

# Evaluation of Optimal Power Systems for Timber Extraction Using High-Payload Drones: A Simulation-Based Approach

Shigetoshi Tokuoka<sup>1</sup>, Yoshiaki Ohkami<sup>1</sup>, Yoshiki Yamagata<sup>1</sup>

1 Graduate School of System Design and Management, Keio University, 223-8521 Kanagawa, , Japan  
(Corresponding Author Email: tokusige@keio.jp (S., Tokuoka))

## ABSTRACT

This study proposes a modeling framework and power system selection process for the deployment of high-payload drones in timber extraction operations, with the objective of promoting sustainable forestry practices. The introduction of such drones is expected to improve labor efficiency and operational productivity by reducing hazardous and physically demanding tasks, and lowering the labor and cost requirements associated with forest road development. To support optimal power system selection, evaluation criteria were established from the perspectives of economic efficiency, operational feasibility, and environmental impact. Simulations were conducted for four candidate power systems, battery-powered systems (BPS), BPS with off-grid charging, series hybrid systems (SHS), and tethered power supply systems (TPS), across payload capacities of 100 kg, 200 kg, and 300 kg. The results indicate a general trend of increasing overall performance scores with larger payloads. While both the BPS and TPS exhibited favorable performance, the operational advantages of the BPS were found to be limited in remote forest environments due to challenges in securing high-voltage grid access and operational interruptions associated with battery replacement. In contrast, the TPS demonstrated superior scalability and operational stability at higher payloads in all weighting scenarios, benefiting from a higher payload-to-airframe ratio and a continuous power supply. These findings suggest that the TPS offers strong potential for large-scale deployment, particularly in the transport of heavy thinning and clear-cut timber.

**Keywords:** sustainable forestry, timber extraction, high-payload drones, optimal power system selection, tethered power supply system

## NONMENCLATURE

Abbreviations	
MTOW	Maximum Take-Off Weight
JPY	Japanese Yen

BPS	Battery-powered systems
SHS	Series hybrid systems
TPS	Tethered power supply systems
OPS	Overall Performance Score
<i>Symbols</i>	
$U_e, U_l$	Horizontal speed when empty, loaded
$V_{ce}, V_{cl}$	Climbing speed when empty, loaded
$V_{de}, V_{dl}$	Descending speed when empty, loaded
$P_{he}, P_{hl}$	Required power on hovering when empty, loaded
$P_{ce}, P_{cl}$	Required power on climbing when empty, loaded
$P_{de}, P_{dl}$	Required power on descending when empty, loaded
$v_i$	Rotor induced velocity
$W_e, W_l$	Drone weight when empty, loaded
$\rho$	Air density
$A$	Total rotor disk area
$FM$	Figure of merit of rotor blades

## 1. INTRODUCTION

Japan is among the most forested countries, with approximately 70% of its land area covered by forests. However, Japan's forestry industry faces a severe decline in labor force and profitability due to its aging workforce, fragmented ownership, and underdeveloped infrastructure. These structural constraints have led to inefficient, small-scale operations, and reduced competitiveness against imported timber<sup>[1]</sup>. Since the 1960s, efforts have been made to mechanize hazardous timber transportation processes, and numerous studies have quantitatively evaluated the productivity of forestry mechanization<sup>[2]</sup>. However, such mechanization requires well-developed forest road infrastructure and appropriate machinery selection tailored to the terrain<sup>[3]</sup>. In remote mountainous areas with limited road access, aerial logging using large helicopters has been extensively studied and is already implemented in real-world forestry operations<sup>[4-10]</sup>. Nevertheless, due to high

infrastructure and equipment costs, these methods are generally restricted to large-scale operations handling high-value timber.

Recently, drones have gained attention as a viable alternative for addressing these limitations. Compared with helicopters, drones offer substantially lower barriers to adoption and operational costs, making them accessible even to small-scale operators. Their use is expected to reduce labor requirements and streamline work processes<sup>[11,12]</sup>. Furthermore, integrating high-payload drones into timber extraction operations has the potential to reduce the labor and the cost burdens associated with forest road construction. Accordingly, drones represent a promising solution for reducing hazardous forestry operations, while simultaneously achieving labor savings and improved operational efficiency in forestry, thereby contributing to the broader goal of sustainable forest management<sup>[13]</sup>.

This study focuses on the application of high-payload drones in timber extraction operations and proposes a method for selecting the optimal power system. Evaluation criteria are established from the perspectives of economic efficiency, operational feasibility, and environmental impact, and four candidate power systems are assessed. As the choice of power system directly influences drone performance, the objective of this study is to identify the most suitable power system for high-payload drones used in forestry timber extraction by modeling row-thinning operations and selecting the optimal power system accordingly.

## 2. MATERIAL AND METHODS

### 2.1 Preconditions

#### 2.1.1 Analysis model

This study assumes an analysis model for row thinning on a 25% slope, in which 25 trees with each 15 meters height are evenly spaced at 2-meter intervals (Fig. 1).

#### 2.1.2 Flight profile

The drone is assumed to perform timber extraction following the flight profile shown in Fig. 2, operating at the flight speeds listed in Table 1 and maintaining a target altitude of up to 30 meters. Although lower flight altitudes are generally advantageous in terms of energy consumption and operation time, a flight altitude of 30 meters was adopted—twice the assumed tree height of 15 meters in the thinning forests—to ensure safe clearance. The time axis in Fig.2 varies depending on the distance between the forest road and the felling point.

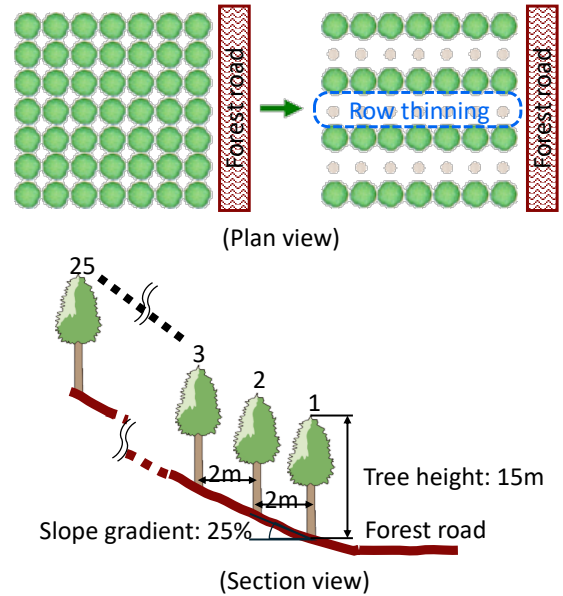


Fig. 1 Analysis model of row thinning

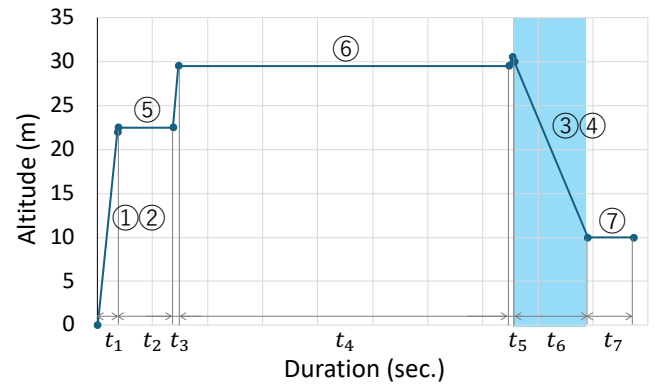


Fig. 2 Flight profile during timber extractions

Table 1 Flight speed and operating time

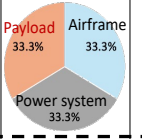
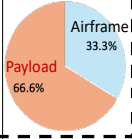
① Climbing/descending speed when empty: $V_{ce}$ , $V_{de}$	$V_{ce} = 2.0$ m/s $V_{de} = -2.0$ m/s
② Horizontal speed when empty: $U_{he}$	$U_{he} = 10$ m/s
③ Climbing/descending speed when loaded: $V_{cl}$ , $V_{dl}$	$V_{cl} = 0.5$ m/s $V_{dl} = -0.5$ m/s
④ Horizontal speed when loaded: $U_{hl}$	$U_{hl} = 2.5$ m/s
⑤ Loading time	30 sec.
⑥ Felling time	180 sec.
⑦ Unloading time	25 sec.

#### 2.1.3 Candidate power systems and specifications

Four power systems, as listed in Table 2, were considered as candidates, and simulations were conducted assuming payload capacities of 100kg, 200kg, and 300 kg. In this study, the weight allocation for the

BPS and SHS is assumed to follow a conventional drone design, wherein the airframe (including propulsion and ancillary systems), the power system, and the payload each account for approximately one-third of the maximum takeoff weight (MTOW). In contrast, for the TPS, owing to the ground-based power source, the weight fraction that would otherwise have been allocated to the onboard power system was reassigned to the payload, allowing the payload to constitute two-thirds of the MTOW.

Table 2 Power system candidates and specifications

Candidate power systems	BPS	BPS w/off-grid CHG.	SHS	TPS
MTOW (kg)	300/600/900	←	←	150/300/450
Airframe (kg)	100/200/300	←	←	←
Power system(kg)	100/200/300	←	←	(off board)
Energy capacity(kWh)	21/41/62	←	62/103/117	(off board)
Payload (kg)	100/200/300	←	←	100/200/300
Weight allocation		←	←	
Max power (kW)	43/108/163	←	←	20/43/79
Number of rotors	4/8×2/12×2	←	←	4/4/4

### 2.1.4 Other preconditions and assumptions

- Electricity unit cost: 18 JPY/kWh (2023 actual basis)
- Fuel price: Gasoline 170 JPY/L, Diesel 150 JPY/L (as of Jun. 2023)
- Battery unit cost: 115 \$/kWh = 17,300 JPY/kWh (FY2024) <sup>[14]</sup>
- Battery replacement cycle: 500 cycles
- CO<sub>2</sub> emission coefficient  
Average CO<sub>2</sub> factor of Japan's grid electricity : 0.423 kg-CO<sub>2</sub>/kWh (as of 2023) <sup>[15]</sup>  
Gasoline: 2.32 kg-CO<sub>2</sub>/L, Diesel: 2.58 kg-CO<sub>2</sub>/L
- Maintenance cost per flight hour is assumed to be following rate of the total drone cost.
  - BPS, TPS: 0.004% same level as eVTOL aircraft <sup>[16]</sup>
  - SHS: 0.008% assuming double the cost of BPS
- Annual operating days: 150 days

### 2.2 Theory/calculation

When the horizontal flight speed is low, aerodynamic drag and lift are negligible. Accordingly, the required power for flight is determined primarily by the vertical flight speed, and is calculated for each payload condition and flight phase, as summarized in Equation (1) to (6) <sup>[17]</sup>.

Hovering power when empty

$$P_{he} = \frac{W_e^{3/2}}{FM\sqrt{2\rho A}} \quad (1)$$

Hovering power when loaded

$$P_{hl} = \frac{W_l^{3/2}}{FM\sqrt{2\rho A}} \quad (2)$$

Climbing power when empty

$$P_{ce} = P_{he} \left( \frac{V_{ce}}{v_i} + \sqrt{\left(\frac{V_{ce}}{v_i}\right)^2 + 1} \right) \quad (3)$$

Climbing power when loaded

$$P_{cl} = P_{hl} \left( \frac{V_{cl}}{v_i} + \sqrt{\left(\frac{V_{cl}}{v_i}\right)^2 + 1} \right) \quad (4)$$

Descending power when empty

$$P_{de} = P_{he} \left( \frac{V_{de}}{v_i} + \sqrt{\left(\frac{V_{de}}{v_i}\right)^2 + 1} \right) \quad (5)$$

Descending power when loaded

$$P_{dl} = P_{hl} \left( \frac{V_{dl}}{v_i} + \sqrt{\left(\frac{V_{dl}}{v_i}\right)^2 + 1} \right) \quad (6)$$

Here,  $v_i$  is the induced velocity through the rotor disk during hover, expressed in Equation (7),(8) <sup>[17]</sup>

When empty

$$v_i = \sqrt{\frac{W_e}{2\rho A}} \quad (7)$$

When loaded

$$v_i = \sqrt{\frac{W_l}{2\rho A}} \quad (8)$$

Once the flight profile is defined, the corresponding power requirements and durations are obtained from Table 1, and the total energy demand for the entire mission is then calculated.

### 2.3 Procedure for selecting the optimal power system

Based on the methodology established in previous study<sup>[18]</sup>, the procedure for selecting the optimal power system is defined as follows. To evaluate power systems for timber extraction drones, performance indicators are developed from three evaluation criteria: economic efficiency, operational feasibility, and environmental

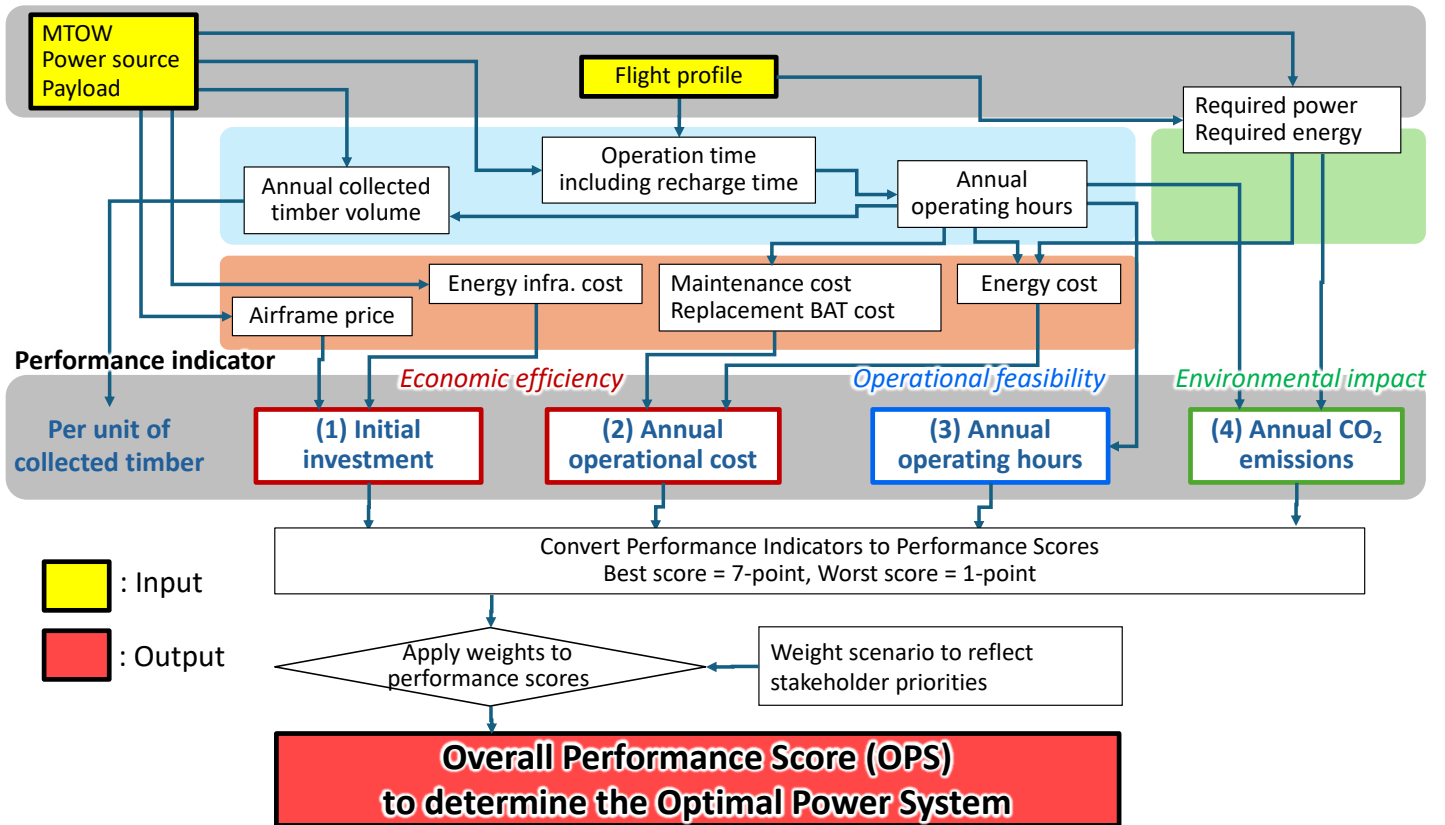


Fig. 3 Procedure for determining the optimal power system

impact. Specifically, to facilitate the evaluation of the impact on timber pricing, the metrics were formulated on a per-unit timber extraction basis. Accordingly, the evaluation framework comprises four Performance Indicators, each normalized by the annual amount of timber extracted: (1) Initial investment, (2) Annual operational cost, (3) Annual operating hours, and (4) Annual CO<sub>2</sub> emissions. The overall optimal power system selection process is illustrated in Fig. 3. Given input parameters such as the drone’s MTOW, power source, payload, and the flight profile used during timber extraction, four performance indicators are calculated. As each performance indicator represents a physical quantity of different dimensions, these values were converted into nondimensional scores – Performance Scores – to enable an overall evaluation, with the best-performing case assigned 7 points and the worst-performing case assigned 1 point. Weights are then applied to the performance scores to reflect stakeholder priorities. Finally, the Overall Performance Score (OPS) is calculated to determine optimal power system.

### 3. RESULTS

According to the procedure in Fig. 3, the Performance Indicators (1)-(4) were calculated. Based on these results, the corresponding Performance Scores were

derived and summarized by power system and payload as presented in Table 3. The colors are classified into three categories: red (1 ≤ score < 3; low), yellow (3 ≤ score < 5; medium), and green (5 ≤ score ≤ 7; high). The TPS exhibits a high proportion of green scores, whereas the proportion of red scores increases for the BPS and

Table 3 Performance score by power system and payload

Candidate Power systems	BPS	BPS w/ off-grid CHG.	SHS	TPS
(1) Initial investment	7.0	1.0	6.5	6.3
	7.0	2.3	5.3	6.7
	7.0	2.9	4.9	6.8
(2) Operational cost	3.0	1.3	3.8	6.7
	2.8	1.2	3.3	7.0
	2.8	1.0	3.1	6.9
(3) CO <sub>2</sub> emissions	7.0	2.6	1.8	6.1
	6.1	1.9	1.6	6.6
	6.1	1.0	1.6	5.9
(4) Operating hours	1.0	1.0	1.6	2.2
	5.2	5.2	5.6	5.8
	6.6	6.6	6.8	7.0

#### Legend

Score at Payload 100kg  
200kg  
300kg

#### Score level

Low : 1 ≤ score < 3  
Mid : 3 ≤ score < 5  
High : 5 ≤ score ≤ 7

the SHS, the BPS with off-grid charging showing the highest proportion of red. From these scores and weights, the Overall Performance Scores (OPS) were calculated. To assess the sensitivity of the OPS with respect to weighting, three scenarios were established, as shown in Table 4.

Table 4 Weighting scenario

Weighting Scenario	Sc.1 Balanced	Sc.2 Environment -prioritized	Sc.3 Productivi -prioritize
(1) Initial investment	0.17	0.15	0.2
(2) Operational cost	0.17	0.15	0.2
(3) CO <sub>2</sub> emissions	0.33	0.4	0.2
(4) Operating hours	0.33	0.3	0.4

The OPS results under each scenario are presented in Fig. 4. For timber-extraction drones, although the scores vary across scenarios, the OPS generally increases with payload capacity. Among all power systems, the TPS consistently achieved the highest OPS across all payload capacities from 100 to 300 kg, followed by the BPS and the SHS. However, when off-grid charging is required, the advantage of the BPS diminishes, resulting in the lowest OPS among the evaluated systems.

#### 4. DISCUSSION

The results of this study indicate that, in drone-based timber extraction operations, increasing the payload generally enhances overall performance. The consistent superiority of the TPS across all payload capacities underscores its robustness and scalability. This finding

suggests that, unlike the BPS and the SHS, the TPS is particularly well-suited for accommodating larger payloads and holds strong potential for real-world applications in transporting heavy logs. This advantage is attributed to the external placement of the power system, which reduces airframe weight and lower energy consumption per unit timber extracted during flight. In addition, it eliminates the need for operational interruptions such as battery replacement. The off-grid charging generator for the BPS requires roughly 1.5 times the power output of that used in the TPS to complete recharging within the battery swap cycle. Consequently, fuel consumption increases, making the BPS less advantageous in terms of operating hours, operational cost, and environmental impact. The SHS was assumed to employ a reciprocating gasoline engine, commonly used in aviation, as its power generation unit due to constraints in required output and engine weight, as no suitable diesel engine was available under the present assumptions. For onboard power systems, the energy capacity is limited to one-third of the MTOW, and the required number of refueling or battery-swap operations is determined by the total energy demand.

#### 5. CONCLUSIONS

In this study, a modeling framework was developed to evaluate the suitability of high-payload drones for timber extraction in forestry operations. Evaluation criteria were established from the perspectives of economic efficiency, operational feasibility, and environmental impact. Simulations were conducted for four candidate power systems – battery-powered systems (BPS), BPS with off-grid charging, series hybrid systems (SHS), and tethered power supply systems (TPS) – to identify the optimal configuration. The results revealed that the TPS consistently achieved the highest

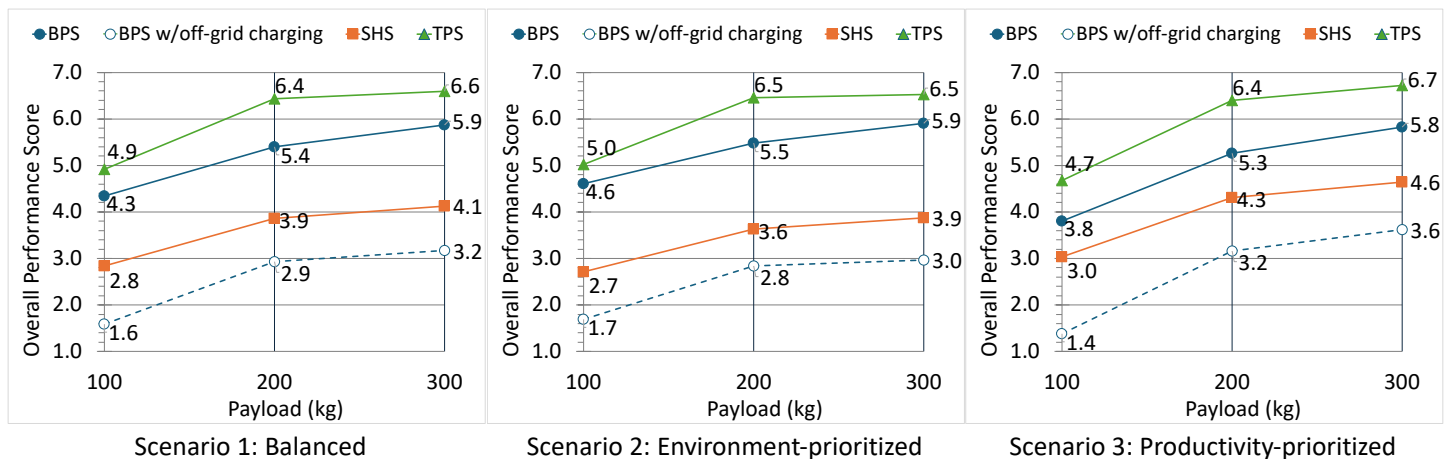


Fig. 4 Overall performance score for each weighting scenario

overall performance scores across payload capacities, demonstrating robustness and scalability for accommodating larger payloads. While the BPS also showed competitive performance under grid electricity, its advantages diminished significantly when off-grid charging is required. These findings highlight the strong potential of the TPS for practical forestry applications, particularly for transporting heavy thinning and clear-cut timber. Nonetheless, the TPS entails inherent limitations, including restricted operational range due to the power supply cable length, necessitating careful route planning according to site conditions. Additional operational challenges include avoiding cable entanglement with trees during transport and minimizing the risk of disconnection.

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