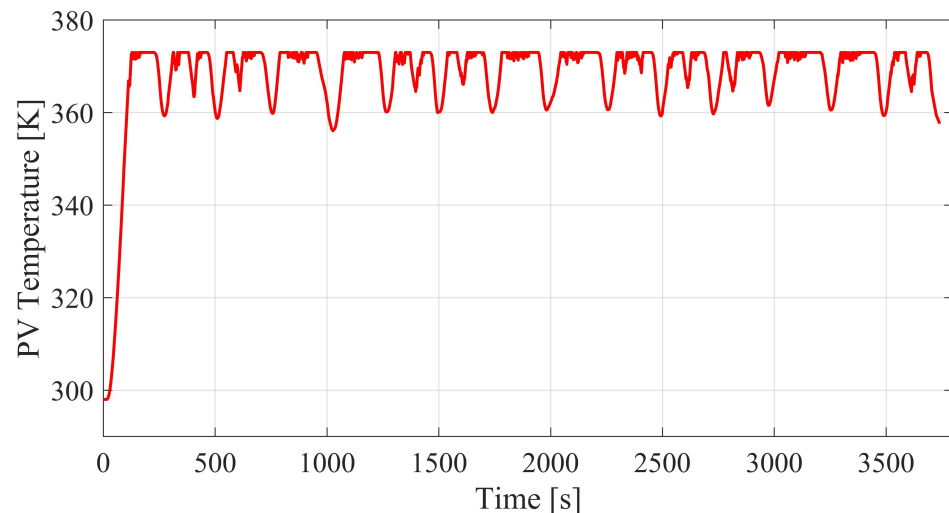


Figure 5. Instantaneous PV array temperature change curve.

Figure 6 shows the time-dependent heat dissipation, Q_{loss} , of the PV panel for the 298 K, laser-assisted scenario. The curve fluctuates between 0 W, corresponding to the periods in which the beam does not reach the panel ($\cos \lambda_{PV} = 0$), and a maximum of 626.3 W, reached whenever the laser operates near its rated power while the incidence angle remains favorable. The mission-averaged heat dissipation is 235.7 W, corresponding to a cumulative thermal load of 244.9 Wh over the course of the flight. Comparison with Figure 5 shows that the sustained high- Q_{loss} intervals coincide with the periods during which the PV panel temperature reaches the imposed ceiling of $T_{pv,max} = 373$ K, confirming that the panel's convective and radiative heat-rejection capacity, rather than the laser power itself, becomes the limiting factor during these intervals.

Figure 7 presents, for the 298 K laser-assisted scenario, the battery discharge power and state of energy plotted together on a common time axis. The discharge power follows the periodic loading pattern imposed by the UAV's repeated patrol maneuvers, fluctuating between 0 W and a maximum of 507.2 W with a mission-averaged value of 266.1 W; this reduction relative to the UAV's raw power demand reflects the instantaneous offset provided by the PV array shown in Figure 4. Correspondingly, the state of energy, initialized at a fully charged value of 396 Wh for the $n_b = 33$ battery pack required in this scenario, declines monotonically—despite the intermittent PV recharging contribution—to a final value of 105.0 Wh by the end of the 3739.5 s mission, confirming that the selected battery capacity is sufficient to complete the mission while remaining above the prescribed lower bound.

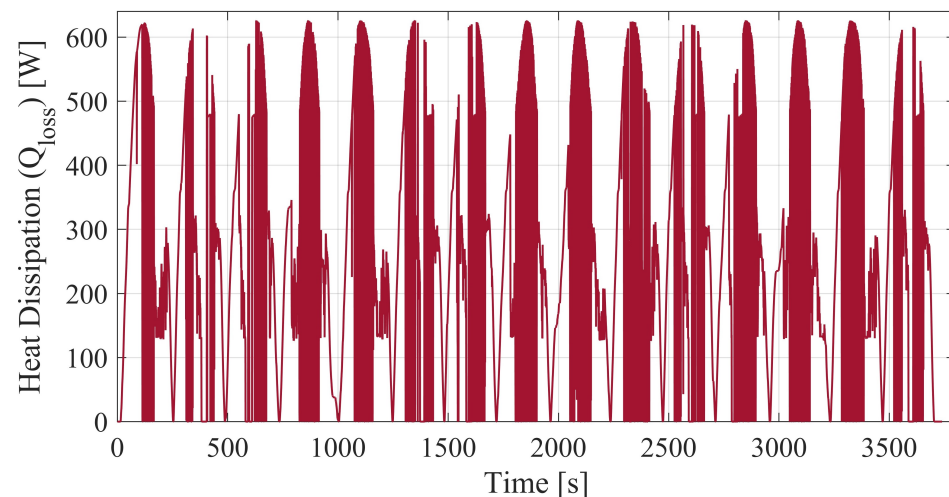


Figure 6. Time-dependent heat dissipation (Q_{loss}) curve.

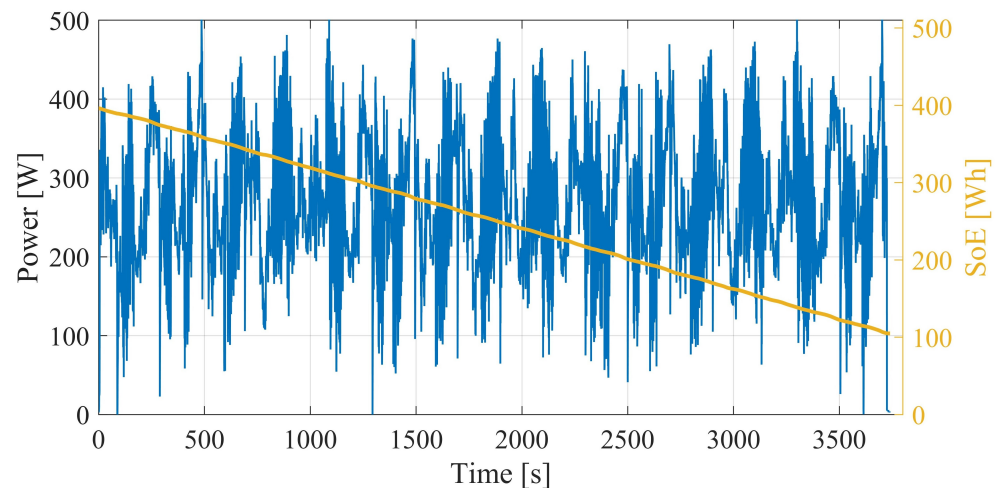


Figure 7. Time-dependent battery discharge power and state-of-energy (SoE) curves for the laser-assisted (298 K) scenario.

4. Discussion

The obtained results provide several important insights into the design of laser-powered UAV systems. First, the achievable reduction in battery capacity is governed not only by the available laser power but also by the effectiveness of the optical-to-electrical energy conversion process. In this regard, both the PV operating temperature and the laser–PV incidence angle play a decisive role. As the incidence angle increases, the effective irradiance on the PV surface decreases according to the cosine projection, directly reducing the harvested optical power. Simultaneously, elevated PV temperatures lower the conversion efficiency, further limiting the electrical energy delivered to the battery. Consequently, the net benefit of laser-assisted operation depends on the combined optical and thermal conditions rather than on the laser-output power alone.

The results also demonstrate that ambient temperature has a measurable influence on the system performance. Lower ambient temperatures enhance convective cooling of the PV module, resulting in lower operating temperatures and slightly higher conversion efficiencies. Although the corresponding reduction in battery size is modest, the improvement consistently increases the endurance benefit of laser-assisted operation. This observation highlights that thermal management should be considered an integral part of LWPT system design, particularly for long-endurance missions in which the PV receiver remains illuminated for extended periods.

From a practical perspective, the findings indicate that laser-assisted power transfer can be exploited in two complementary ways. The harvested laser energy may be used either to reduce the required onboard battery capacity, thereby lowering the takeoff mass, or to extend the achievable mission duration while maintaining the same battery pack. These two design options provide additional flexibility for disaster-response UAV operations, where mission requirements may prioritize either longer endurance or reduced vehicle weight depending on the operational scenario.

To assess the sensitivity of the battery-sizing result to the imposed maximum PV temperature, additional simulations were performed for the 298 K ambient-temperature case. When $T_{pv,max}$ was reduced from 373 K to 363 K and 353 K, the required battery-cell count increased from 33 to 34 and 35 cells, respectively. This monotonic trend confirms the strong influence of the receiver thermal constraint on the achievable benefit of laser power transfer. Nevertheless, the laser-assisted system continues to require fewer battery cells than the battery-only case even under the more restrictive thermal limits.

5. Conclusions

The limited endurance imposed by onboard battery capacity remains one of the principal obstacles to the sustained operation of UAVs in long-duration missions such as post-disaster surveillance, where continuous area coverage can be critical to relief efforts. LWPT offers a promising means of alleviating this limitation without increasing the UAV's payload.

In this study, particular emphasis was placed on the energy management of a hybrid battery–laser-powered UAV system. To address this challenge, an integrated optical–thermal–electrical framework was developed for a laser-assisted UAV operating in disaster-response missions. The proposed framework combines experimentally measured UAV power-consumption data with realistic flight trajectories, laser beam propagation, temperature-dependent PV conversion, and battery dynamics within a nonconvex MIQCP optimization model for battery sizing. The results demonstrate that the proposed hybrid system reduces the required battery capacity by up to 23.8% compared with the laser-off baseline under the most favorable operating conditions. Equivalently, for the same battery capacity, laser-assisted operation extends the achievable mission duration by a comparable margin. Furthermore, the results show that maximizing mission endurance depends not only on the available laser power but also on the combined effects of optical and thermal performance. Specifically, the achievable benefit is jointly governed by the alignment between the laser beam and the PV array along the flight trajectory and by the thermal state of the PV receiver, highlighting the importance of integrated optical and thermal design. More broadly, the proposed framework demonstrates how experimentally measured UAV power-consumption data can be integrated with optical, thermal, and battery models to support mission-oriented battery sizing for laser-powered aerial platforms. This provides a practical methodology for the design and analysis of next-generation long-endurance UAVs operating in infrastructure-limited environments.

The present battery model assumes temperature-independent battery parameters; therefore, the effects of low temperature on usable capacity and charge/discharge efficiency are not explicitly considered. Future work will extend the framework by incorporating temperature- and aging-dependent battery characteristics to provide a more comprehensive assessment of battery performance under different environmental conditions. Future work will focus on experimental validation of the proposed framework through a small-scale prototype, including comparison of measured and simulated PV electrical output, receiver temperature, and battery state-of-energy profiles. The experimental results will also be used to refine the semi-empirical thermal-model parameters and to assess the accuracy of the coupled optical–thermal–electrical formulation.

Author Contributions: Methodology, H.Y.; software, H.Y.; writing—original draft preparation, H.Y.; writing—review and editing, A.T. and M.K.; visualization, H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Istanbul Topkapi University.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: While preparing this study, the authors used ChatGPT 5.6 and Claude to improve the language and readability of the article and to generate Figure 1. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the final version of the published article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CdTe	Cadmium Telluride
c-Si	Crystalline Silicon
GaAs	Gallium Arsenide
LWPT	Laser Wireless Power Transfer
MIQCP	Mixed-Integer Quadratically Constrained Programming
MPPT	Maximum Power Point Tracker
NOCT	Nominal Operating Cell Temperature
PV	Photovoltaic
STC	Standard Test Condition
UAV	Unmanned Aerial Vehicle
VMJ	Vertical Multi-Junction
WPT	Wireless Power Transfer

Nomenclature

Sets and indices

t Set of time periods

Parameters

$dis(t)$	Instantaneous slant distance between the UAV and the laser source (km)
$\cos \lambda_{PV}(t)$	Cosine of the beam incidence angle on the PV panel
$h(t)$	Convective heat-transfer coefficient (W/m^2K)
$\eta_t(t)$	Atmospheric transmission efficiency of the laser beam
A	PV active area used in irradiance/power calculations (cm^2)
A_{th}	Thermal surface area (m^2)
$P_{max,laser}$	Maximum laser optical power (W)
G_{ref}	Reference irradiance (W/cm^2)
$P_{PV,298}$	Reference PV power at 298 K and G_{ref} (W)
T_{ref}	Reference temperature (K)
β	PV power temperature coefficient ($\%/K$)
T_∞	Ambient temperature (K)
$T_{pv,max}$	Maximum allowable PV temperature (K)
C_{th}	Lumped thermal capacitance of the PV array (J/K)
$P_{load}(t)$	UAV electrical power demand (W)
CR_{bat}	Battery charge rate per cell (W)
DR_{bat}	Battery discharge rate per cell (W)
CE_{bat}	Battery charging efficiency (%)
DE_{bat}	Battery discharging efficiency (%)
SoE_{bat}^{ini}	Initial state of energy per battery cell (Wh)
$SoE_{BAT,min}$	Minimum state of energy per battery cell (Wh)
$SoE_{BAT,max}$	Maximum state of energy per battery cell (Wh)
Δt	Time step (s)
N	Sufficiently large constant

Variables

$P_{laser}(t)$	Instantaneous laser optical output power (W)
$P_{rec}(t)$	Optical power received at the UAV (W)
$G(t)$	Actual irradiance incident on the PV panel (W/cm^2)
$P_{PV,ref}(t)$	PV power at reference irradiance, temperature-corrected (W)
$P_{PV}(t)$	PV electrical output power (W)
$T_{pv}(t)$	PV panel temperature (K)
$Q_{loss}(t)$	Heat dissipated by the PV panel (W)
$P_{b,ch}(t)$	Battery charging power (W)

$P_{b,dis}(t)$	Battery discharging power (W)
$SoE_{BAT}(t)$	Battery state of energy at time t (Wh)
$u(t)$	Binary charge/discharge indicator variable
n_b	Number of battery cells

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