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# Optimal Power Source Selection of Advanced Air Mobility for Passenger Transport Use Cases

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**ABSTRACT**

Advanced Air Mobility (AAM) is anticipated to be a new mode of transportation, with battery-powered systems frequently being considered due to their simple architecture, ease of maintenance, and zero in-flight emissions. However, technical limitations of batteries impose constraints on mission profiles, making the selection of the most suitable power source crucial for each application. This study focuses on passenger transport use cases for AAM and proposes an approach to identify the optimal power source between two candidates: Battery-powered and Series-hybrid system. The analysis considers various scenarios involving different annual number of passengers, flight distances, and Sustainable Aviation Fuel (SAF) mixing ratios. Our findings suggest that without the use of SAF, the Battery-powered system covered 28% of all scenarios for flight distances exceeding 150 km and an annual passenger count between 10,000 to 25,000. Meanwhile, when the SAF mixing ratio reached 50%, the Series-hybrid system was identified as the optimal and more versatile power source in over 60% of all scenarios.

**Keywords:** Optimal power source, Annual passenger number, Flight distance, SAF mixing ratio, Series-hybrid

**NONMENCLATURE**

| | |
|---|---|
| *Abbreviations* | |
| MTOM | Maximum Take-Off Mass |
| JPY | Japanese Yen |
| FH | Flight Hour |
| PAX | Passengers |
| DOC | Direct Operating Cost |
| *Symbols* | |
| $v_j$ | Horizontal speed in each flight phase |
| $t_j$ | Flight time in each flight phase |
| $P_j$ | Required power in each flight phase |
| $E_{total}$ | Total required energy for flight |
| $R$ | Flight range |

## 1. INTRODUCTION

AAM is attracting attention as a new mode of transportation, with many studies currently focused on its social implementation[1]. For passenger transport applications, key considerations include flight distance, passenger capacity, and cost efficiency. These factors are heavily influenced by the selection of the power source, which not only determines the mobility's performance but also impacts its weight, cost, operational expenses, and environmental footprint. Additionally, compatibility with energy infrastructure in the operating area must be considered. While many AAM designs favor battery-powered systems due to their simple architecture, high reliability, ease of maintenance, and zero emissions during flight[2], these systems face technical limitations that can restrict mission capabilities[3][4]. Consequently, alternative power sources have been explored in various studies[5][6]. In this study, we propose a methodology for selecting the optimal power source for AAM, tailored to specific passenger transport scenarios. This approach evaluates flight distance, annual number of passengers and SAF mixing ratios using evaluation functions related to environmental impact, economic performance, and transport capability.

## 2. MATERIAL AND METHODS

### 2-1. PRECONDITION

Considering EASA Special Conditions for small-category VTOL aircraft (SC-VTOL-01), we conducted the study in the range of 9 passengers or less and MTOM of 3,175 kg or less. This study was based on a fixed-wing with canard configuration, vectored-thrust type aircraft because the range and cruising speed are advantageous from the previous studies[7][8] and the precise aircraft specs. and formulas of the required power and energy during flight are available from the paper by P.Nathen et al.[9]. Regarding power source candidates, we considered two types of power sources: a Battery powered type and

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a Series-hybrid type in which the motor is driven by the electricity generated by the engine using liquid fuel. Prior to the study, we defined the flight profile as shown in (Fig. 1). The altitude was set to 300 meters because the minimum safe flight altitude is 300 meters above sea level in accordance with MLIT Guidelines for the Examination of Operational Specifications.

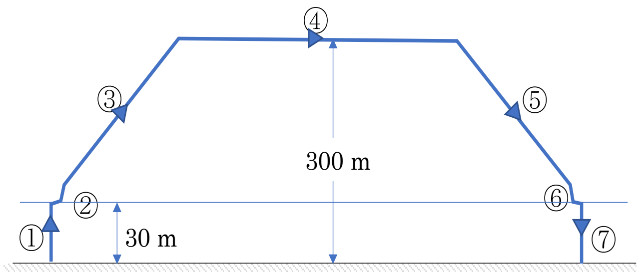


*Fig. 1 Flight profile definition*

From the interviews with a helicopter pilot who commented that they usually do not perform vertical landings from high altitude except when landing space is limited, and that careful maneuvering is required during landing due to the instability of the landing site, we set the takeoff and landing altitude to 30 meters, and the landing time was set to be three times as long as the takeoff time (Table 1).

*Table 1 Each flight phase description*

| Flight phase | Description | Horizontal speed [m/s] | Time [s] |
|---|---|---|---|
| ①Take off | Vertical take-off till 30m | $v_1$ =0 | $t_1$=15 |
| ②Transition | | $v_2$ =0 | $t_2$=20 |
| ③Ascend | Horizontal speed 0→300km/h<br>Climb angle 5° till 300m alt. | $v_3$ =41.5 | $t_3$=75 |
| ④Cruise | Cruise speed 300km/h,<br>Cruise altitude 300m | $v_4$ =83.3 | $t_4$ |
| ⑤Descend | Horizontal speed 300→0km/h<br>Descent angle 5° till 30m alt. | $v_5$ =41.5 | $t_5$=75 |
| ⑥Transition | | $v_6$ =0 | $t_6$=20 |
| ⑦Landing | Landing from 30m alt. | $v_7$ =0 | $t_7$=45 |

As for other preconditions and assumptions,

- Electricity unit cost: 10 JPY/kWh [10] (Japan FY2030 outlook)
- Battery unit cost: 10,000 JPY/kWh (from METI Storage Battery Industry Strategy FY2030 target)
- Power generation system unit cost: 0.9M JPY/kW based on vehicle diesel engine [11]
- Japan's $CO_2$ emission coefficient for electricity: 370 g-$CO_2$/kWh [12] (FY2030 target)
- Battery replacement cycle: 1,000 cycles [13]
- Pilot labor cost: 9,000 JPY/FH assumed from the labor cost of helicopter pilots in Japan.
- Maintenance cost: Battery type: 10,000 JPY/FH [14], Series hybrid type: 20,000 JPY/FH (assuming double the cost of Battery type.)
- Passenger Fare: 10,000 JPY for first 50km and plus 5,000JPY per 50km.
- Annual Operation rate: 75%, Average occupancy rate: 65% from passenger transport helicopter rate

### *2-2. EVALUATION FUNCTION*

In the context of passenger transport use cases, several key indices are critical, including safety, operational efficiency, environmental impact, economic viability, customer satisfaction, operational flexibility. For the purpose of our optimization approach, we have identified three evaluation functions from these indices that are particularly significant in differentiating between power sources. These functions are: Transport capability, defined as PAX capacity, which reflects operational efficiency and versatility; Operational profitability, derived from economic efficiency and profitability; and $CO_2$ emission per PAX per kilometer during flight, representing environmental impact.

### *2-3. SELECTION FLOW*

The flow of optimal power source selection is indicated as follows (Fig. 2).

1) Calculate the power and energy consumption required to fly specified distance at MTOW, based on each passenger and energy capacity condition.
2) Determine annual flight hours (FH) from flight distance and annual number of flights (passengers).
3) Calculate the major annual DOC (items in the top 80% of cumulative DOC [15]) : depreciation cost of the aircraft price, pilot labor cost, aircraft maintenance cost, and replacement battery cost , energy cost from the energy consumption in 1), depreciation cost of the energy infra (fast charging facilities for a battery powered system).
4) Calculate annual passenger revenue from the annual number of passengers and the fare.
5) Define "PAX capacity" as the evaluation function of the transport capability.
6) Define "Operational Profitability" as the evaluation function of the economic performance.
7) Define "$CO_2$ emissions per PAX per kilometer" as the evaluation function of the environment impact.
8) Calculate the scores for the three evaluation functions, with the best value receiving 7 points and the worst receiving 1 point. Assign weight factors between 0 and 1 based on project priorities, ensuring the total equals 1. In this study, we assumed weight

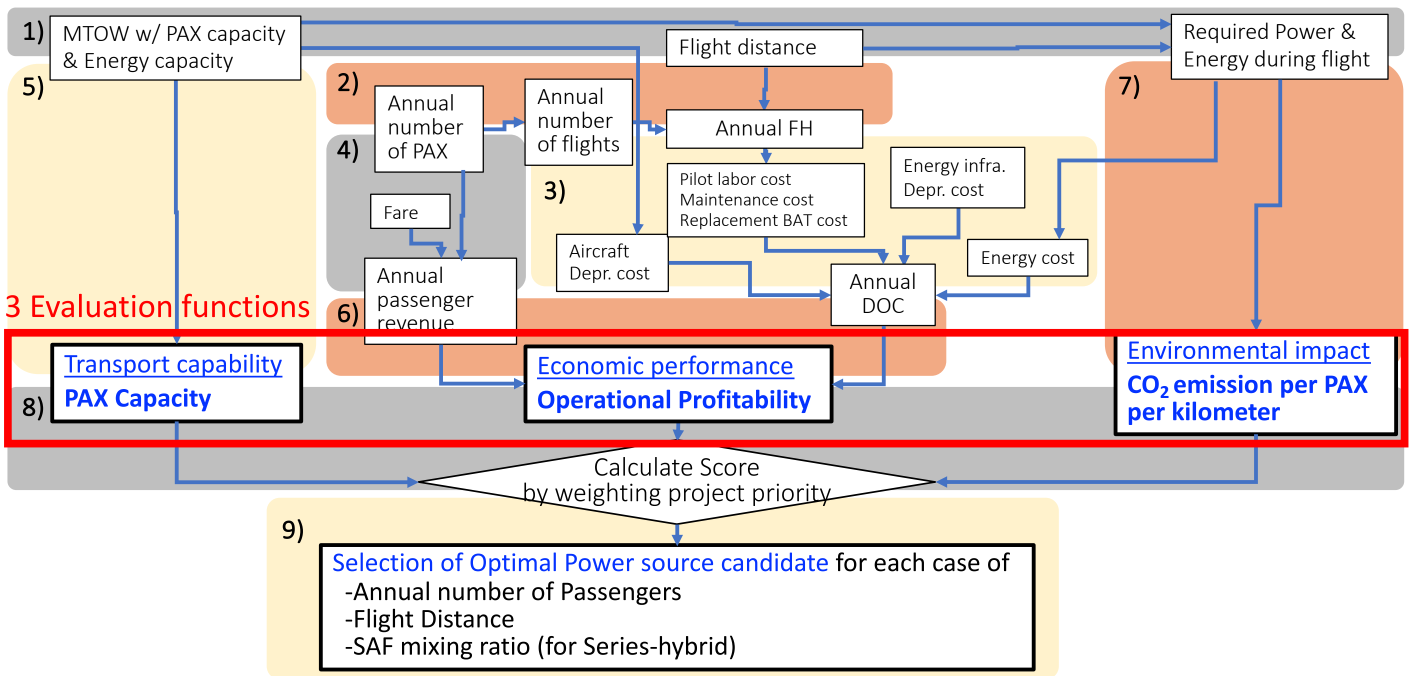


*Fig. 2 Optimal power source candidate selection flow*

factors of (0.2, 0.4, 0.4) for PAX capacity, Operational Profitability, and $CO_2$ emission per PAX per kilometer. The total score is then calculated by summing the weighted values.

9) Select the optimal power source candidate for each scenario of the Annual number of passengers, the Flight distance, the SAF mixing ratio.

## 3. RESULTS

### *3-1. CORRELATION BETWEEN MTOM AND FLIGHT RANGE*

The total required energy for flight: $E_{total}$ is expressed by Equation (1)

$$E_{total} = \sum_{j=1}^{7} P_j \cdot t_j \qquad (1)$$

where $P_j$ is the required power in each flight phase of the flight profile and was defined in the reference [9].

$$t_4 = \left( E_{total} - \sum_{j=1}^{3} P_j \cdot t_j - \sum_{j=5}^{7} P_j \cdot t_j \right) \Big/ P_4 \qquad (2)$$

Based on the horizontal velocity $v_j$ and flight time $t_J$ in each flight phase in (Table 1), and $t_4$ derived from Equation (2), Flight Range $R$ was calculated as follows.

$$R = \sum_{j=1}^{7} v_j \cdot t_J \qquad (3)$$

We illustrated the correlation between MTOM and Flight Range with each PAX capacity and energy capacity for each power source in Fig. 3.

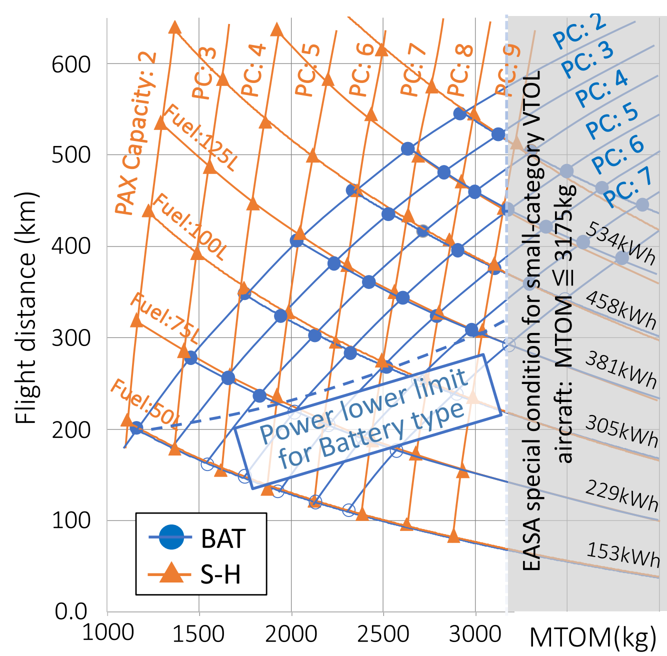


*Fig. 3 Correlation between MTOM and Flight Range*

The dashed line indicated the lower limit of the battery power required for take-off and landing of the battery type, thus, points below that curve were not valid (plotted with open circles). Under the same Flight Range conditions, as PAX capacity increases, the MTOM of the Battery type becomes heavier than that of the Series-hybrid type. This is due to the significantly lower energy density of batteries compared to that of liquid fuel. In other words, the Series-hybrid type can carry additional PAX equivalent to the energy mass difference compared to the Battery type under the same MTOM and Flight Range conditions. Under the EASA special condition for small-category VTOL aircraft (SC-VTOL-01), the maximum PAX capacity is 7 for the Battery-powered type and 9 for the Series-hybrid type.

### *3-2. AIRCRAFT PRICE ESTIMATION*

Regarding the aircraft price estimation, we referenced Equation (4) from a previous study [16] to roughly estimate the aircraft price from MTOM.

$$\begin{aligned} \text{Aircraft price} &= 250{,}000\$/750\text{lb} \times MTOM \\ &= 0.11\text{million JPY/kg} \times MTOM \end{aligned} \quad (4)$$

### *3-3. OPERATIONAL PROFITABILITY*

The aircraft depreciation cost and the energy cost are high when the aircraft is heavy. Therefore, higher PAX capacity leads to increased DOC. However, it also generates more passenger revenues that exceeds the increased DOC. Consequently, higher PAX capacity is advantageous from an economic perspective when the annual number of passengers is sufficient (Fig. 4).

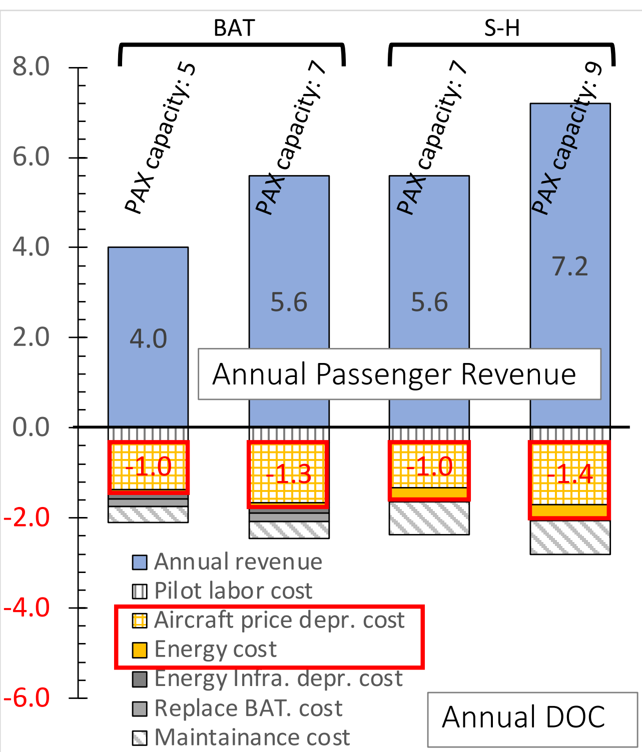


*Fig. 4 Annual DOC and Passenger Revenue*

### *3-4. SAF $CO_2$ REDUCTION EFFECT AND COST*

Currently there are various production processes and materials for SAF and they are still under consideration. Further, the $CO_2$ reduction effect and the minimum selling price of SAF will vary depending on the production methods. According to the paper by Braun, et al.[17], HEFA (Hydroprocessed Esters and Fatty Acids) conversion pathway is the most intensively studied production process. Therefore, in this paper, the $CO_2$ reduction effect and the cost quoted from the median values obtained through the statistical analysis for various HEFA processes in [17]; the $CO_2$ reduction effect of -75% compared to normal jet fuel, and the SAF cost assumed from the minimum selling price of 1,544 $USD_{2020}$/metric ton = 135 JPY/L.

### *3-5. $CO_2$ EMISSION PER PAX PER KILOMETER*

For fixed-wing VTOL aircraft, the energy efficiency is lower during takeoff & landing ,and higher during cruising. It means the CO2 emission per kilometer becomes better as the flight distance (cruising range) increases. In addition, as PAX capacity increases, the CO2emission per PAX decrease (Fig. 5).

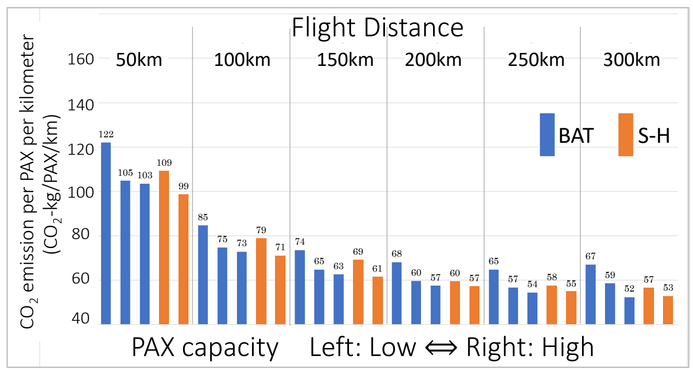


*Fig. 5 $CO_2$ Emission per PAX per kilometer with SAF mixing ratio: 50%*

When the SAF mixing ratio changed from 50% to 10%, the $CO_2$ emission of the Series-hybrid types significantly increased. (Fig. 6). Thus, the SAF mixing ratios have a huge impact on $CO_2$ emission of the Series-hybrid types.

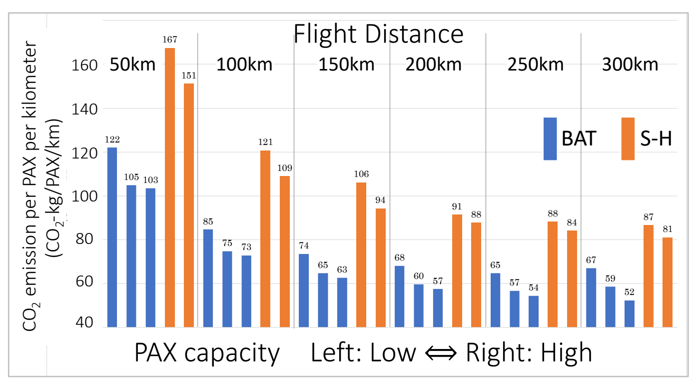


*Fig. 6 $CO_2$ Emission per PAX per kilometer with SAF mixing ratio: 10%*

## 4. DISCUSSION

We evaluated the selection of optimal power sources across 36 different scenarios, varying in Annual number of passengers and Flight distances under various SAF mixing ratios. The results of these calculation were visualized on the “Optimal power source MAP”, with the Annual number of passengers plotted on the X-axis and the Flight distance on the Y-axis. Scenarios yielding a total score of less than 5 were represented in the gray area, highlighting that lower total scores tend to occur with shorter Flight distances and smaller Annual number of passengers. For scenarios where the total score was 5 or higher, the Battery type emerged as the optimal power source in the blue area, while the Series-hybrid type was optimal in the orange area. When SAF mixing ratio was 0% and fuel cost was set to 100 JPY/L (equal to jet fuel cost), the gray area occupied 56% of scenarios primarily in shorter flight distance under 150km or with fewer than 10,000 passengers per year. The blue area covered 28% of scenarios for flight distance over 150km and fewer than 25,000 passengers per year. The orange area occupied 17% of scenarios, positioned to the right of Battery type’s maximum PAX capacity 7 line (Fig. 7).

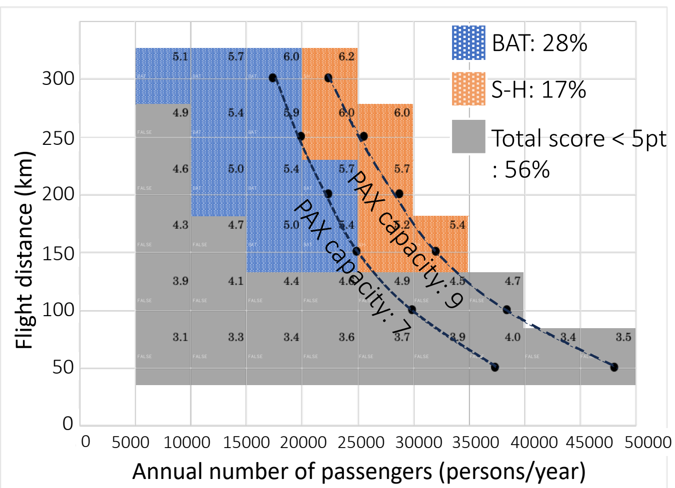


*Fig. 7 Optimal power source MAP*
*when SAF Mixing ratio:0%/ Fuel cost: 100 JPY/L*

As the SAF mixing ratio increased from 0% to 20%, the gray and blue areas gradually decreased (gray area: 56% to 53%, blue area: 28% to 22%). In contrast, the orange area expanded both downward and to the left, increasing from 17% to 25% (Fig. 8). When the SAF mixing ratio reached 50%, the gray area further narrowed to 39%, and the blue area disappeared entirely, with the orange area expanding to 61% (Fig. 9). This expansion of indicates that the Series-hybrid type becomes capable of covering a broader range of scenarios, including those with shorter flight distance around 100km and fewer annual number of passengers up to 5,000.

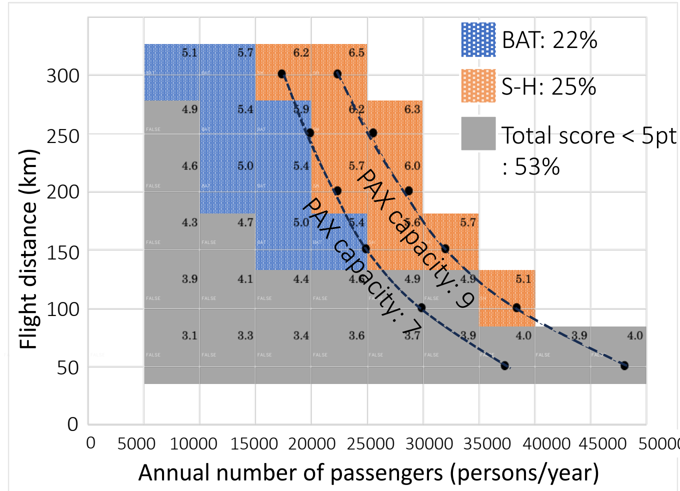


*Fig. 8 Optimal power source MAP*
*when SAF Mixing ratio:20%/ Fuel cost: 107 JPY/L*

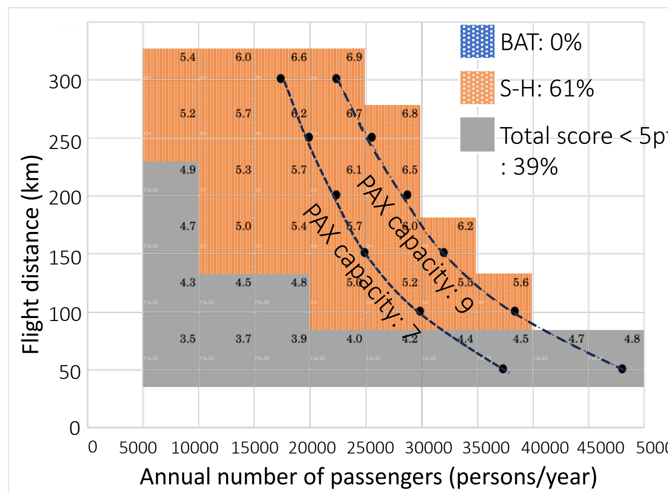


*Fig. 9 Optimal power source MAP*
*when SAF Mixing ratio:50%/ Fuel cost: 118 JPY/L*

## 5. CONCLUSIONS

This study presents a methodology for selecting the optimal power source for AAM passenger transport use cases by evaluating Battery and Series-hybrid systems under the various conditions, including different Flight distances, Annual number of passengers, and SAF Mixing ratios. From Optimal power source MAP, we found the following results, “Without the use of SAF, the Battery-powered system covered 28% of all scenarios for flight distances exceeding 150 km and an annual passenger count between 10,000 to 25,000. Meanwhile, when the SAF mixing ratio reached 50%, the Series-hybrid system was identified as the optimal and more versatile power source in over 60% of all scenarios.” This finding indicates

1) Higher PAX capacity enhances transport efficiency and operational flexibility while reducing $CO_2$ emissions per PAX and generating more passenger revenue that offsets the increased DOC due to larger PAX capacities. Consequently, a higher PAX capacity proved advantageous across all evaluation criteria.
2) The Series-hybrid types have higher PAX capacity than the battery types under the same MTOM and Flight distance conditions. Therefore, with increasing SAF mixing ratios, they can become more favorable and versatile power sources.
3) However, the SAF cost and mixing ratio significantly influenced the evaluation of the Series-hybrid type. Although the SAF cost reference was based on the minimum selling price [17], actual price is anticipated to rise due to non-technical factors. Therefore, future SAF cost and supply stability are crucial in determining its feasibility as the optimal power source.

In AAM passenger transport use cases, shorter flight distances will reduce the evaluation of economic performance and environmental impact, especially when there are no significant time advantages over existing marine or ground transportation such as ferries, buses, trains, the implementation of AAM becomes challenging.

The proposed approach is valuable because it enables the early identification of specification gaps with the optimal power source candidates during the initial stages of AAM planning and development. It allows for timely reconsideration of project preconditions, requirements, and priorities, potentially saving time and reducing rework. Moreover, this methodology is not limited to passenger transport AAM but can also be extended to VTOL logistics drones.

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