# Energy Augmentation Concepts for Advanced Air Mobility Vehicles

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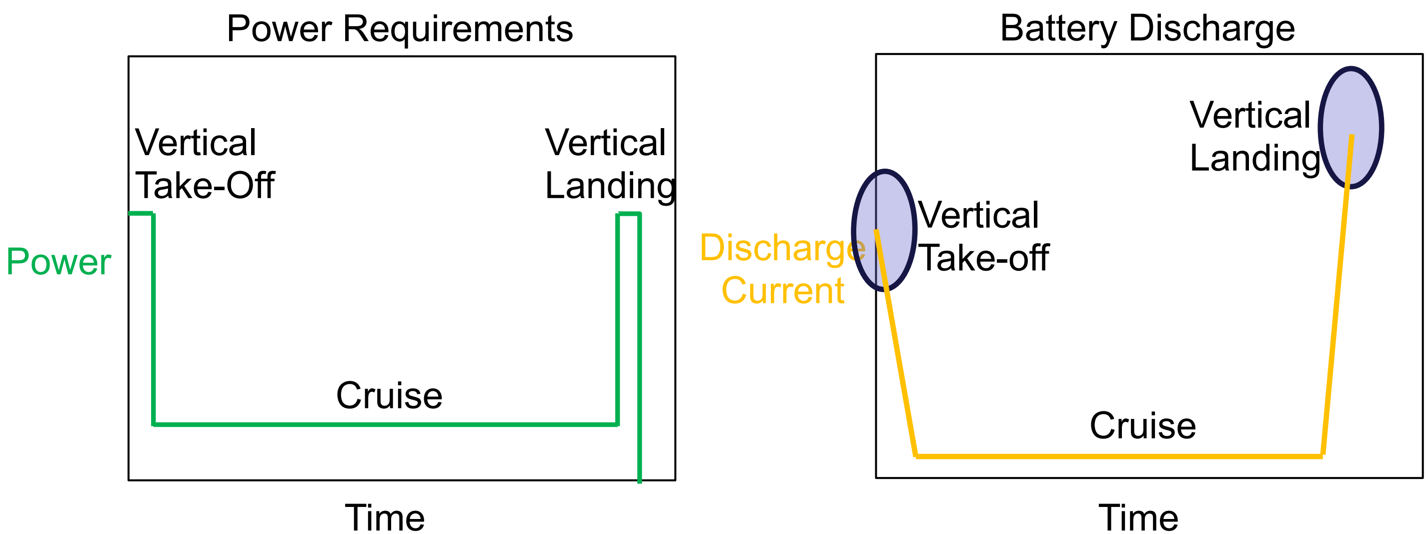
# AAM Vehicle Battery Use

- Planned operations and vehicle designs are limited by the power and the capacity of batteries
- Takeoff, landing, and reserves consume ~40% of available energy
- eVTOL# takeoffs and landings require high power (~8 times horizontal flight), adding safety risk and additional aircraft mass
- Low energy or emergency landing (especially under extreme weather) uses even more energy and are a severe threat to safe AAM operations




**We developed concepts to recharge the battery before the vehicle reaches its destination.**

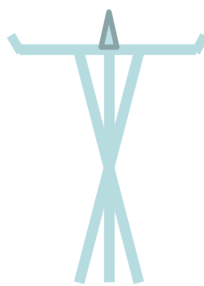
#eVTOL = electric Vertical Take-Off and Landing

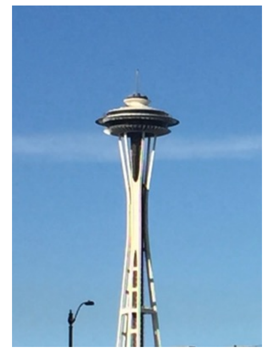
# Outline

- Proposed concepts
- Factors description
- Barriers addressed
- Proposed activities
- Concluding remarks

# Direct Charging
## 1. Charging Platforms

- Analogy: Electric car charging stations or gas stations
- Space Needle (Seattle, WA, ~600 ft) as a representative structure





- Advantage: Serves single/multiple vertiports, stable and always available power, high physical and cyber security, long-lasting solution, almost all-weather capability, functions as an alternate vertiport
- Disadvantage: High initial cost, must land on tall structure to charge, requires some coordination from ATC for arrival and departure with lesser traffic density

# Direct Charging

## 2. Swappable batteries

- Spare battery as a contingency, standardized design of vehicles
- Analogy: Two-gallon spare gas tank

- Advantage: Removing unnecessary batteries reduce weight for the vehicle, creates a system that is more comparable to current fuel systems, reduces cost of vehicle ownership
- Disadvantage:  Manufacturers profit margin, design complexity for hot-swapping

# Direct Charging

## 3. Flying Batteries

- Floating platforms are impractical and expensive to maintain
- Analogy: SpaceX reusable rockets

Image used with permission from SpaceX

- Advantage: Battery pack provides extra power for take-off, more batteries can be delivered for additional power requirements, no need for augmented battery weight to be carried for entire flight
- Disadvantage: Onboard battery docking bay necessary, GNC* system for flying batteries needs reserved power for control systems, can be complex, requires certification

*GNC = Guidance, Navigation, and Control

# Direct Charging

## 4. Cable Power

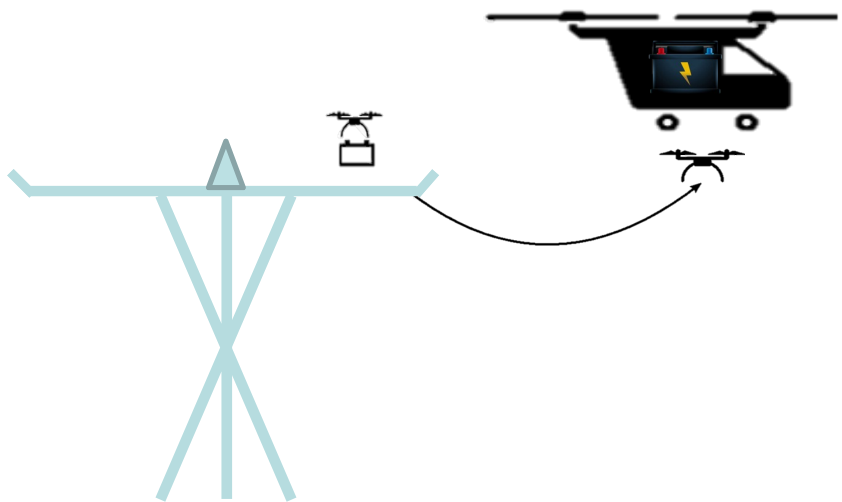
- Carry the charging cable to the AAM vehicle
- Analogy: Towing a ship by a tug-boat

- Advantage: High power transfer efficiency, other capabilities (thermal management)
- Disadvantage:  Cable weight (1 kg/m) limits takeoff power augmentation effectiveness

# Direct Charging

## 5. Hybrid

- A combination of previous four concepts



- Advantage: High power transfer efficiency, partially supported cable weight, keeps battery and AAM vehicle traffic separated, allows option of battery packs hot-swap for takeoff/landing
- Disadvantage:  Cable weight (1 kg/m) limits takeoff power augmentation effectiveness, complex design and rendezvous process

# Indirect Charging

## 3 Concepts

- Three Radio Frequency (RF) power beaming concepts
  - Optical/Infrared (laser)
  - Millimeter Wave
  - Microwave

| | Optical | Millimeter Wave | Microwave |
|---|---|---|---|
| Penetration clouds/rain/fog | No | Poor | Excellent |
| Conversion efficiency performance limits for DC-to-RF & RF-to-DC | OK | OK | Good |
| Required transmit and receive antenna aperture size | Small | Medium | Large |
| Safety required due regard, pointing, user perception | OK | Good | Good |
| Economy of scale based on present state of the art to deliver 1000s of kW over 1000s of km | Poor | Poor | Good |

- Advantage: Silent, invisible, no moving parts, reduces enroute power requirements and complicated ground infrastructure and maintenance operations
- Disadvantage: Safety issues uncharacterized, RF spectrum availability & increase airspace complexity

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# Factors Considered

- Desirability (D)
  - Interest from invested parties and public
- Viability (V)
  - Economic practicability
- Feasibility (F)
  - Technological plausibility
- Wickedness (W)
  - Creativity and difficulty
- Each barrier classified as D, V, F, and W

# Common Barriers Addressed

- (D) Public perception
- (D) Additional Noise
- (V) Lifecycle costs (Operations and Maintenance)
- (F) Rendezvous Flight Autonomy
- (F) Power Management System
- (F) Thermal Management during charging
- (F) End to end efficiency
- (W) Airspace complexity

(D) Desirability, (V) Viability, (F) Feasibility, (W) Wickedness

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# Proposed Activities*

## 1. Development of Concept of Operations (ConOps)

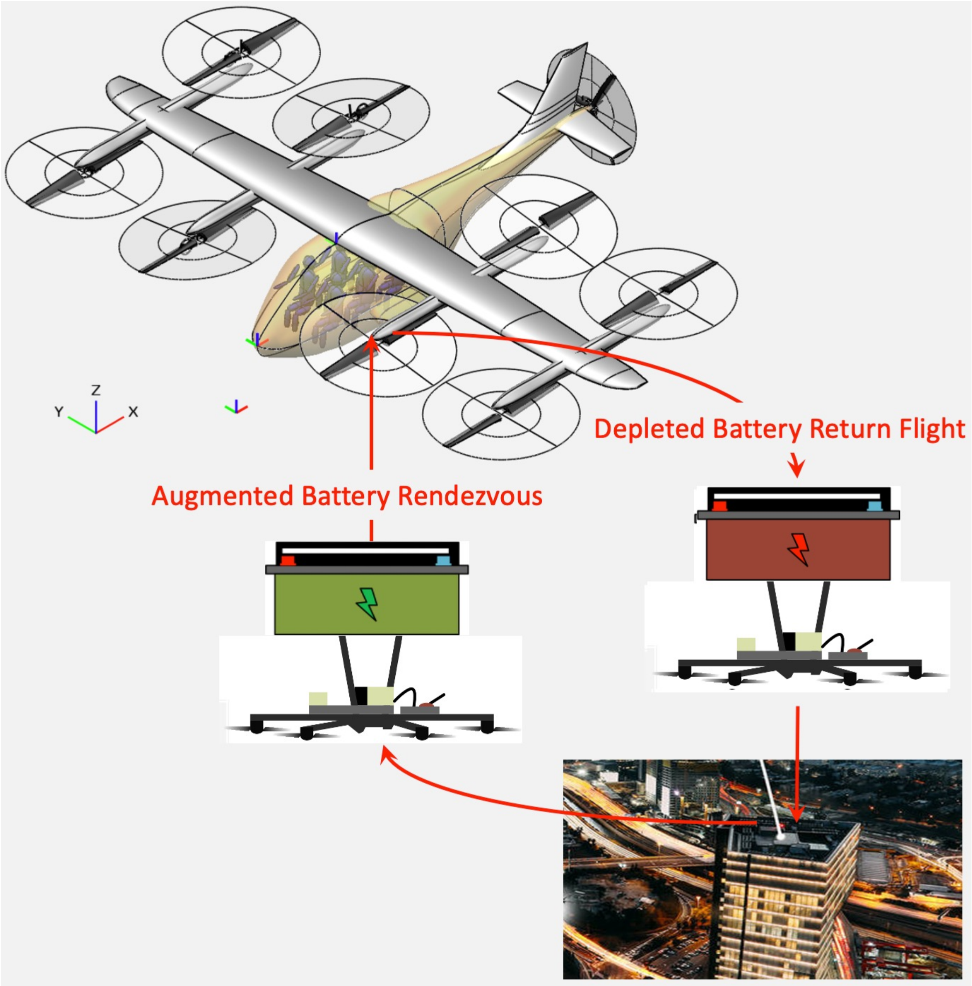

* All of the concepts are for implementation in 2045 timeframe

# Proposed Activities

## 2. Study of Energy Augmentation Methods and Airspace Complexity (SEAMAC)

# Proposed Activities

3. Autonomous Rendezvous and 4. Aerial Docking (ARAD)



# Proposed Activities

5. Energy Augmentation Power Beaming Safety Study (EMPRESS)

# Concluding Remarks

- Insufficient battery charge is a key risk
- Eight initial concepts proposed for direct and indirect charging of AAM eVTOL vehicles
- Four factors with nine barriers addressed for selection of concepts for additional inquiry
- Five activities covering concept of operations, airspace complexity, autonomous rendezvous and aerial docking, and power beaming being investigated further
- Research for 2045 timeframe so concepts can be improved for implementation

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