# Parametric Study of State of Charge for an Electric Aircraft in Urban Air Mobility

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# Outline

- **Motivation**
- **Optimal Control Framework**
- **Lithium-Ion Polymer Battery Models**
  - **Energy-Based**
  - **Electrochemical-Based**
- **Parametric Study and Results**
- **Conclusions**

# Motivation

- Urban Air Mobility (UAM) will be enabled using Lithium-ion polymer (Li-Po) battery powered electric vertical takeoff and landing (eVTOL) aircraft

- Current battery technology imposes constraints on flight duration and range of eVTOLs because of:
  - low specific energy (energy/mass)*
  - nonlinear discharge behavior**

- Planning and flying minimum-energy trajectories are important from safety and efficiency perspective

*https://www.energytech.org/wp-content/uploads/2017/11/Energytech_MISRA_presentation-rev2.pdf
**Daigle, Matthew J., and Chetan Shrikant Kulkarni. "Electrochemistry-based battery modeling for prognostics." Annual Conference of the Prognostics and Health Management Society (PHM 2013)

# Research Objectives

- Understand minimum-energy flight profiles for a multirotor eVTOL

- Compare final state of charge results from two different Lithium-Ion polymer battery models (Energy-Based and Electrochemical-Based) for different trajectories.

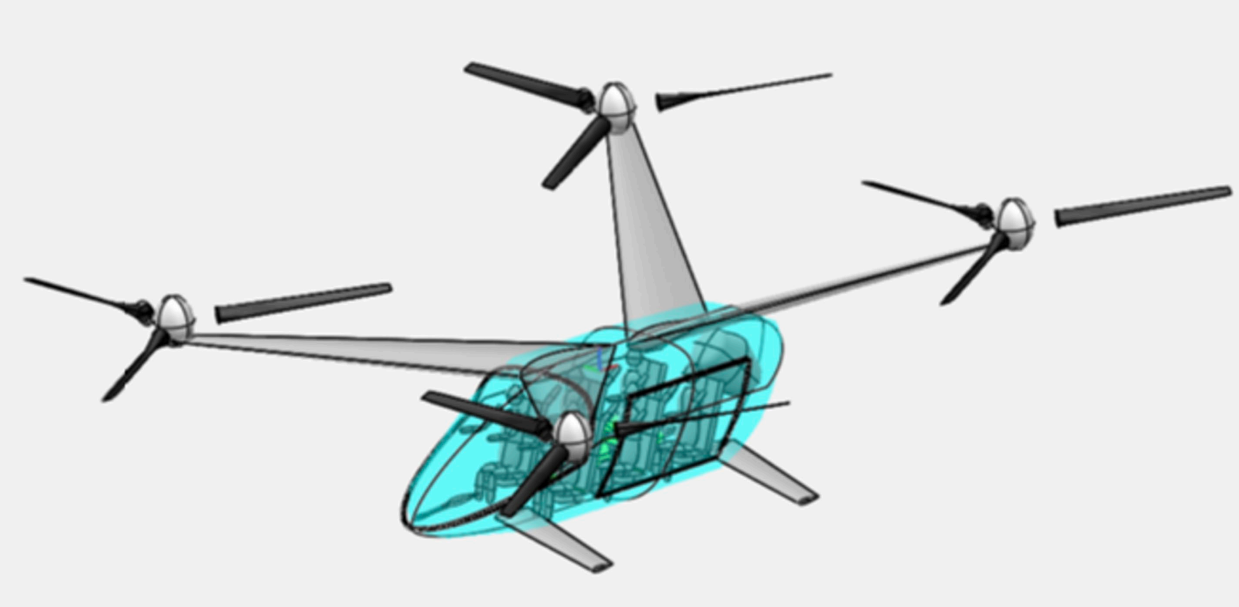
# NASA's Conceptual eVTOL Model*

State Variables:

- λ (Latitude)
- $\tau$ (Longitude)
- h (Altitude above MSL)
- $\Psi$ (Heading Angle)
- $V_l$ (Lateral Component of True Airspeed)
- $V_v$ (Vertical Component of True Airspeed)

Control Variables:

- T (Thrust)
- $\Theta$ (Rotor Tip-Path-Plane Pitch Angle)
- $\Phi$ (Rotor Tip-Path-Plan Bank Angle)



Quadrotor eVTOL Aircraft*

*Silva et al., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018 Aviation Technology, Integration, and Operations Conference, 2018, p. 3847.

# Optimal Control Framework

- Point Mass Kinetic Model*
- Drag and Power Models**
- Path Constraints:
  - Cruise: Constant altitude along great-circle lateral path*
  - Climb: 10-deg flight path angle climb along great-circle lateral path*

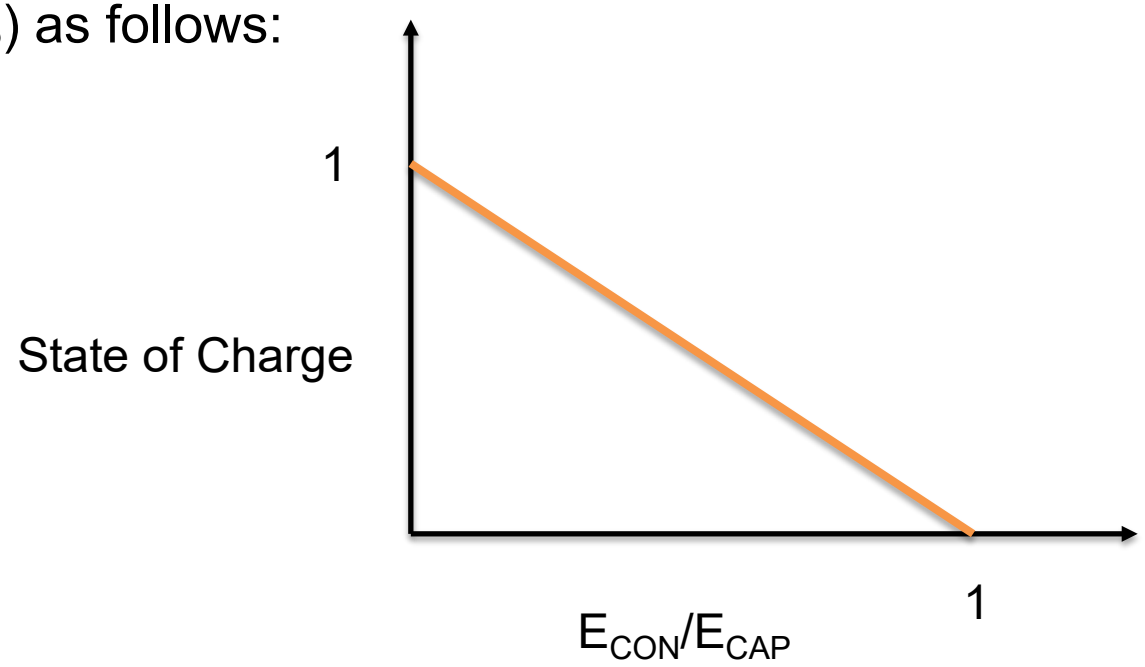
- Performance index – Energy Consumption
- 4D Trajectory generated using Direct Collocation Method (PSOPT)

*Pradeep et al., "Wind-Optimal Trajectories for Multirotor eVTOL Aircraft on UAM Missions," AIAA 2020-3271. *AIAA AVIATION 2020 FORUM*. June 2020.
**Johnson, Wayne. "NDARC NASA Design and Analysis of Rotorcraft-Theory, Appendix 7." (2018).
**Silva et al., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018 Aviation Technology, Integration, and Operations Conference, 2018, p. 3847.

# Energy-Based Battery Model*

- The maximum usable capacity ($E_{CAP}$) of the onboard Li-Po battery pack for the eVTOL aircraft considered is 1331 MJ**

- The state of charge (SOC) of a battery is defined in terms of energy consumption ($E_{CON}$) and maximum usable capacity ($E_{CAP}$) as follows:



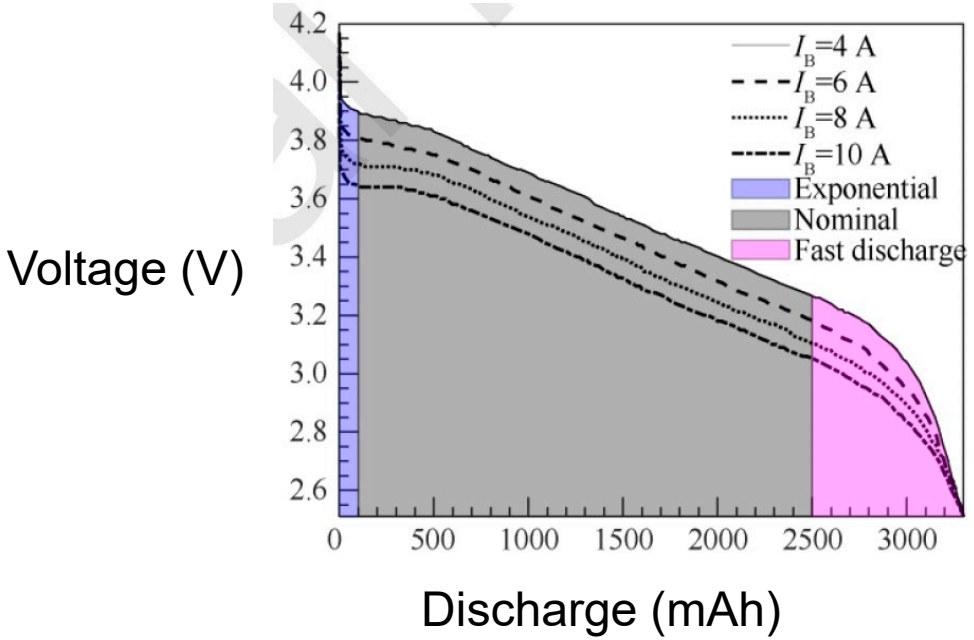

*Johnson, Wayne. "NDARC NASA Design and Analysis of Rotorcraft-Theory, Appendix 7." (2018).

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# Electrochemical-Based Battery Model*

- Model captures the significant electrochemical processes, and predicts state of charge (SOC) and end-of-discharge (EOD)**

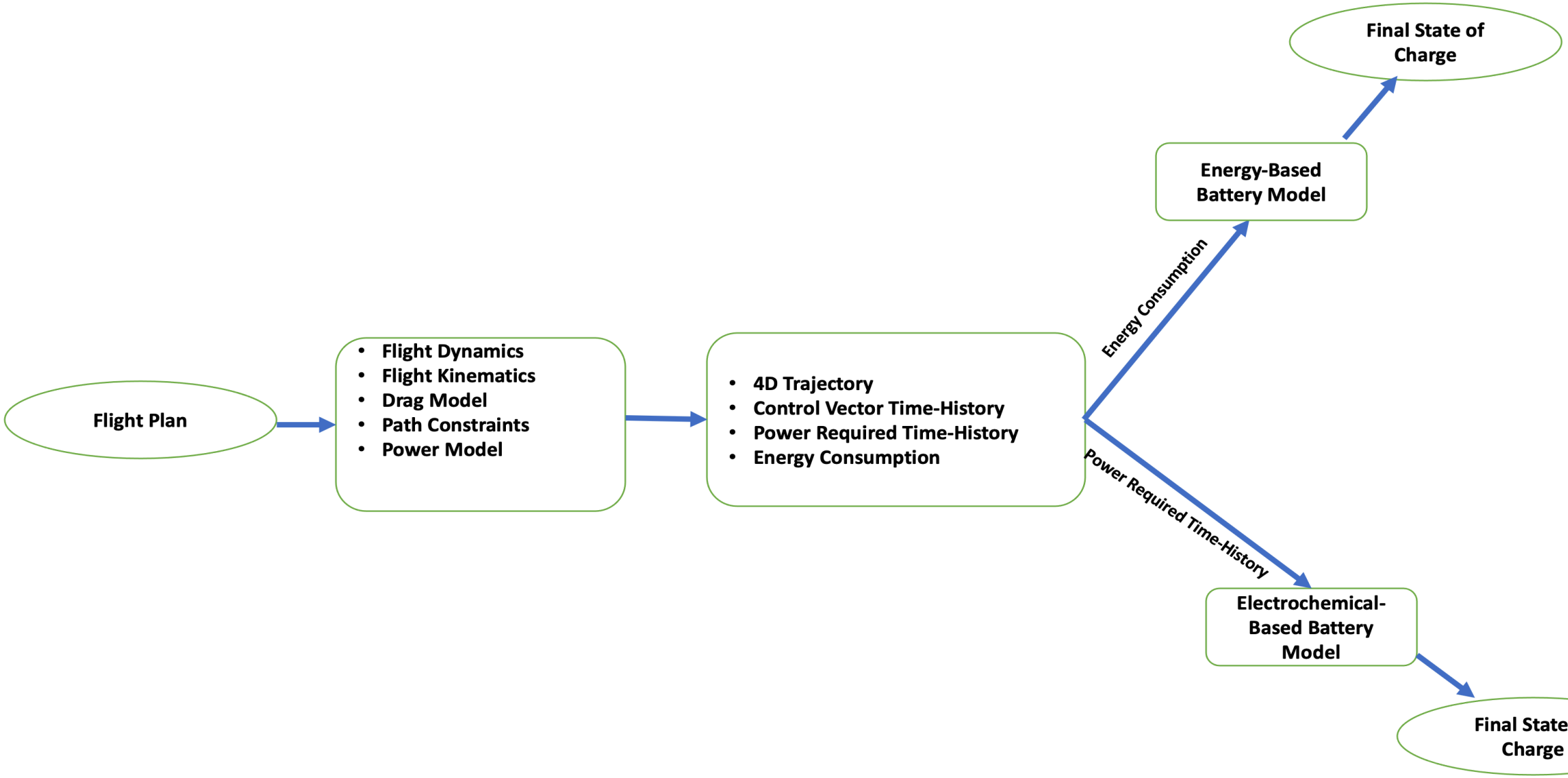
- In electrochemical-based model, the discharging process consists of three discharging zones, i.e.,
  - **exponential zone**,
  - **nominal zone**, and
  - **fast-discharging zone**[*, $]



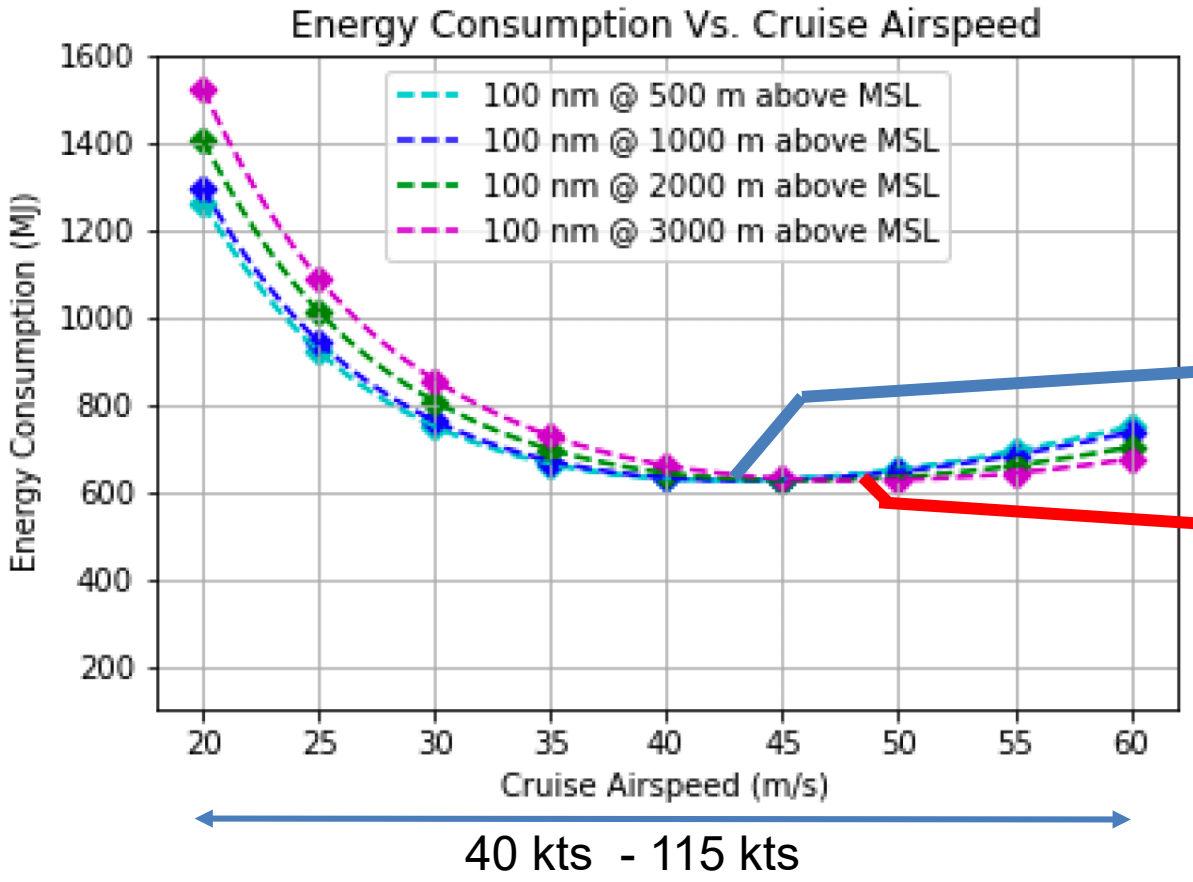

- This model and prognostics algorithms have been verified and validated on electric UAVs in earlier research work***

*Daigle, Matthew J., and Chetan Shrikant Kulkarni. "Electrochemistry-based battery modeling for prognostics." Annual Conference of the Prognostics and Health Management Society (PHM 2013)
$ Wang et al., “Battery package design optimization for small electric aircraft”, ScienceDirect, Volume 33, Issue 11, 2020
**https://github.com/nasa/prognosticsalgorithmlibrary
***Hogge et al., “Verification of Prognostic Algorithms to Predict Remaining Flying Time for Electric Unmanned Vehicles,” International Journal of Prognostics and Health Management, ISSN 2153-2648, 2018

# Final SOC Computation Method



# Best-Range Cruise Airspeed

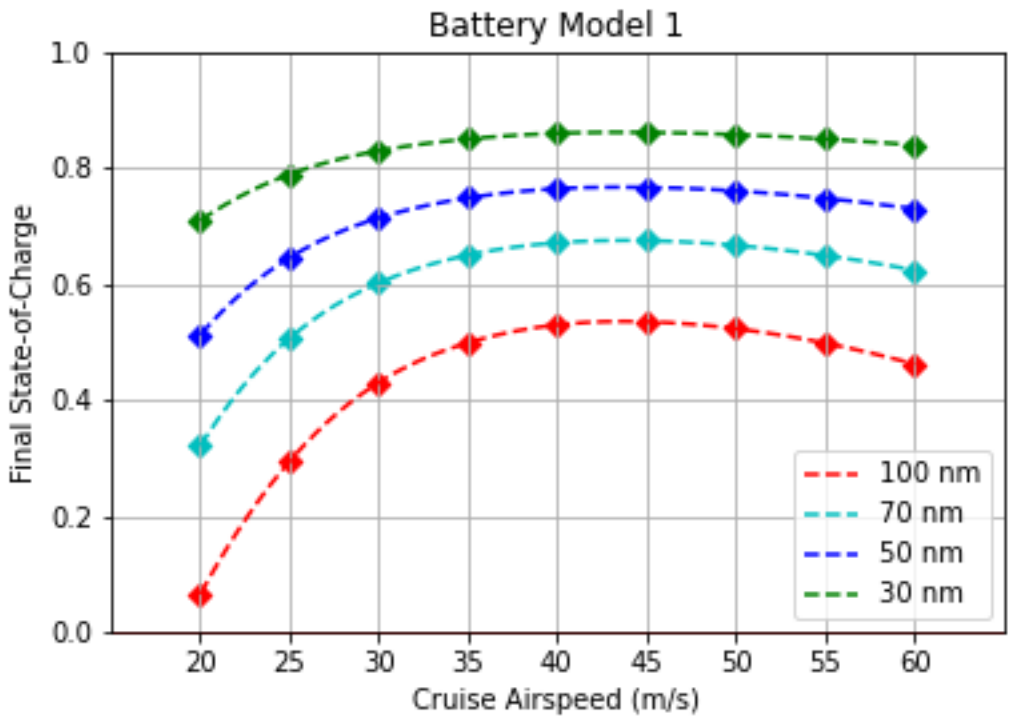



## Minimum-Energy Cruise Airspeed

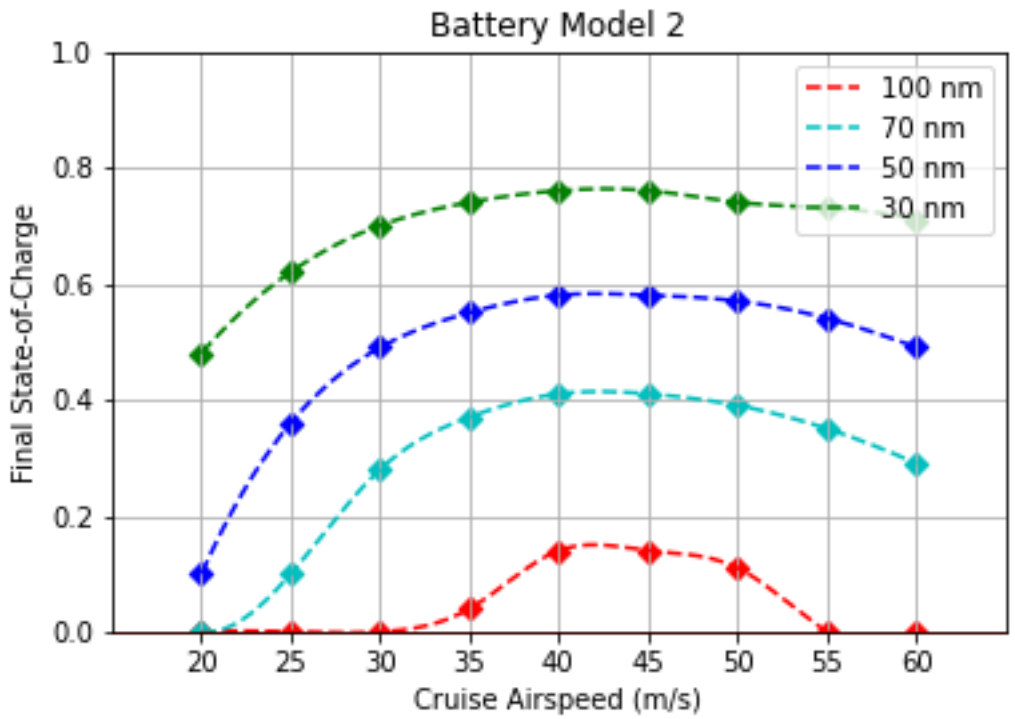
| Cruise Altitude (MSL) | Cruise Airspeed |
|---|---|
| 500 m (1640 ft) | 43 m/s (83.6 kts) |
| 1000 m (3280 ft) | 44 m/s (85.5 kts) |
| 2000 m (6561 ft) | 46 m/s (89.4 kts) |
| 3000 m (9842 ft) | 48 m/s (93.3 kts) |

# Various Cruise Segments @ 500 m MSL

Energy-Based Battery Model



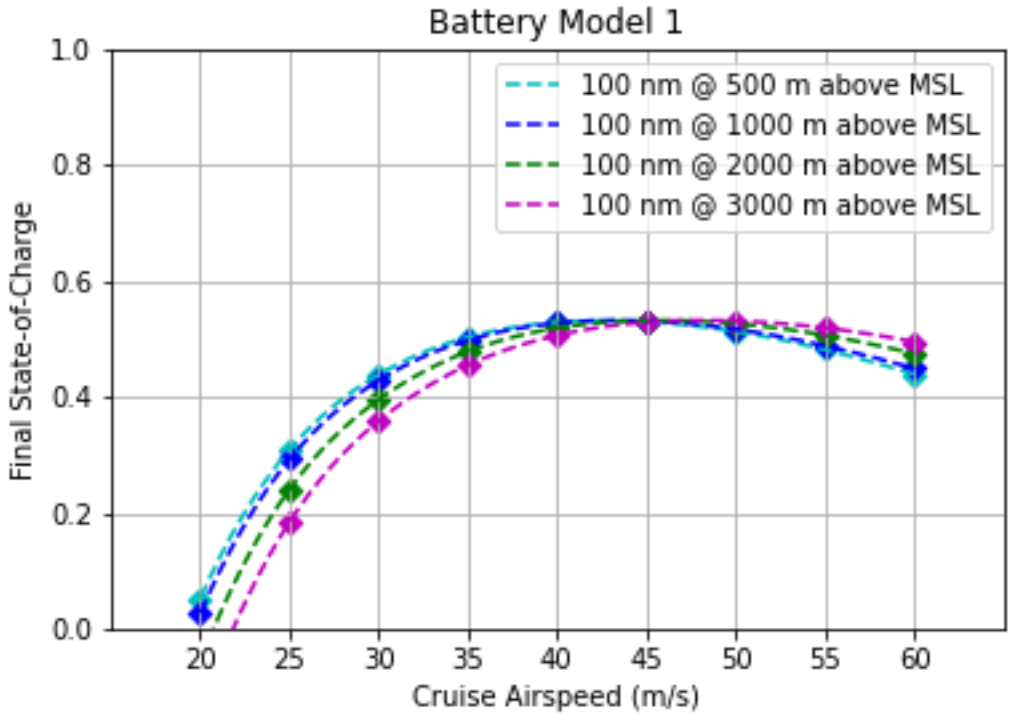

Electrochemical-Based Battery Model



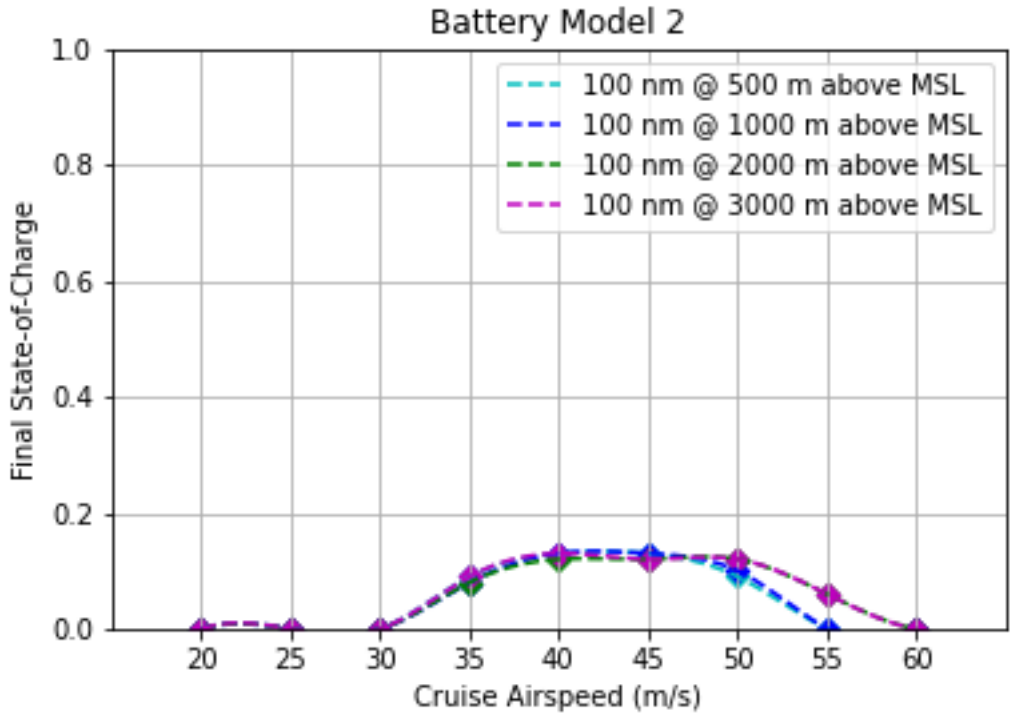

- Lower final SOC predictions using electrochemical-based battery model than energy-based battery model (irrespective of the cruise airspeed and range)
- This behavior can be attributed to differences between the discharge characteristics of the two models

# 100 nm Cruise Segment @ Various Cruise Altitudes

Energy-Based Battery Model



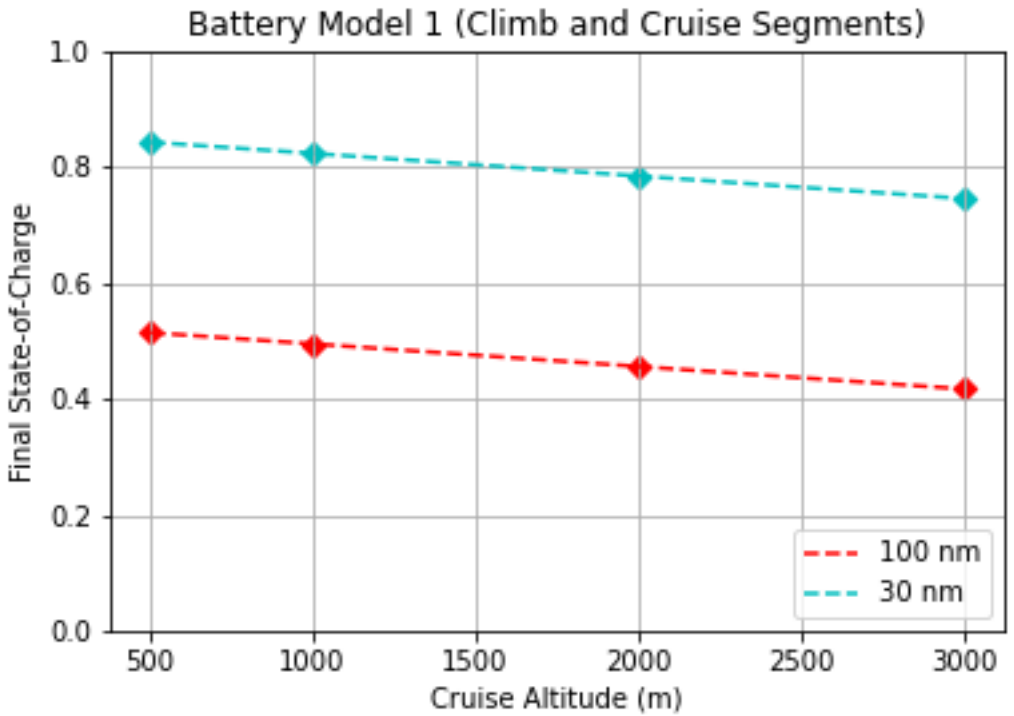

Electrochemical-Based Battery Model



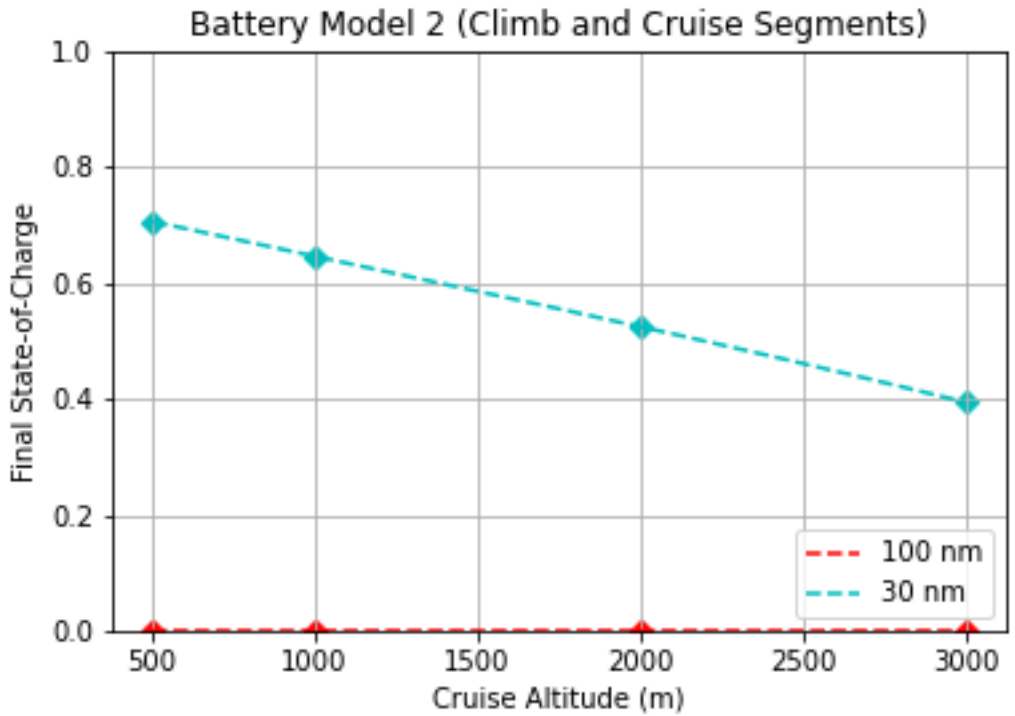

- Energy-based battery model predicted flying slower than 20 m/s is infeasible
- Electrochemical-based battery model predicted flying slower than 30 m/s is infeasible
- Slight advantage in terms of energy consumption and battery usage of cruising at higher altitude at best-range airspeed

# Climb (10-deg) and Cruise (Best-Range Airspeed) Segments

Energy-Based Battery Model




Electrochemical-Based Battery Model

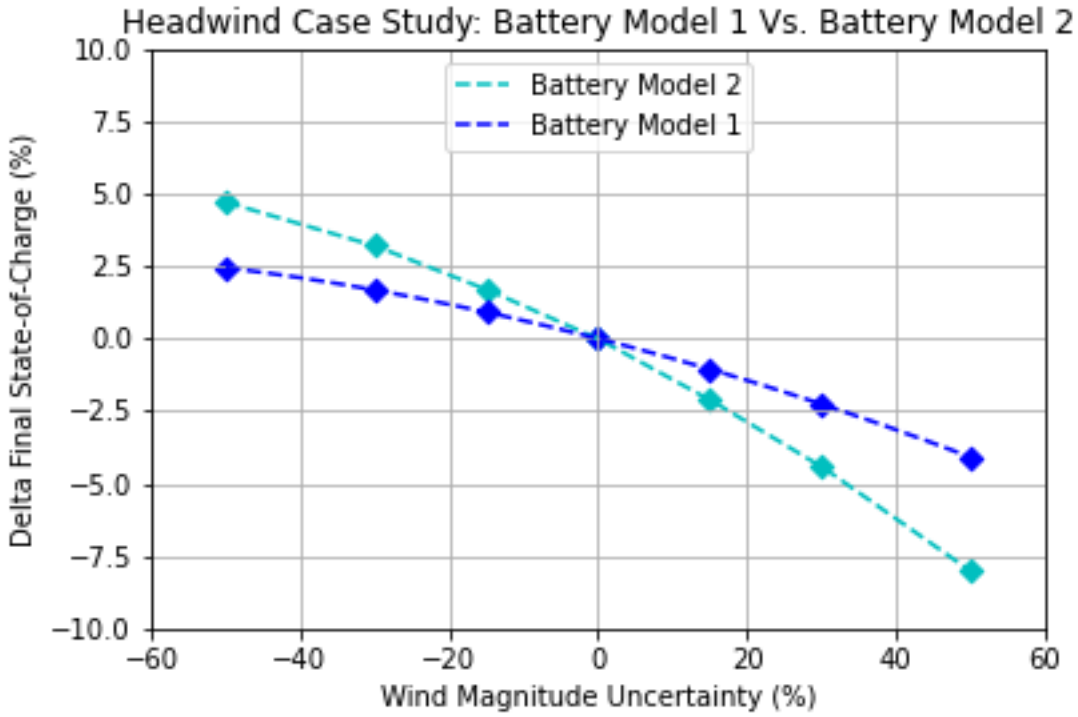


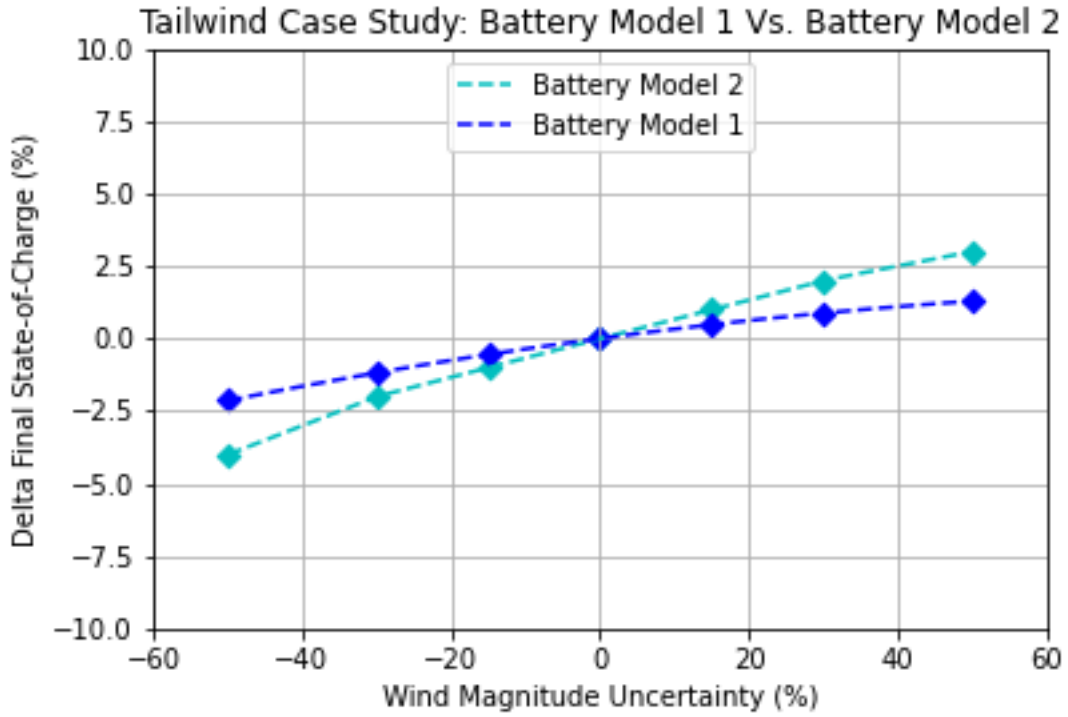

From an energy consumption and battery usage perspective:

i) power required in climb (10-deg at max endurance airspeed) ~ 2* power required in cruise (best-range airspeed)
ii) minimize climb flight duration
iii) design cruise corridors at the lowest possible safe altitude

# Wind Magnitude Uncertainty

Wind Magnitude: 26 kts; Direction: Headwind and Tailwind; Wind Magnitude Error: -50 % to +50 %; RTA (Best-Range Airspeed): 83 kts; Metering Fix Distance: 30 nm

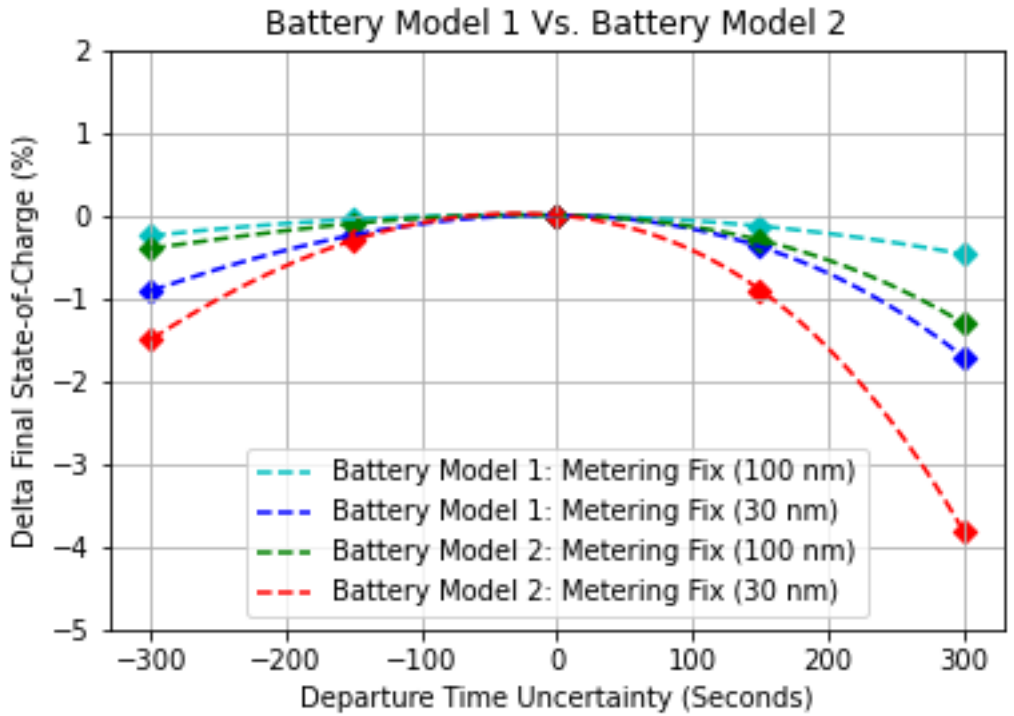



The eVTOL aircraft may consume more or less of the battery than predicted by the fleet operator for the UAM trip. Therefore, wind magnitude uncertainty could directly impact fleet planning.

# Departure-Time Uncertainty

Departure-Time Uncertainty: -300 to +300 Seconds




Electrochemical-based model shows higher adverse impact of the departure-time uncertainty on the usage of the onboard Li-Po battery pack in the time-controlled air traffic flow environment.

# Conclusions

- The minimum-energy cruise airspeed:
  - increases with an increase in cruise altitude;
  - is independent of range;

- To minimize energy consumption and battery usage:
  - Set cruise corridors at the lowest possible safe altitude for rotorcraft
  - such that climb segment /climb flight duration is minimized

- Wind and departure-time uncertainties could adversely impact the predictability of battery usage

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