AAM - A DEMAND RESPONSE ASSET

Powering the AAM Revolution

FAA Challenge 2022

PURDUE UNIVERSITY | School of Aeronautics and Astronautics

Overview

Agenda

- Advanced Air Mobility
- The UAM Energy Problem
- Our Solution – UDS & Development
- MIMIC Simulation & Systems Performance
- Life Cycle Analysis

Industry Advising Partners:

American Airlines

GE Aviation

Introductions

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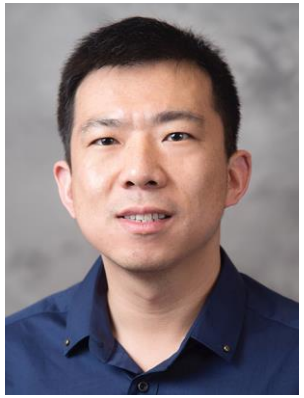


Dr. ShaoShuai Mou
Faculty Advisor
Focus: Multi-Agent Control (AAE)

Introduction

What is Advanced Air Mobility (AAM)?

A revolutionary air transport system:

Key aspects of AAM

- Novel aviation systems – electric propulsion
- Transport passengers and cargo
- Service underserved communities
- On Demand Mobility (ODM)

Electrified Airports - The Future of Clean Aviation

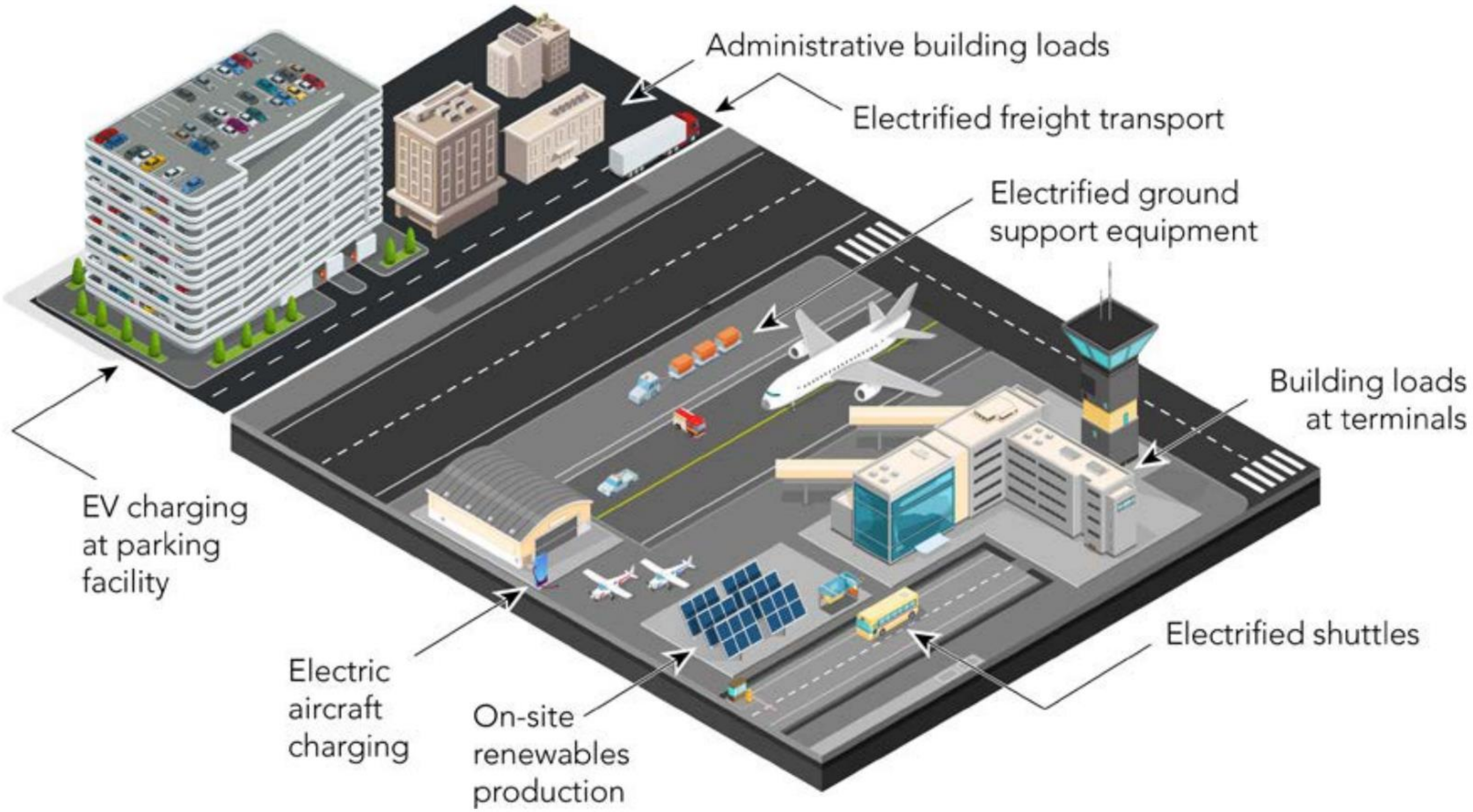


Figure 6. Integrated energy requirements of future airports

Illustration by Josh Bauer, NREL

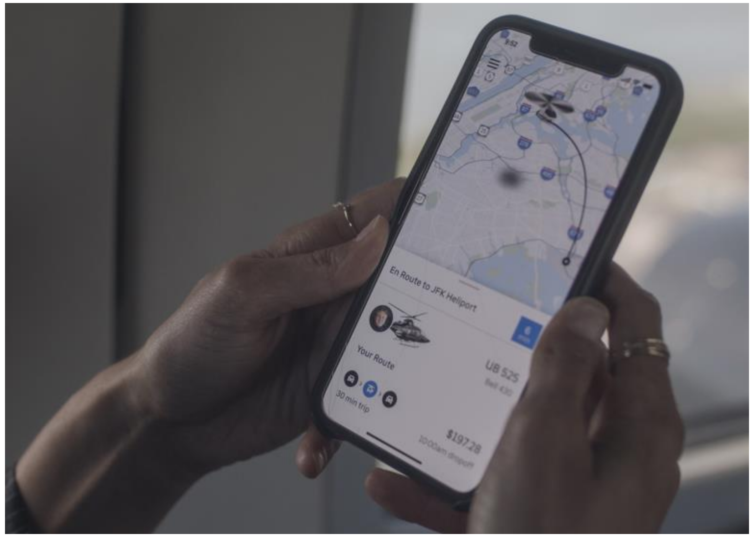
Advanced Air Mobility

Civil Transport
- Passenger-Carrying UAM
- Cargo (middle-mile delivery)
- RAM – Regional Air Mobility

Emergency Response
- Air Ambulance
- Aerial Firefighting

Small UAS Operations
- Cargo (last-mile delivery)
- Small-scale commercial (real estate, mapping, etc.)
- Recreational

Urban Air Mobility and the ODM "Air Taxi" CONOPS

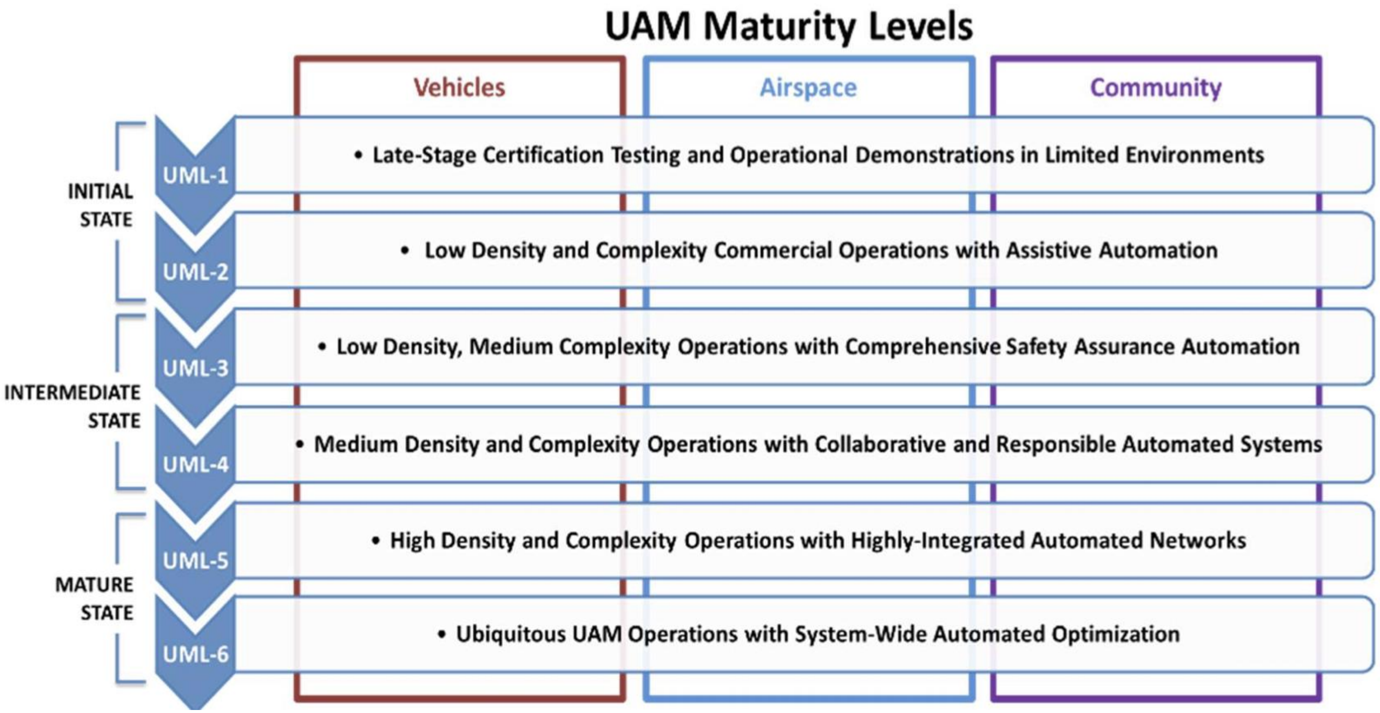


https://evtol.com/features/evtol-ride-hailing-apps/

UAM – Hailing Air Taxis from your phone

- Uber Elevate white paper 2016
- Hundreds of UAM vehicles currently in varying stages of development

UAM at Scale – Sooner Than We May Expect



https://ntrs.nasa.gov/api/citations/20205010189/downloads/UML%20Paper%20SciTech%202021.pdf

"Hailing a piloted air taxi by 2024 is well within the realm of possibility"

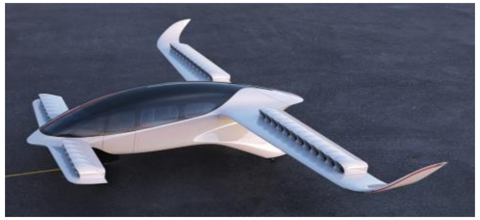
-Billy Nolen, FAA Acting Administrator

https://www.cbsnews.com/news/evtol-flying-vehicles-air-taxi-60-minutes-2022-04-17/?intcid=CNM-00-10abd1h

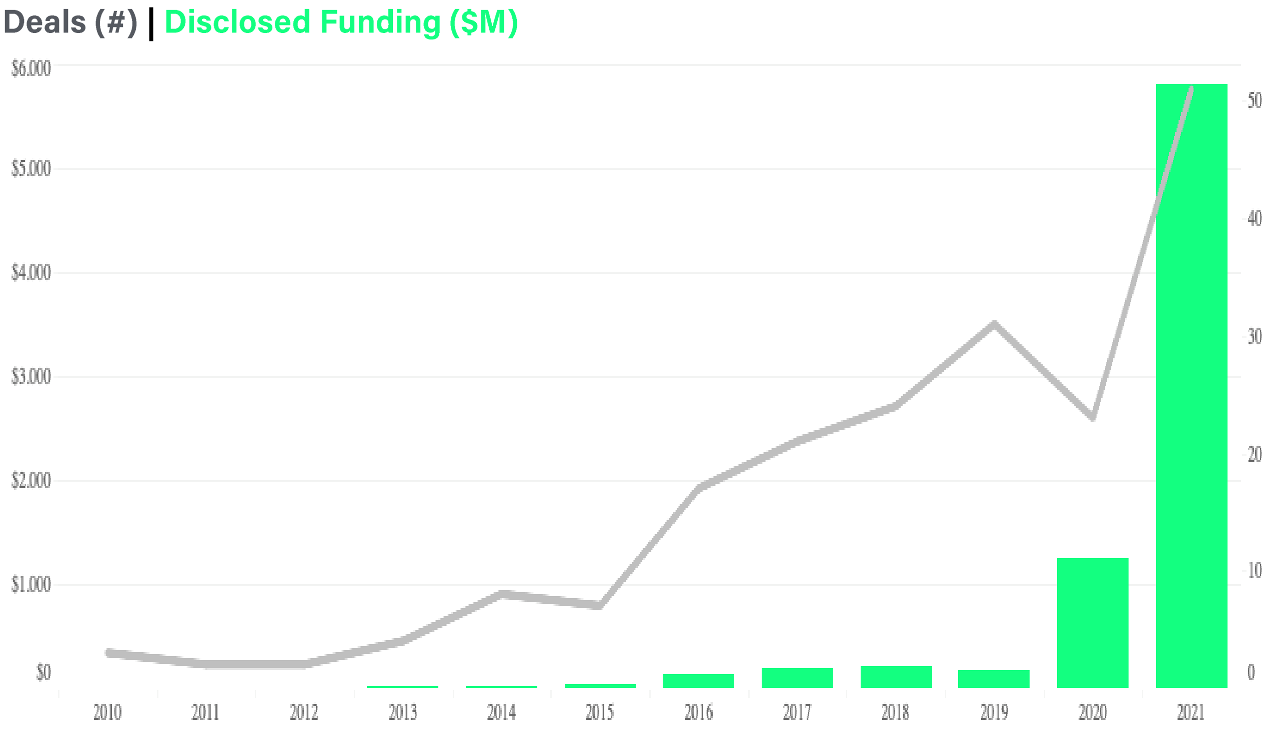
Investments in AAM

Advanced Air Mobility – A Multi-Billion-Dollar Market

- UAM investments
  - $6.3B funding
  - 48 + UAM startups
  - 454 Total Rounds



Investment Activity - AAM



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Sai

Problem Formulation

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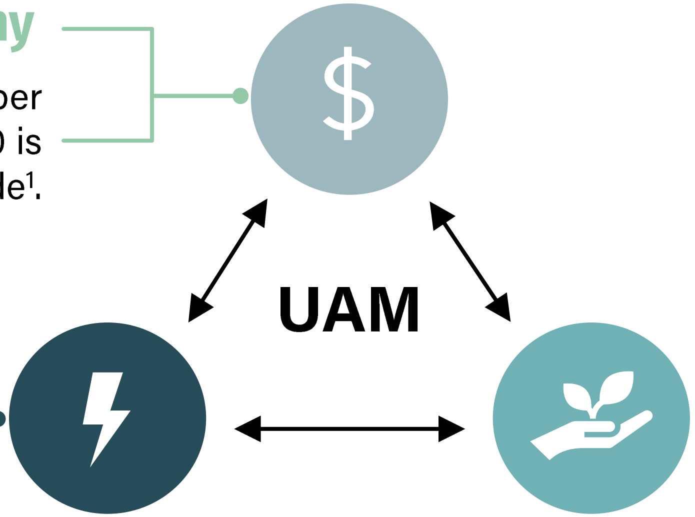
The Problem

Energy infrastructure is simply not prepared to accommodate the energy needs of on demand UAM services.

The Problem

Economy

The estimated cost per UAM Taxi trip in 2030 is >$100 per ride[1].



Energy

A flight consumes as much power (~80 kWh) as an avg. US home over 4 days[3]

Environment

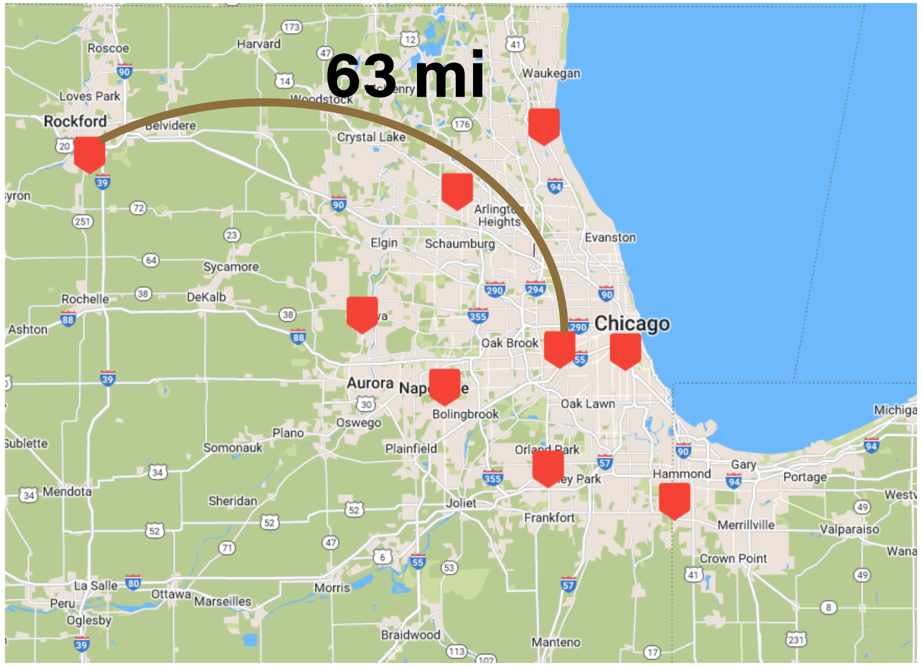
Aviation accounts for 12% of global transportation emissions. Road is 74%[2].

[1]Goyal, R., Reiche, C., Fernando, C., Serrao, J., Kimmel, S., Cohen, A., & Shaheen, S. (2018). *Urban air mobility (UAM) market study* (No. HQ-E-DAA-TN65181).
[2]Aviation: Benefits Beyond Borders (2020) ATAG Beginner's Guide to Aviation Efficiency, Intergovernmental Panel on Climate Change (IPCC), *BBC News, Qantas*.
[3]Maluf, N. (2016) “Making Sense of 100 kWh”. *QNOVO*.
[4]Peter, H., & Derek, S. (2015). Expert consensus on the economics of climate change. *Institute for Policy Integrity, New York University School of Law. Accessed July*, *8*, 2020.

Nick

Supplying Energy for UAM Operations

On Demand UAM presents significant challenges



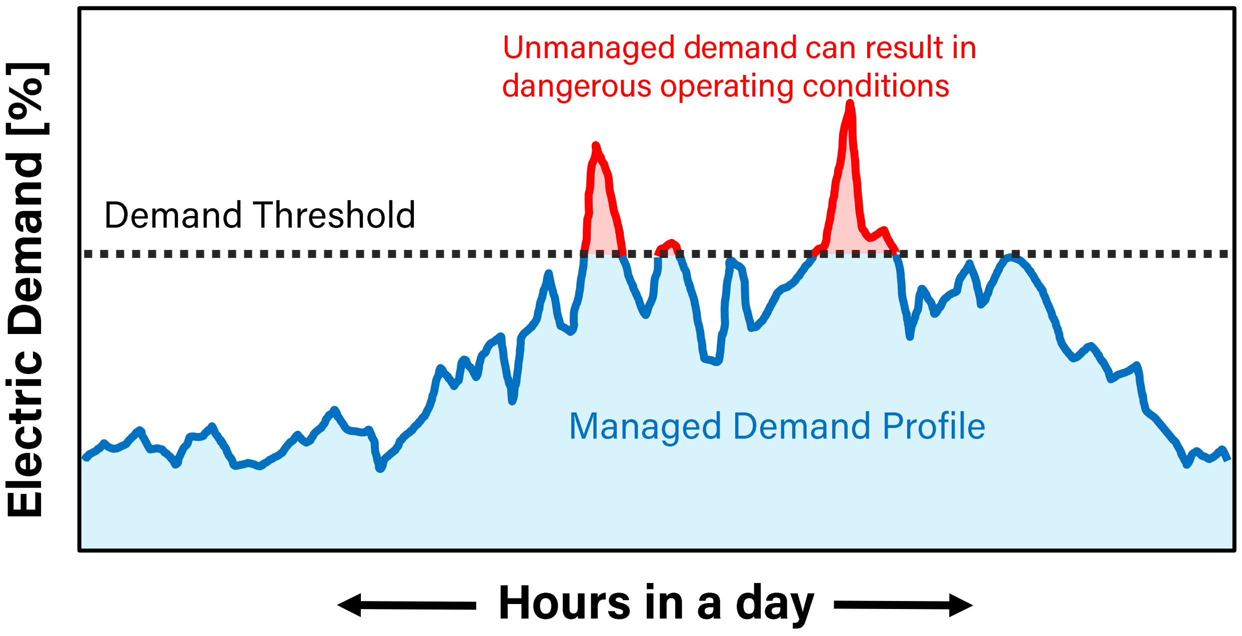
- Est. 50 MWh required for a network of 8 vertiports per day (NASA Langley)
- Local networks are unprepared for large spikes in power demand from UAM (Black and Veath)
- Severe Implications - Blackouts, long-term damage

Vehicle	Uber Elevate Notional Vehicle
Passengers (pax)	4
Cruise Speed (mph)	150
Range (miles)	69
Vehicle Battery Capacity (kWh)	160

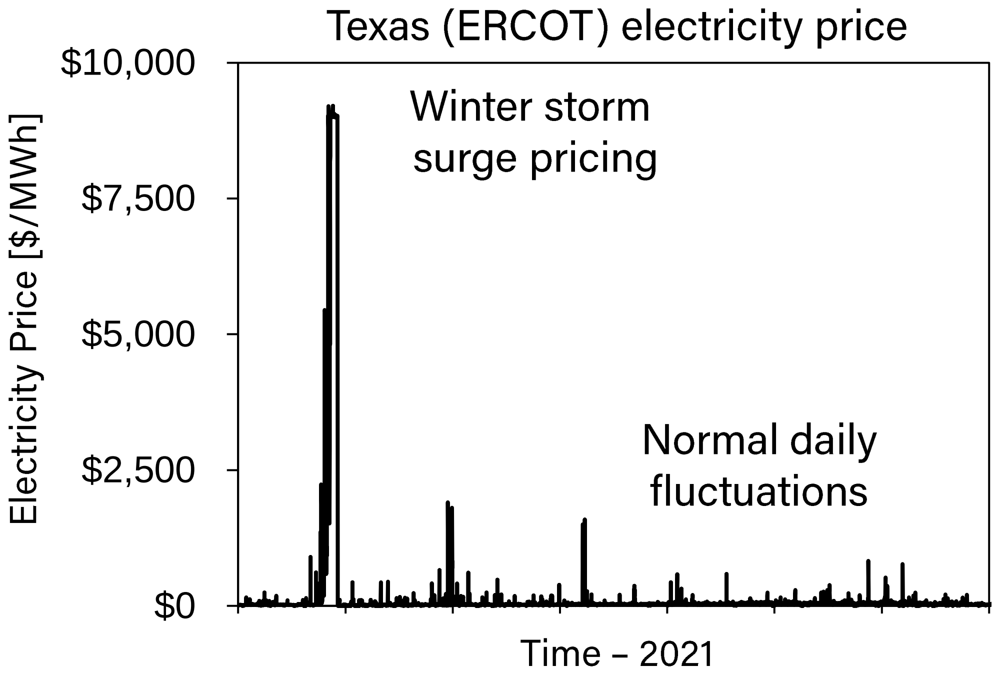
[1] Sells, B. E., Maheshwari, A., Chao, H., Wright, E., Crossley, W., & Sun, D. (2021). Evaluating the impact of urban air mobility aerodrome siting on mode choice. In *AIAA AVIATION 2021 FORUM* (p. 2371).
[2] Schwab, A., Thomas, A., Bennett, J., Robertson, E., & Cary, S. (2021). *Electrification of Aircraft: Challenges, Barriers, and Potential Impacts* (No. NREL/TP-6A20-80220). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Energy Cost of Operating UAM

Managing the energy demand of a UAM fleet is a safety necessity…



Black & Veath, "eVTOL electrical infrastructure study for UAM aircraft," NIA & NASA, 2018.



…and presents an opportunity for operating cost optimization

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Potential Clean Energy Sources for UAM

There is a need for systems to be able to easily integrate with a diverse set of energy systems

Energy System	Pro	Cons
Solar	• Cheapest levelized and capital cost	• Requires a lot of area • Intermittent power
Wind	• Low footprint area	• Aircraft interference • High maintenance cost
Hydrogen	• Stable (no intermittency) • Higher power density than renewables	• More expensive than the energy used to make hydrogen • Low Technology Readiness
Nuclear	• High energy density • Stable (no intermittency)	• High cost • Centralized • Public acceptance

Stakeholder Interviews

Market Research & Industry Interviews

- **Future UAM Operators**
  - American Airlines (partnership with Vertical Aerospace)
  - An Undisclosed UAM Operator

Expressed need for a system to give insights into detailed operating parameters and costs as well as a solution to avoid the restrictions of current infrastructure limits

- **Airports**
  - San Diego International Airport
  - Mineta San Jose International Airport

Airports are seeking robust methods for sizing on-site UAM infrastructure assets for better clarity in planning

- **Aerospace OEM**
  - GE Aviation Systems

OEMs hope to enter the UAM space, but lack the insights required to design for operations that have yet to be fully defined

Stakeholder Interviews – Airports

Types of Airports

Airport Authority

- Controls land usage
- Partners with tenants for infrastructure investments

SAN DIEGO INTERNATIONAL AIRPORT
LET'S GO.

Airport Administration

- Allocates land to tenants
- Tenants provide infrastructure for specific to operations

NORMAN Y. MINETA SAN JOSE INTERNATIONAL AIRPORT

Airports expect UAM Operators will be responsible for energy infrastructure

Problem Formulation

- UAM On Demand Mobility requires significant daily energy and charging throughout the day, causing **spikes in energy usage**
- **Current infrastructure is not prepared** for significant energy spikes
- Upgrading infrastructure for UAM is prohibitively costly for UAM operators
- Renewables such as Hydrogen are lower TRL, and still require significant investment

How can UAM operators effectively supply the energy required for near-term operations and entry into service?

The UAM Dispatch System (UDS)

The Solution

A resource management software framework for intelligently managing UAM operations with demand response.

The UAM Dispatch System (UDS)

Software

Algorithms to optimize UAM operations and energy usage

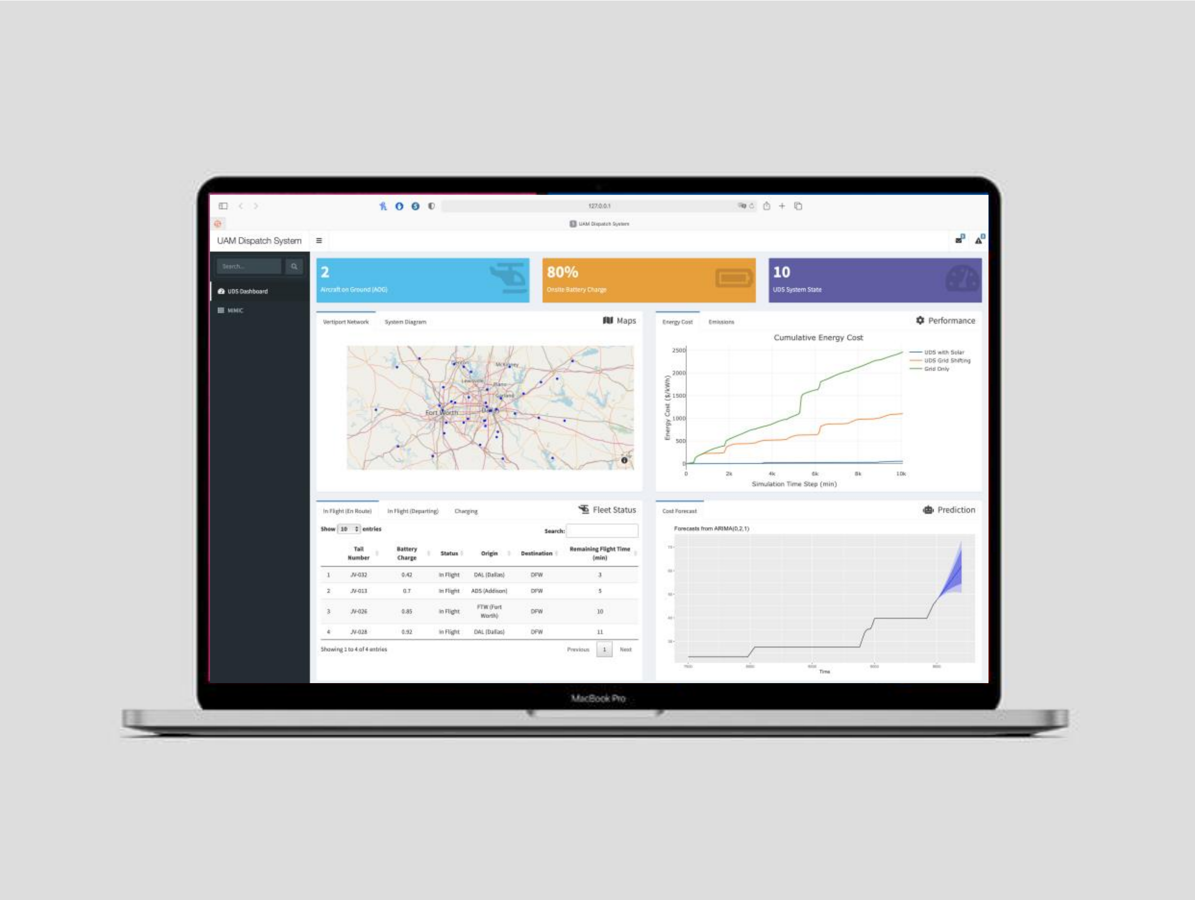
Prediction and Analytics

Access Key Performance Indicators, connecting UAM demand with energy management

Plug and Play

Modular designs allows UAM operators to optimize performance around any energy source

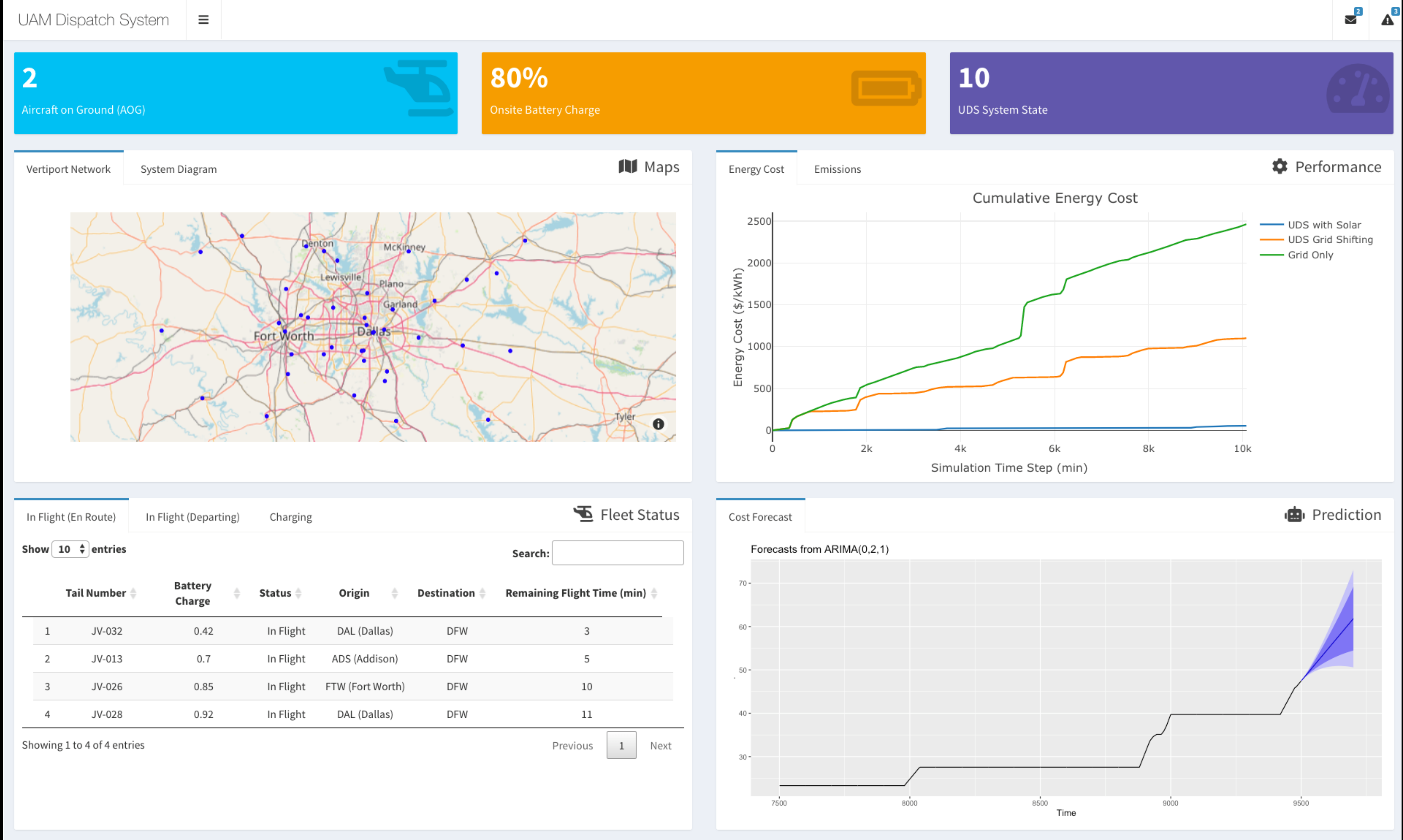
Concept Overview – UDS contd.



UDS provides a high-level decision-support web-app platform to design and operate UAM power infrastructure for the clean vertiports of the future.

Access the UDS Dashboard:

bit.ly/UDSdashboard


UAM Dispatch System
2
Aircraft on Ground (AOG)
80%
Onsite Battery Charge
10
UDS System State
Vertiport Network
System Diagram
Maps
Denton
McKinney
Lewisville
Plano
Garland
Fort Worth
Dallas
Tyler
Energy Cost
Emissions
Performance
Cumulative Energy Cost
UDS with Solar
UDS Grid Shifting
Grid Only
Energy Cost ($/kWh)
Simulation Time Step (min)
In Flight (En Route)
In Flight (Departing)
Charging
Fleet Status
Show 10 entries
Search:
Tail Number
Battery Charge
Status
Origin
Destination
Remaining Flight Time (min)
1 JV-032 0.42 In Flight DAL (Dallas) DFW 3
2 JV-013 0.7 In Flight ADS (Addison) DFW 5
3 JV-026 0.85 In Flight FTW (Fort Worth) DFW 10
4 JV-028 0.92 In Flight DAL (Dallas) DFW 11
Showing 1 to 4 of 4 entries
Previous
1
Next
Cost Forecast
Prediction
Forecasts from ARIMA(0,2,1)
Time

UDS Value Through the Operation

Optimized Operations

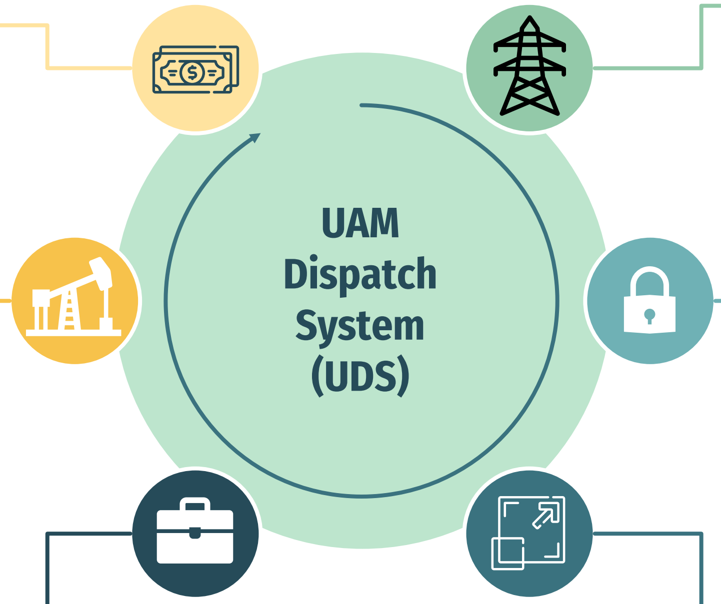
Maximizing asset utilization through optimization

Emissions Reduction

Minimizing operators' and passengers' carbon footprint

Passenger Experience

Minimize wait times, cost reduction



Enabling Renewables

Reducing' dependence on operatorsthe grid

System Redundancy

Minimize downtime, ensuring sufficient energy always

Modular & Scalable

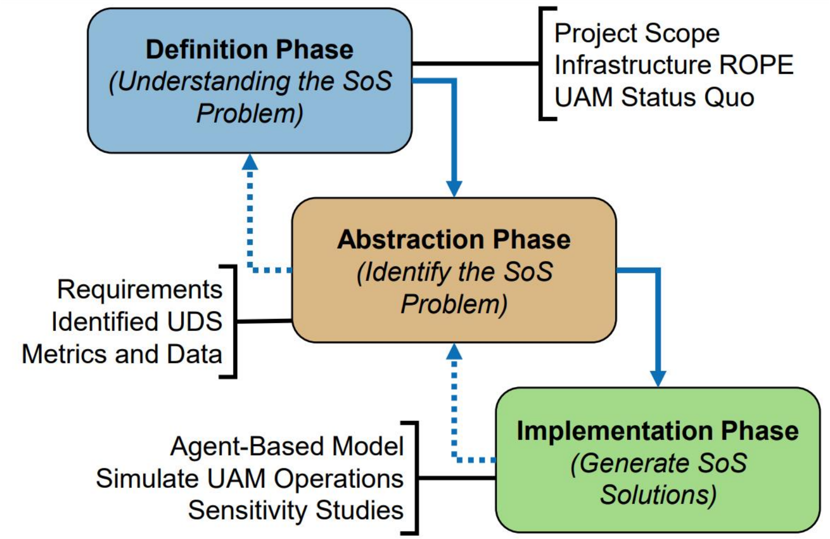
Adaptable to any energy source, fleet size, and AAM mission

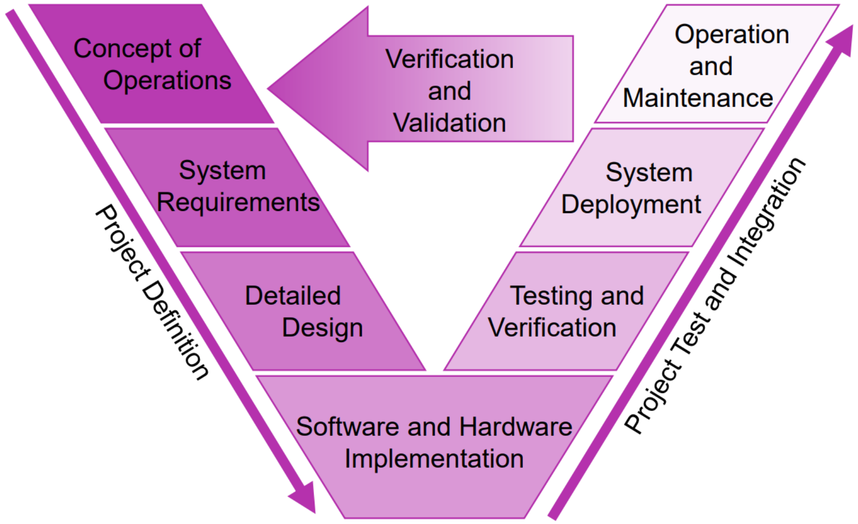
Development

Concept Development Using a 2-Phase Approach

1
Modeling & Analysis of UAM Operations

2
Energy & UAM Dispatch System





Our Problem as a System-of-Systems

UAM Infrastructure is a System-of-Systems (SoS)

What categorizes an SoS?

- Managerial Independence
- Operational Independence

How does an SoS behave differently?

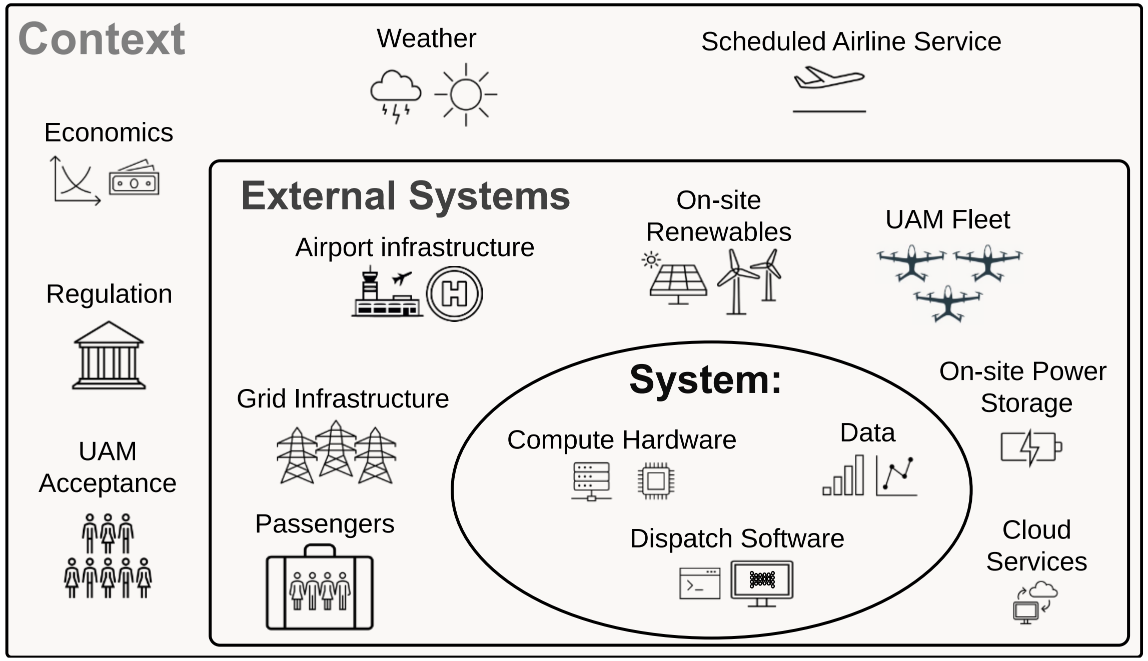
- Emergent Behavior
- Interactions and Intentions

What approach did we use to model this SoS?

- The DAI Approach
- Agent-Based Simulation

What did we accomplish by modeling this SoS?

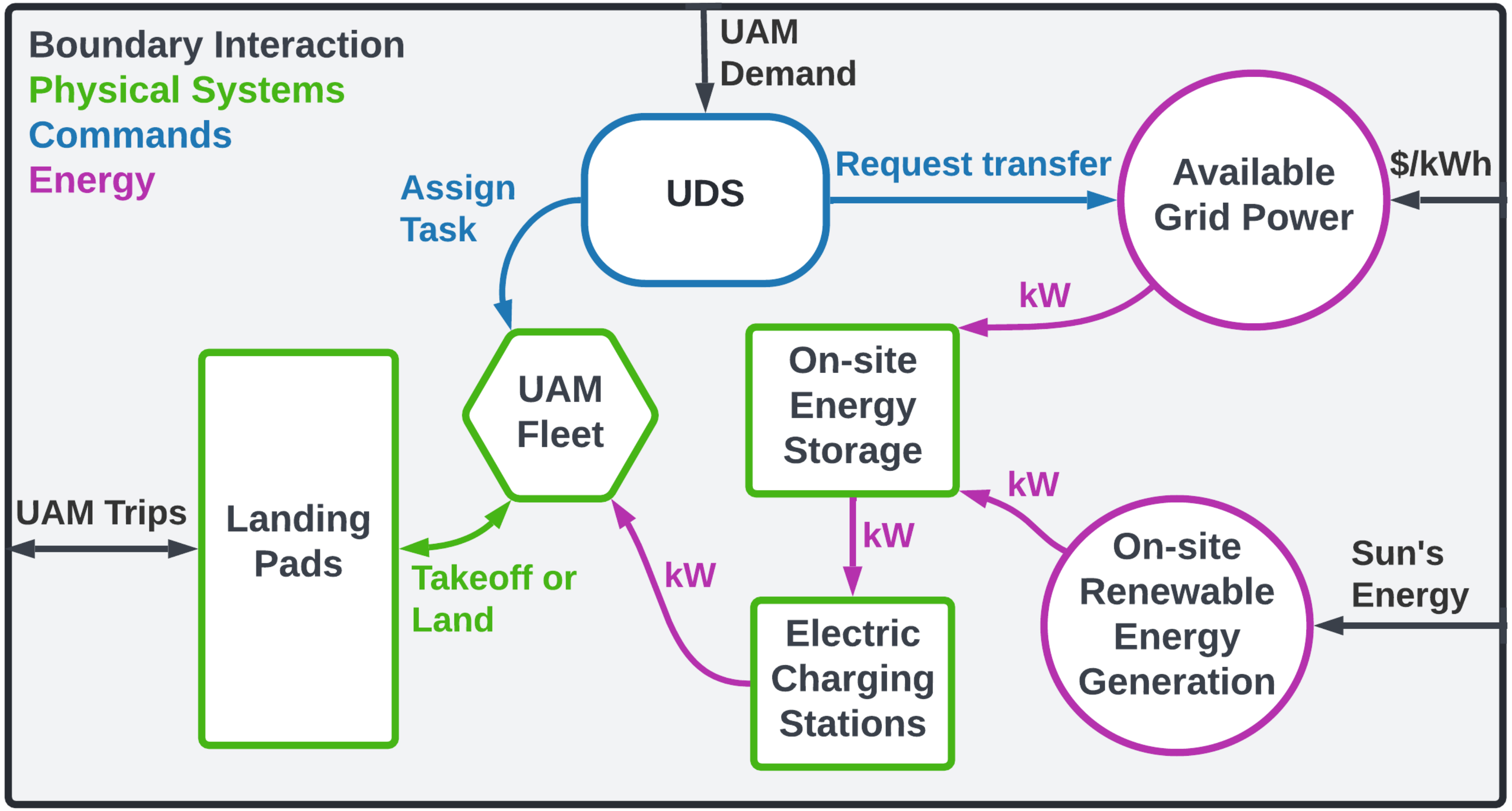
- Evaluation of SoS Metrics
- Sensitivity Analysis



Due to the complexity of UAM systems and their interactions, traditional systems methods are not applicable.

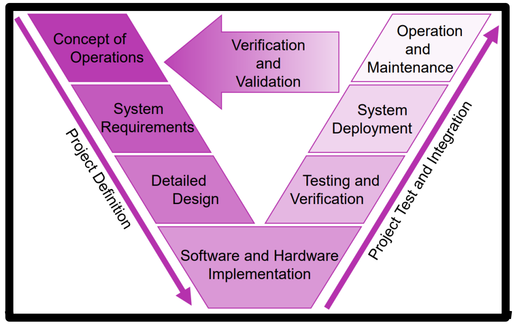
M. W. Maier, “Architecting principles for systems-of-systems,” *Systems engineering*, vol. 1, pp. 267–284, 4 1998

The Interactions and Intentions of UAM



Network Diagram of UAM Systems and Interactions

Designing UAM Dispatch System (UDS)



Customer Needs
- Stakeholder Interviews
- Literature Review

Functional Requirements
- Reducing Reliance on the Electric Grid

Functional Analysis
- Define UDS Actions
- Designed Failure Mitigation

Concept Development
- Designed Controller Logic and Policies

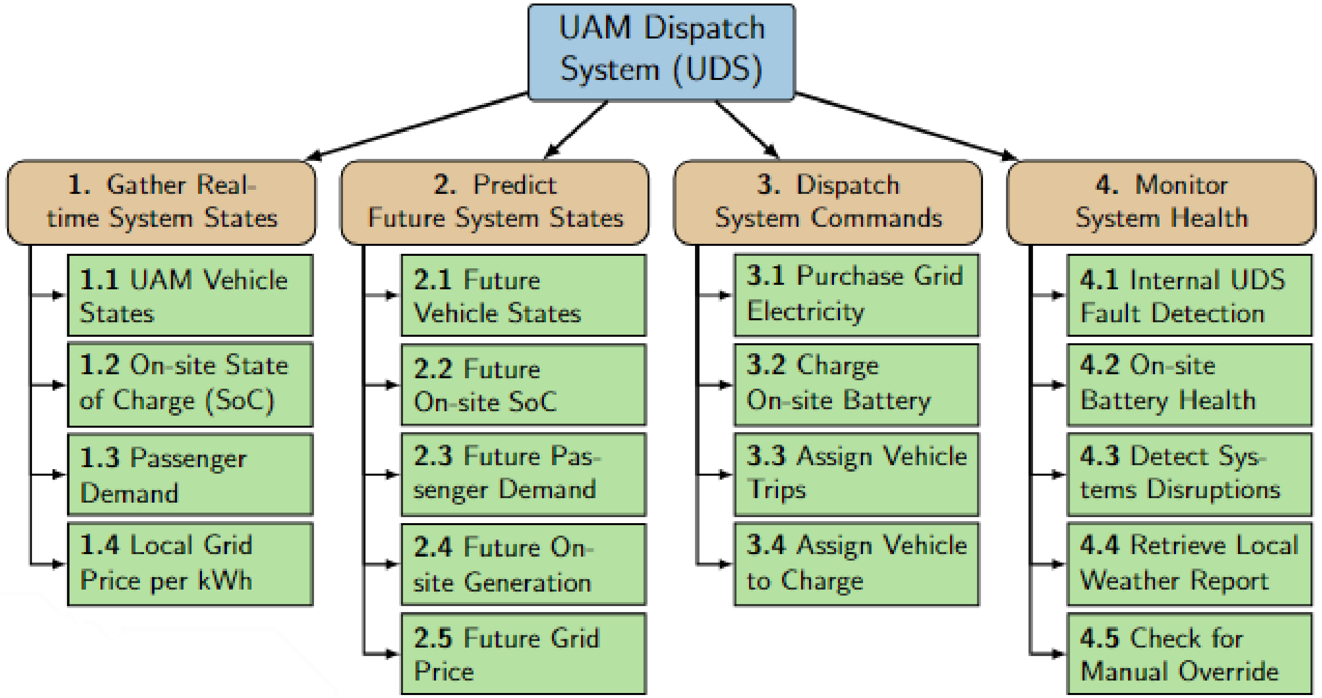
Concept Selection
- Designed Policy Structures
- Implemented Controller in SoS Model

Verification
- Evaluate UDS in Terms of SoS Metrics

System Functional Decomposition

Four Main Functions:

- **Gather Real-time System States**
  - Connectivity and communication
- **Predict Future System States**
  - Forecast key system states
- **Dispatch Energy Commands**
  - Optimal allocation of vehicles and energy
- **Monitor System Health**
  - Failure detection and mitigation



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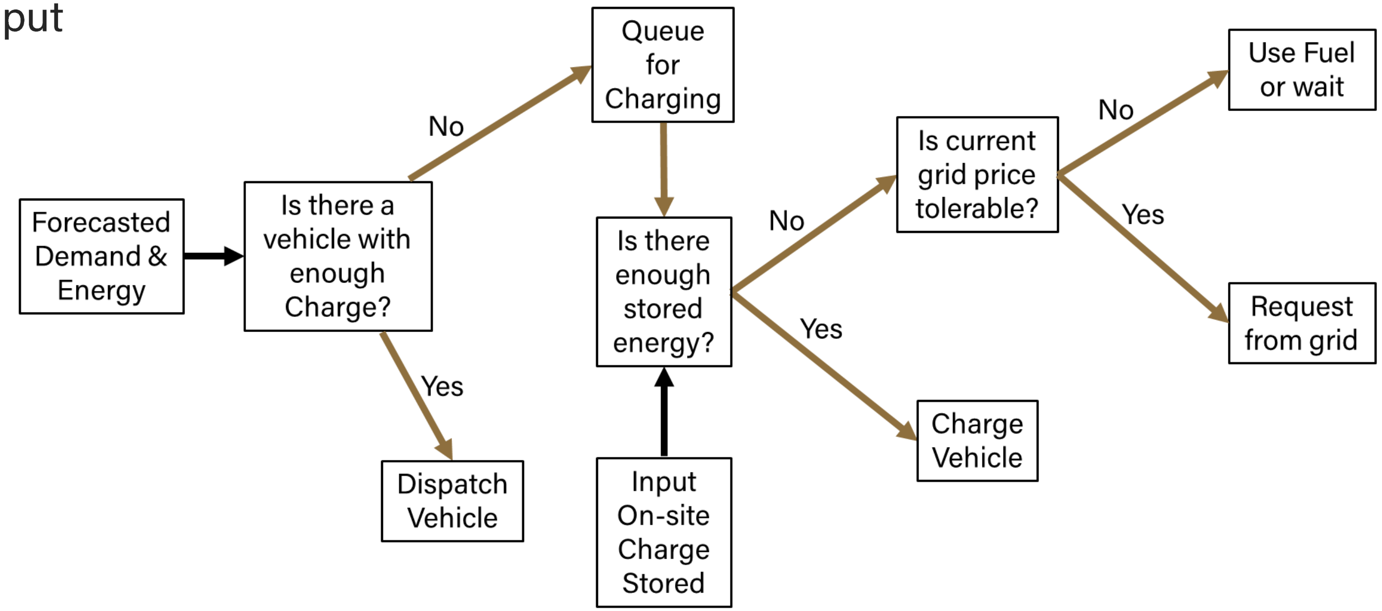
Implementing Demand Response Controller Logic

Controller design development

- UDS controller logic iteration with varying objectives:
  - Maximizing passenger throughput
  - Emissions reduction
  - Operation Cost minimization
  - Multi-objective



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System Performance

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A Framework for Simulating UAM Energy Systems

Weather	Electricity Price	Trip Demand	Vehicle Information
NASA solar radiation and windspeed	Regional operator information	Simulation from UAM literature	Manufacturer and stakeholder interviews

Use high-fidelity data and equations

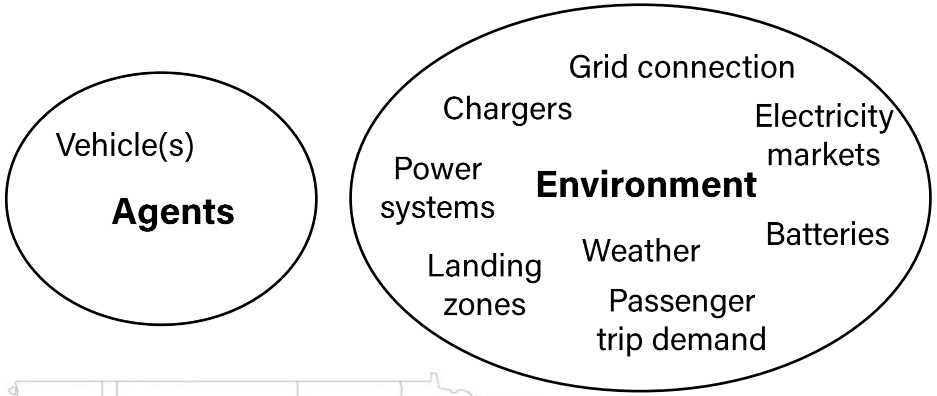
- Physical equations quantify system dynamics (conservation of energy and mass)
- Historic data bases simulation in reality (electricity price, on-site energy, trip demand)

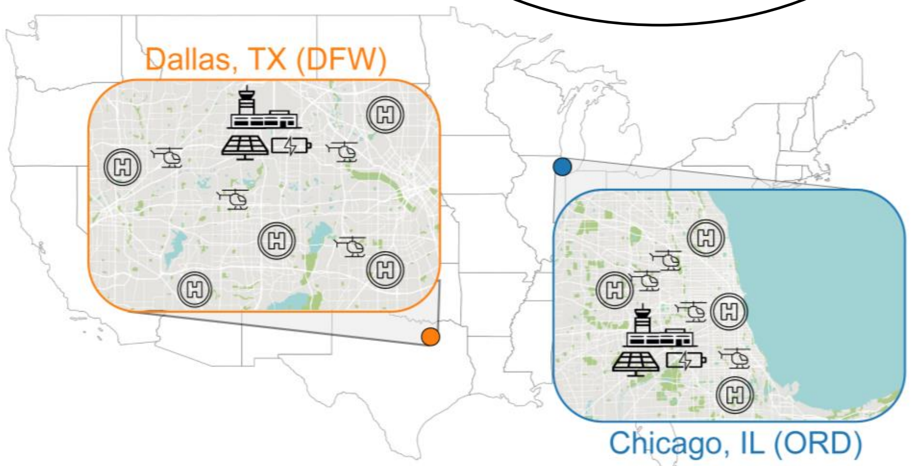
… to study emergent behavior

- Resolve interactions between "agents" and "environment"
- Measure aggregate behavior in complex systems (energy consumption, operational cost, etc.)

… of uses cases and new algorithms

- Evaluate potential UAM fleet deployments
- Design cost-optimization algorithm architectures





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Agent-based model (ABM) framework for UAM

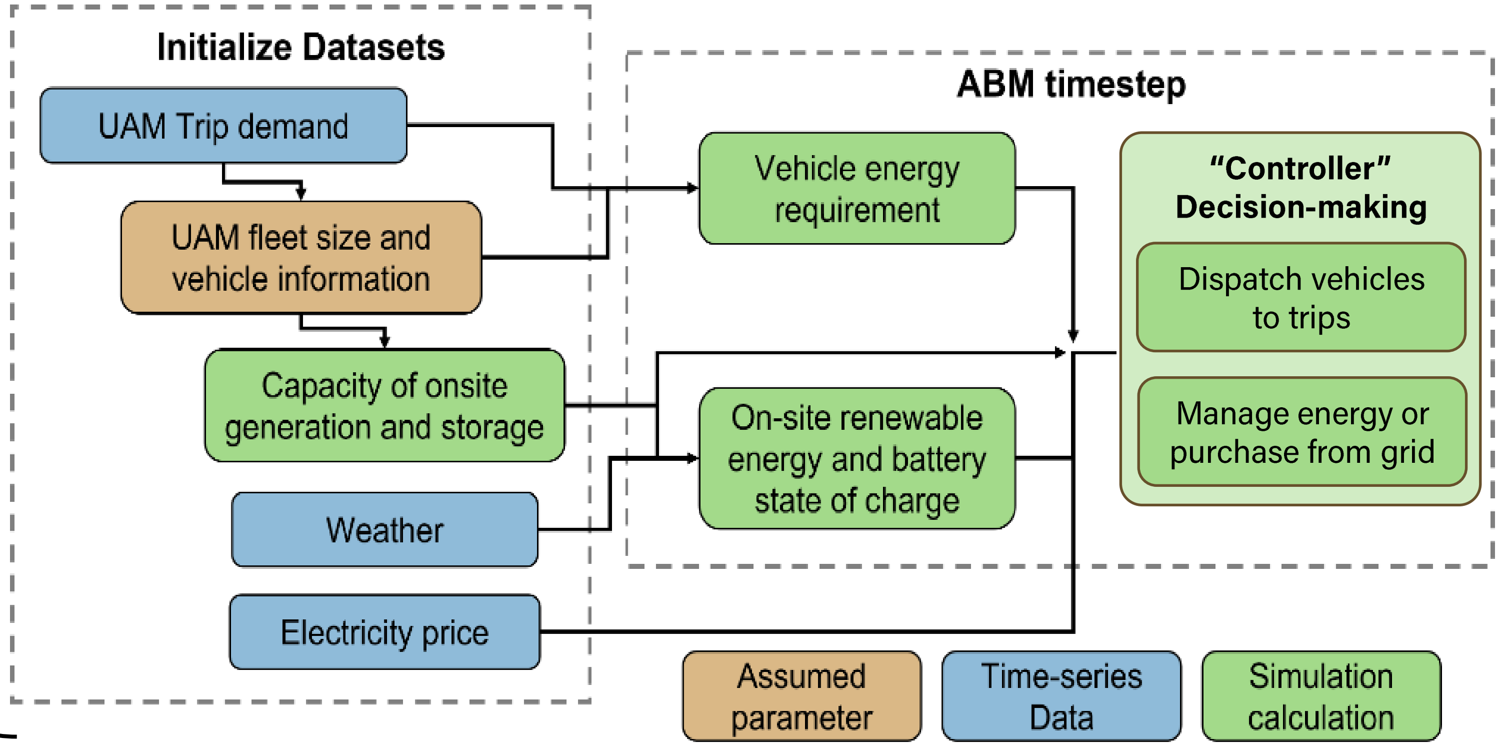
MIMIC
Custom simulation environment for design and operation of UAM energy systems

⇧

Mesa
Library for building agent-based models

⇧

Python
Object-oriented programming language



ABM Assumptions and Parameter sensitivities

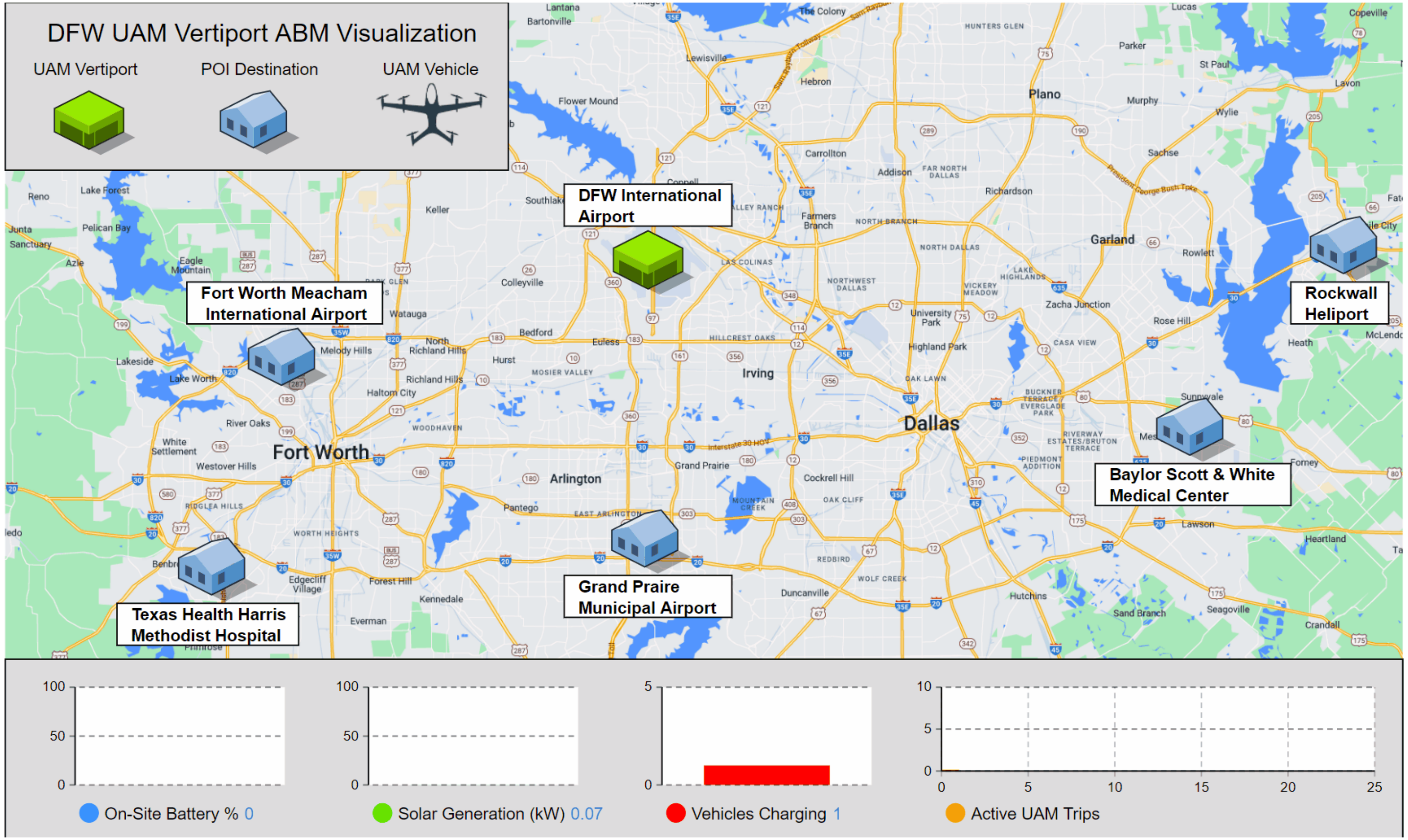
Initial model assumptions

Service to-and-from the airport
Vehicles land and are queued for charging
Controller can direct vehicles from charging to take-off queue
Power draw limits and charging rates are informed by manufacturer specifications

Parameters of interest

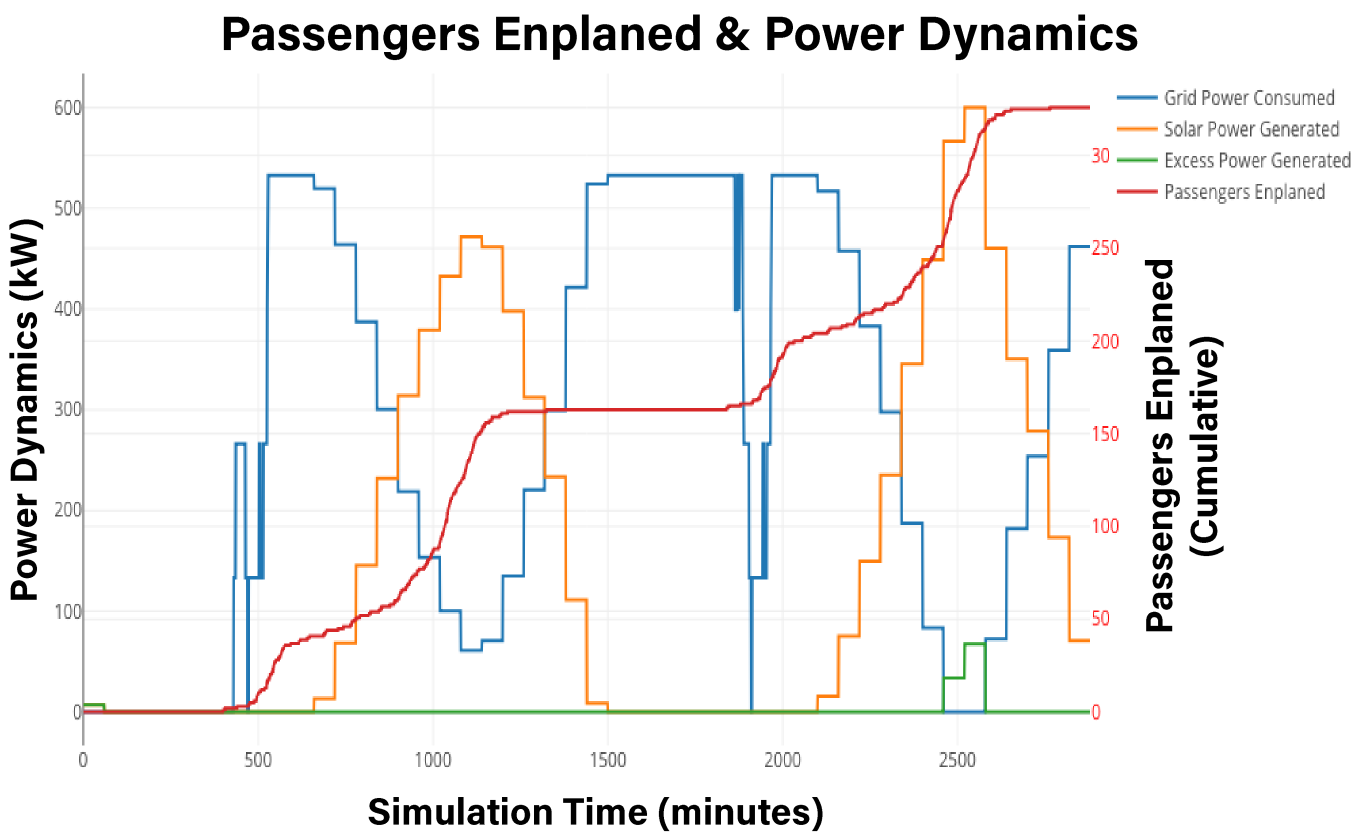
Energy systems	Aviation systems
On-site solar power	Prototypical vehicle (e.g. Archer-5 seater)
On-site battery capacity	Vertiport network
Solar panel efficiency	Passenger demand
Chargers (grid-connections)	Landing zones

Simulation Visualized



MIMIC Solar Case Study

UDS + Solar & Grid Energy utilized in a 24 hr passenger demand profile - Dallas



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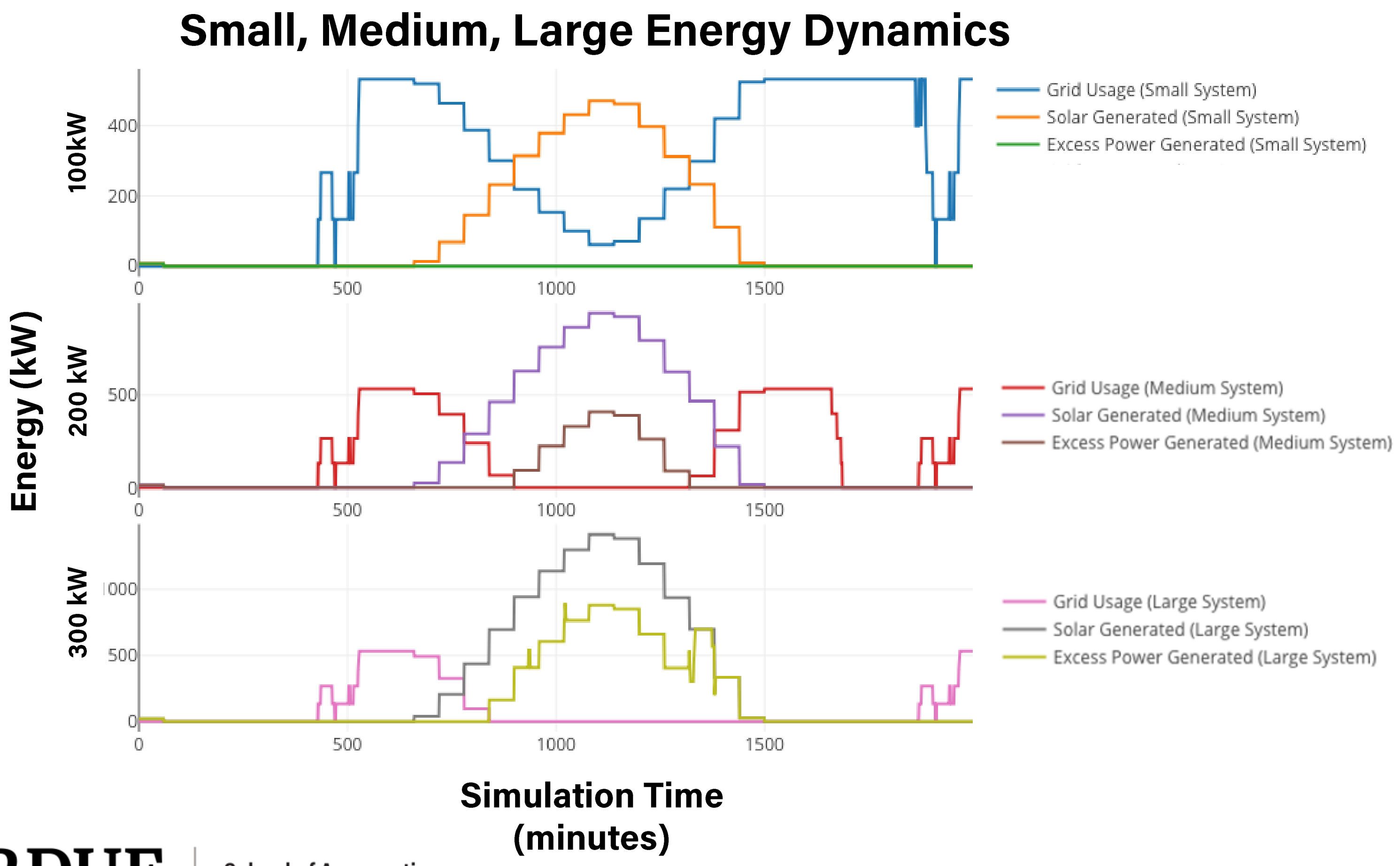
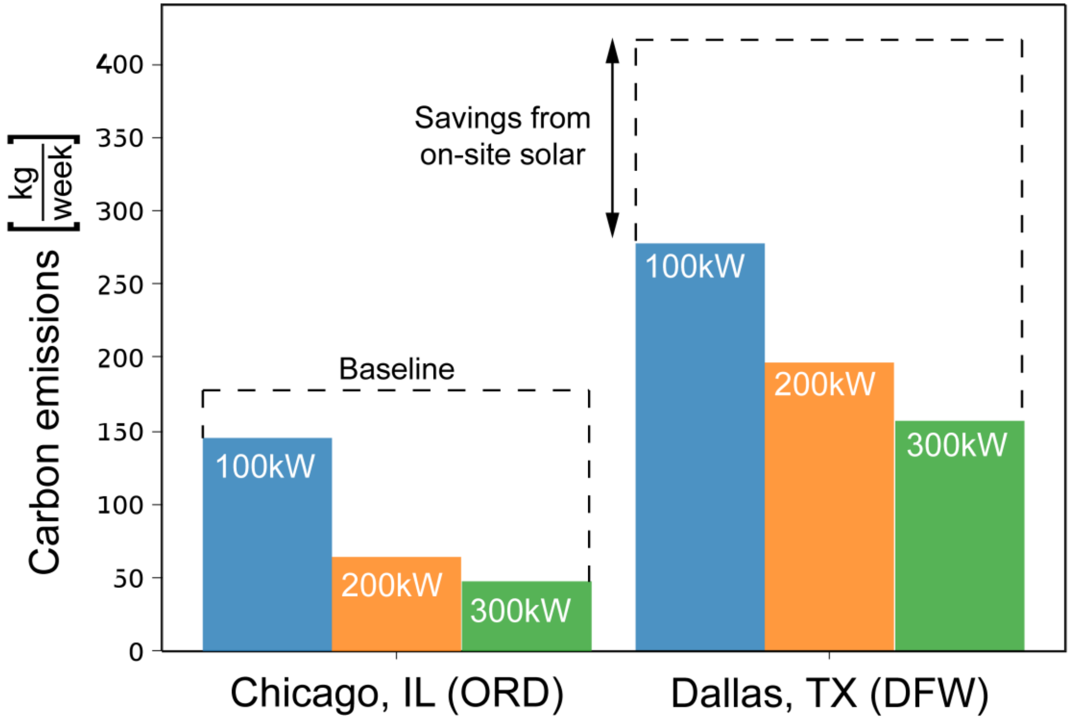
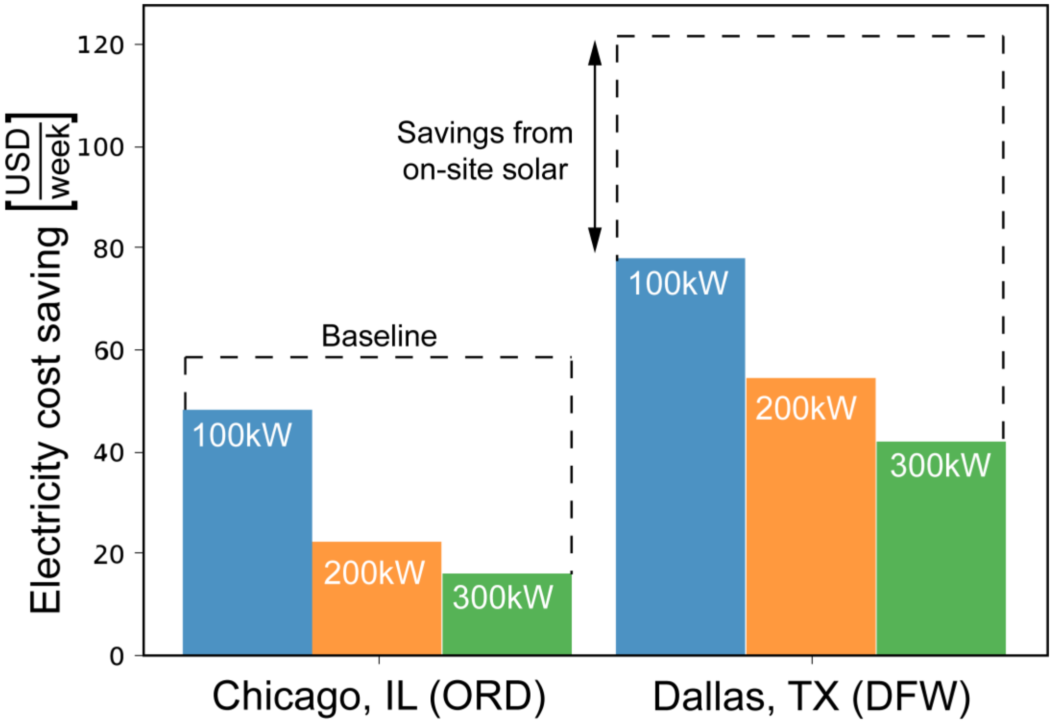
Comparing the energy dynamics of UDS with varying solar sizes - Dallas



MIMIC Case Study - Expected Savings from Solar Energy

Applying UDS + Solar with Minor Load Shifting at ORD, DFW





UDS & MIMIC Web-App Demonstration

Access UDS & MIMIC:

bit.ly/UDSdashboard

Life Cycle Analysis

Long-Term Performance - FAA 2025 & 2035 Vision

1. Deliver Aviation Access through Innovation

2. Sustaining Our Future

3. Fully Shared Information Environment

Challenges

Meeting operational needs, demands, capacity of NAS users to mitigate congestion

Reduce aviation's environmental and energy impacts to a level that does not constrain growth and is a model for sustainability

Analyze and monitor actual system performance, Tailor operational solutions, Reduce operational risks

Opportunities

UDS uses data-rich information of hourly grid prices, renewable resources, passenger demand distributions

- Reduce Significant loads on the grid
- Reduce Electricity Usage Costs
- Reduce Greenhouse gases released from Grids
- Reduce Adverse health impacts on Communities

UDS System Cost Comparison

Our system costs are marginal compared to the capital cost of UAM UML2+

UDS System Costs

Item	Cost
Software development	$4.5k - $500k
Information techology	$150k - $250k

*Based on studies of US microgrid deployments. Controller costs vary by system complexity. Information technology represents computing costs and upgrades over the system lifetime (30 years).

Giraldez Miner, J. I et al., “Phase I microgrid cost study: Data collection and analysis of microgrid costs in the United States” NREL, 2018.

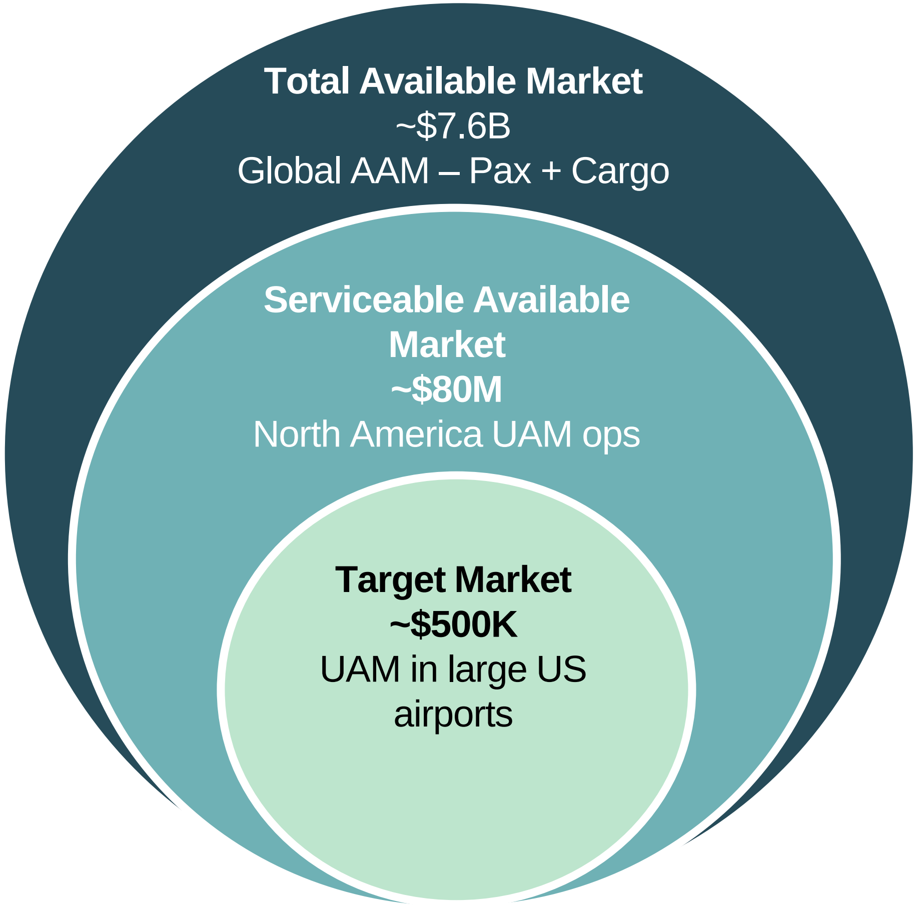
Scale of UAM Investments

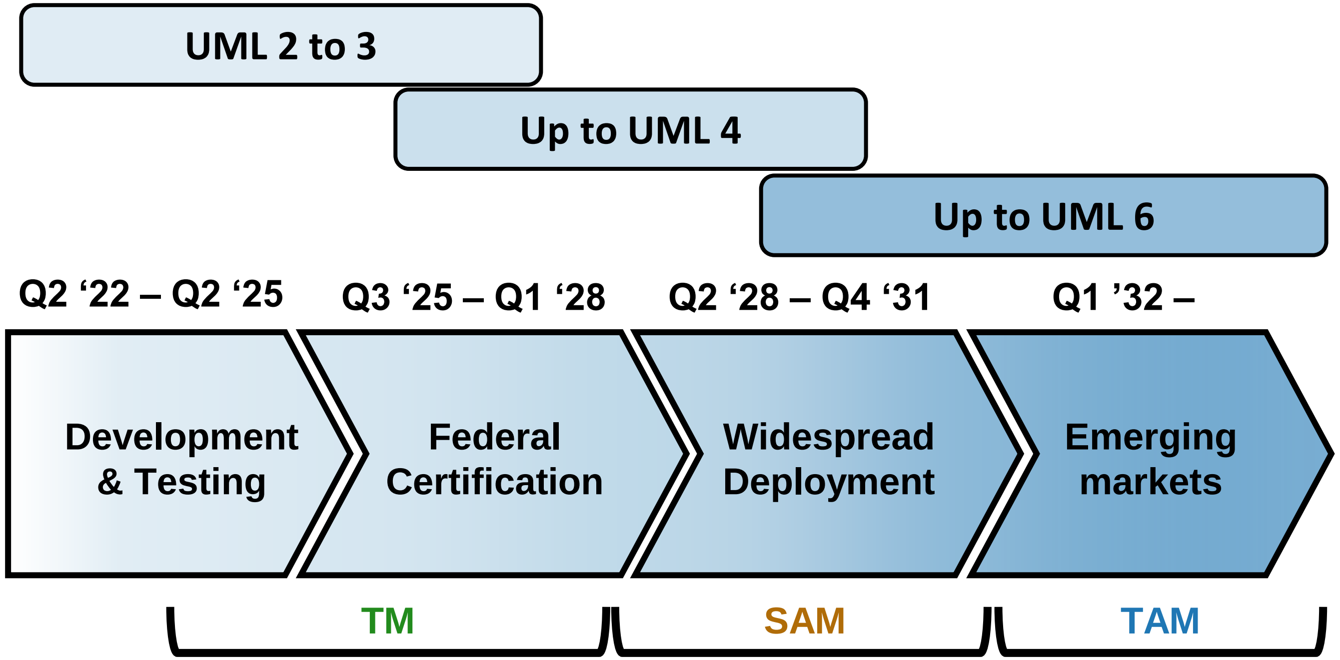
Item	Cost
Batteries	$150k – $1M
Chargers	$200k+ per charger
Vehicles	$1M+ per vehicle
Grid Connections	$100k - $80M**

**Grid connections vary by power draw. Significant charges are incurred for 1+MW chargers.

Black & Veath, “eVTOL electrical infrastructure study for UAM aircraft,” NIA & NASA, 2018

Commercialization Plan





Conclusion

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Akshay

Conclusions & Contributions

We provide a decision-support platform to design (MIMIC) and operate (UDS) demand-response capable infrastructure for clean AAM vertiports of the future.

MIMIC: 1st Agent-based framework for UAM Energy Infrastructure

UDS: A novel, flexible platform for algorithm development and use-case testing

Case studies with on-site solar show dramatic price and emissions savings (>50%) on operational electricity expenditure

In accordance with FAA's 2025 and 2035 plans
(a) delivering access through innovation
(b) sustainability through future development
(c) fully shared information environment

Future Work

Scientific study

- Understanding grid-support and electricity markets
- Platform to see system impacts of certification standards
- Developing new algorithms (deep learning) for enhanced prediction

Product development

- Increased partnerships with UAM manufactuers and operators
- Case studies of deployments in new airports
- Business intelligence to inform energy system investments

Thank you to our partners:

Thank you to all those at FAA & NIA for making this competition possible!

Backup

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UDS Modularity – With and Without Solar

UDS

- Cloud-based algorithms with local backup
- Plug in existing energy sources

UDS with Solar

- Cloud-based algorithms with local backup
- Plug in to grid energy systems
- Onsite power generation (solar)
- Onsite power storage (batteries)

Cost of Energy Infrastructure

Upgrading energy infrastructure requires

Estimated Budget Pricing Summary	Description
$100,000	Service supply extension; up to 1 MW (up to 3 chargers)
$264,000 to $1,300,000 per mile	New conductor / reconductor; up to 5 MW (up to 8 chargers)
$3,000,000 to $11,000,000	New transformer bank; over 10 MW (over 15 chargers)
$40,000,000 to $80,000,000	New substation bank; over 20 MW (over 30 chargers

Black & Veath, "eVTOL electrical infrastructure study for UAM aircraft," NIA & NASA, 2018.

Case Studies (Dallas, Chicago)

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UAM Vehicles for ODM Require Frequent Charging

Archer-like 5-seater

Vehicle	Archer 5-seater
Passengers (pax)	4
Cruise Speed (mph)	150
Range (miles)	60
L/D	11.3
Vehicle Configuration	Vectored Thrust
Max Flight Time (minutes)	24
MTOW (kg)	3175
Vehicle Battery Capacity (kWh)	160
DOC ($/hr)	685
DOC/pax	171

Simulation Functionality

Location-Specific Inputs

Airline / Operator Parameters

- UAM vehicle models
- UAM fleet compositions
- Passenger demand models

Energy Parameters

- Solar energy generation
- Hydrogen energy generation
- Grid power – load & cost
- Onsite energy storage

→ MIMIC →

Simulation Outcomes

Economic Metrics

- High-fidelity operating costs
- Per seat-mile revenue & cost

Aircraft Operating Metrics

- UAM vehicle flight hours
- Passenger throughput
- Emissions

Energy

- Expected grid load & cost

Passenger Demand Generation

Two demand generation protocols

- Baseline Model: Op Limits Trips (ORD to Baseline Network)
  - Baseline network as sited by Sells, et al. [1]
  - Passenger demand datasets from Maheshwari, et. al
- Secondary Implementation: Scheduled Service-driven
  - Use airport arrivals (open-sky / flight radar + T-100 passenger load factor)
  - Estimate % of possible UAM Trips from scheduled passengers arriving at ORD
  - Use customer preference survey from SAN to generate heuristics on mode choice

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[1] Sells, B. E., Maheshwari, A., Chao, H., Wright, E., Crossley, W., & Sun, D. (2021). Evaluating the impact of urban air mobility aerodrome siting on mode choice. In *AIAA AVIATION 2021 FORUM* (p. 2371).
[2] Maheshwari, A., Mudumba, S. V., Sells, B. E., Delaurentis, D. A., and Crossley, W. A., "Identifying and analyzing operational limits for passenger-carrying urban air mobility missions," Vol. 1 PartF, 2020. https://doi.org/10.2514/6.2020-29

UAM Trip Demand dataset

Simulated Airport shuttle service using flight schedule and survey data in literature

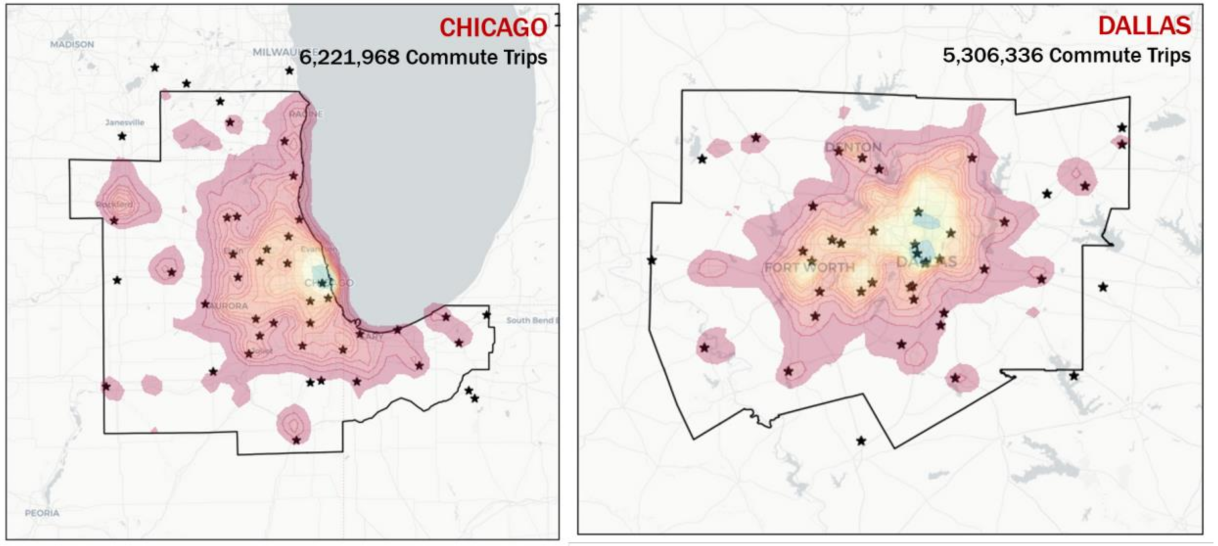
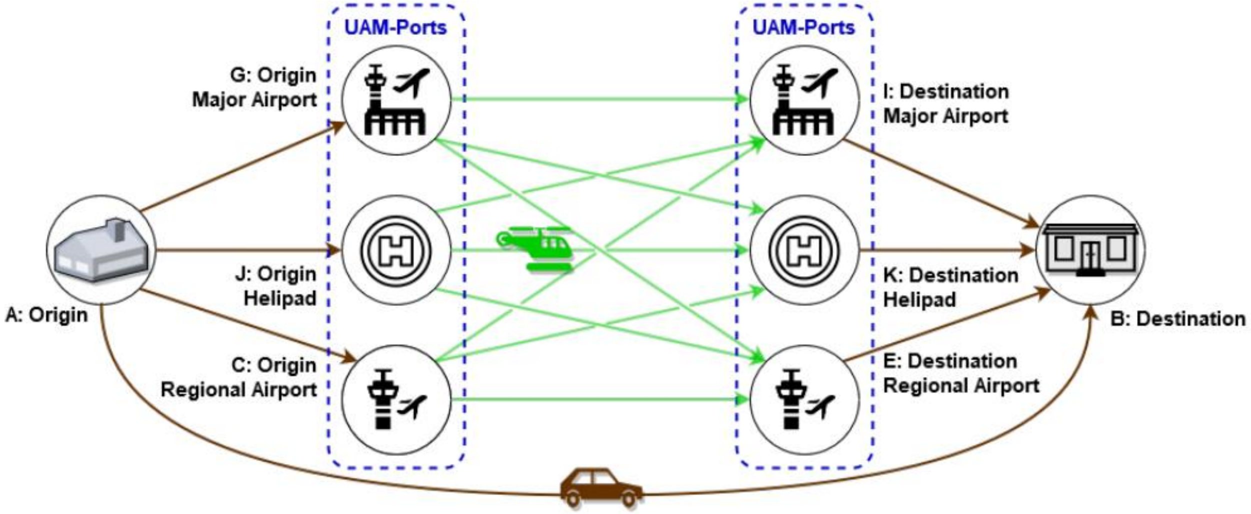


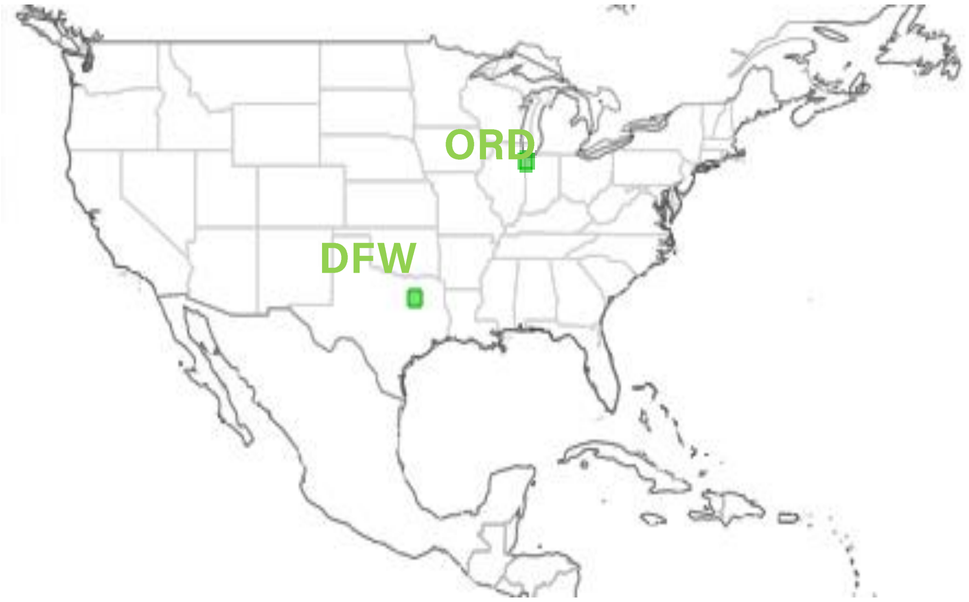
Fig. 3 Geographic distribution of all commute trips in Chicago and Dallas Metropolitan Areas, along with all the "existing infrastructure" locations (marked with ★). Areas with trip density lower than a threshold are not colored on the map for brevity.



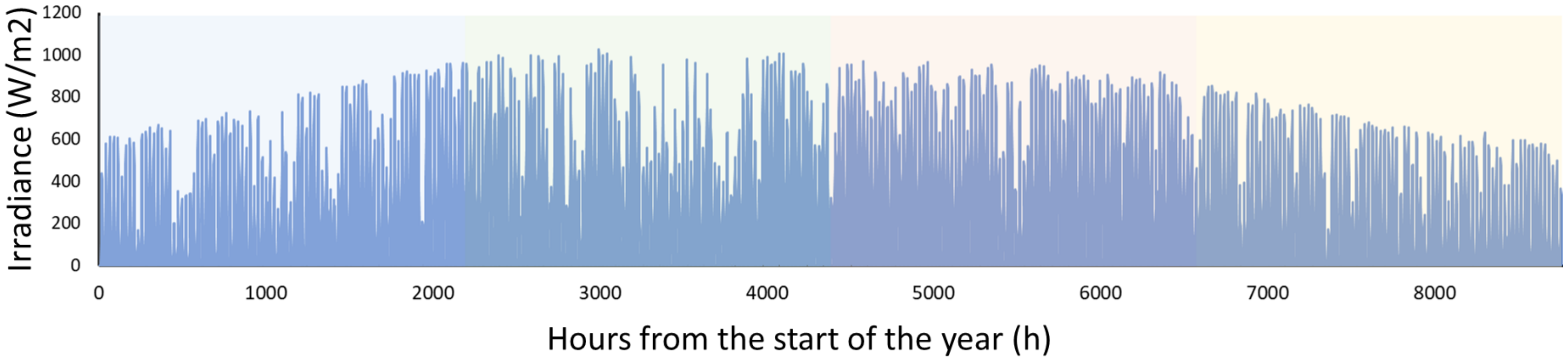
Maheshwari, A., Sells, B. E., Harrington, S., DeLaurentis, D., & Crossley, W. (2021). Evaluating impact of operational limits by estimating potential uam trips in an urban area. In *AIAA Aviation 2021 Forum* (p. 3174).

Solar irradiance data

- Satellite reanalysis from NASA-MERRA2
- Data resolution: 1hr, 0.5° x 0.625°
- Irradiance: Shortwave EM radiation that is incident upon the Earth's surface $\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$



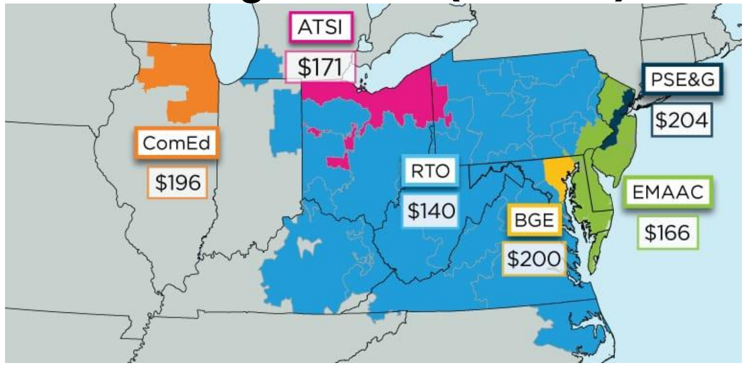
Example data for DFW:



Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavg1_2d_rad_Nx. Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: April 02, 2022. 10.5067/Q9QMY5PBNV1T

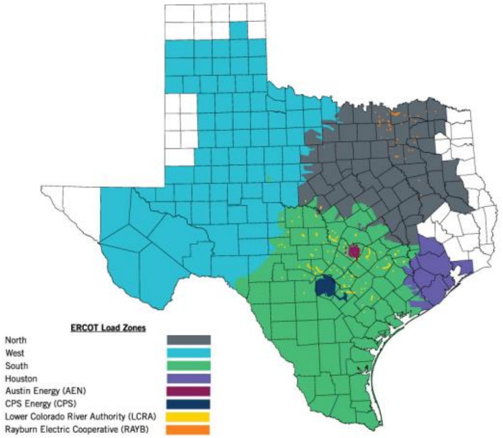
Electricity price data ($/MWh)

Chicago – ORD (ComEd)

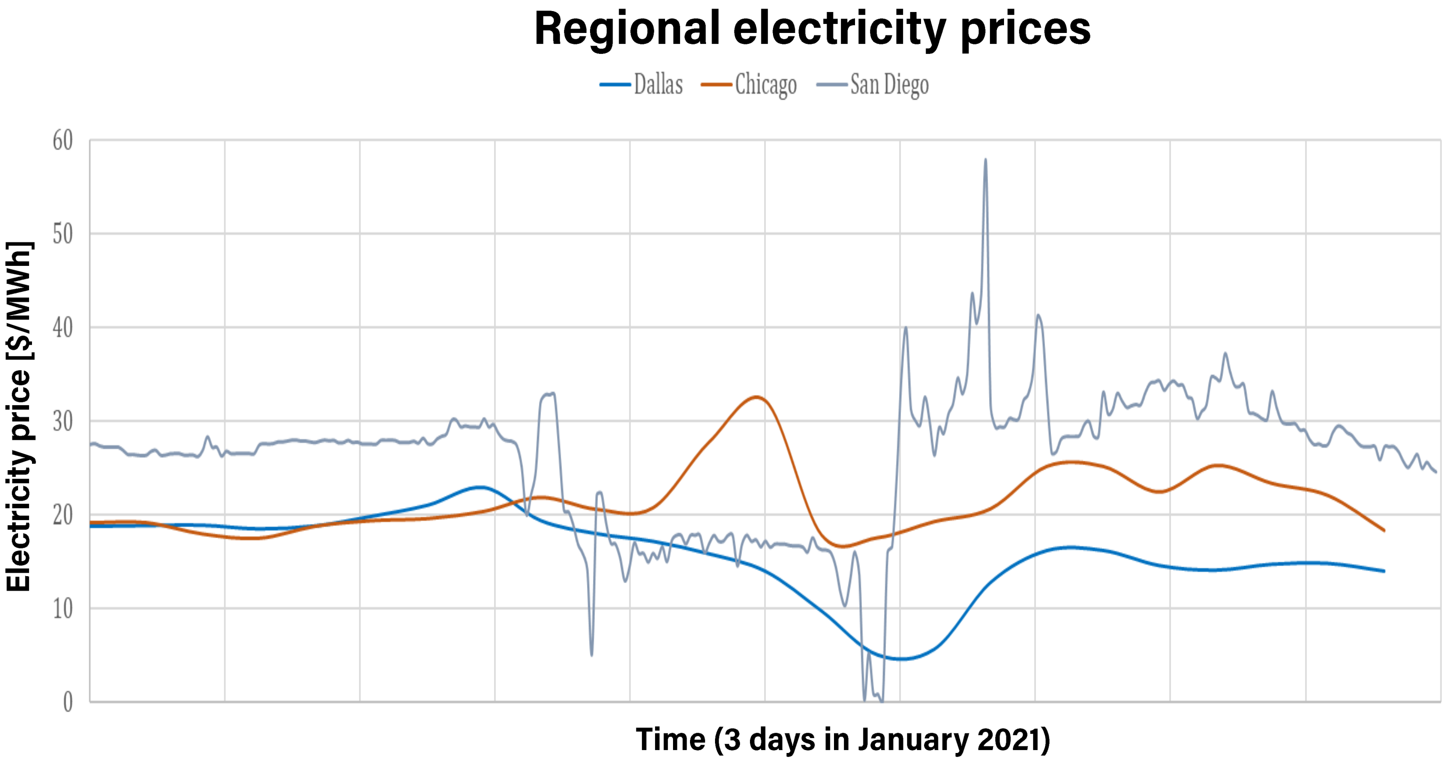


https://insidelines.pjm.com/2018-map-bra-results-inside-lines-banner-2/

Dallas – DFW (ERCOT)



https://www.ercot.com/news/mediakit/maps

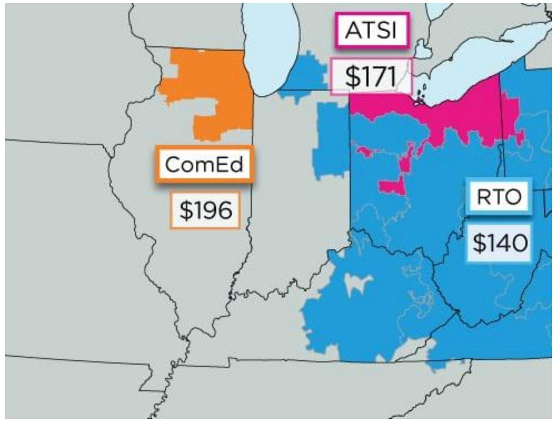


http://www.energyonline.com/Data/GenericData.aspx?DataId=4

Simulation Development – Summary of Datasets Used

Case Studies in Chicago and Dallas

- **Calculating On-site Solar Generation**
  - NASA Merra-2 historical data on location-based solar irradiance
- **Calculating Grid Price and Emissions**
  - Data from local Utility Providers gathered for each location
  - Each Grid has a different emissions index
- **Simulating UAM Demand**
  - Simulated Airport shuttle service using flight schedule, survey data, and previous research



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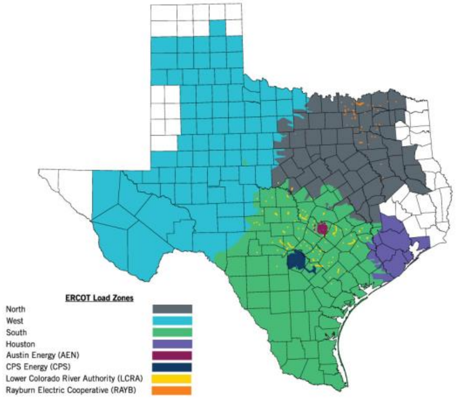

https://www.ercot.com/news/mediakit/maps

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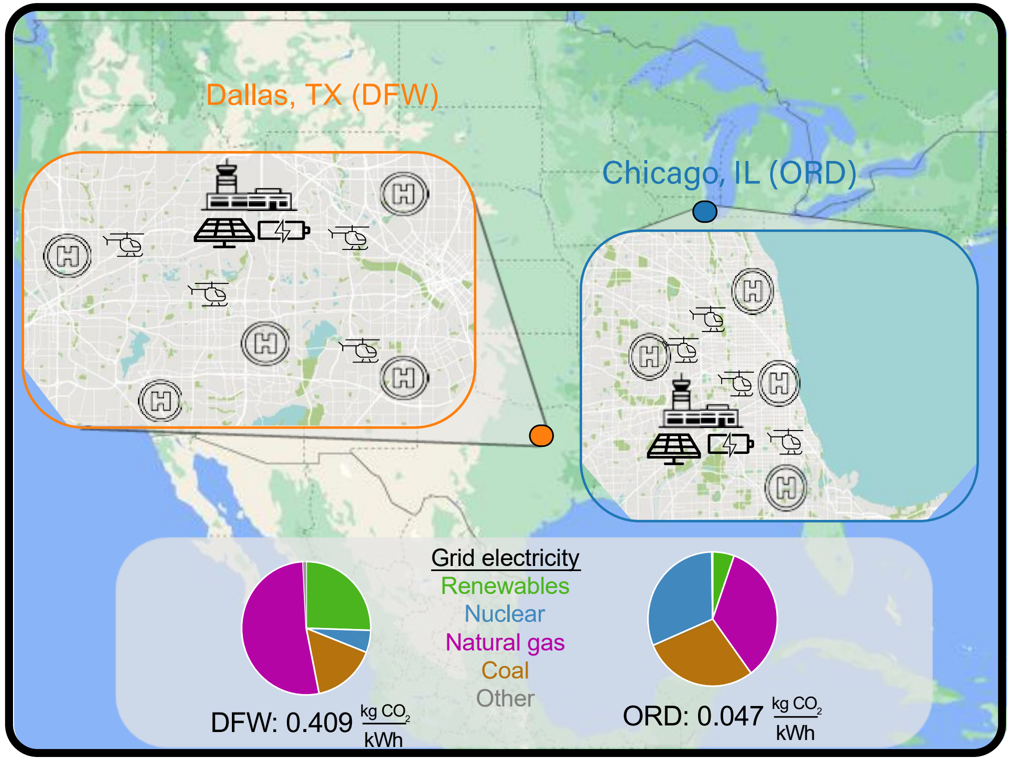
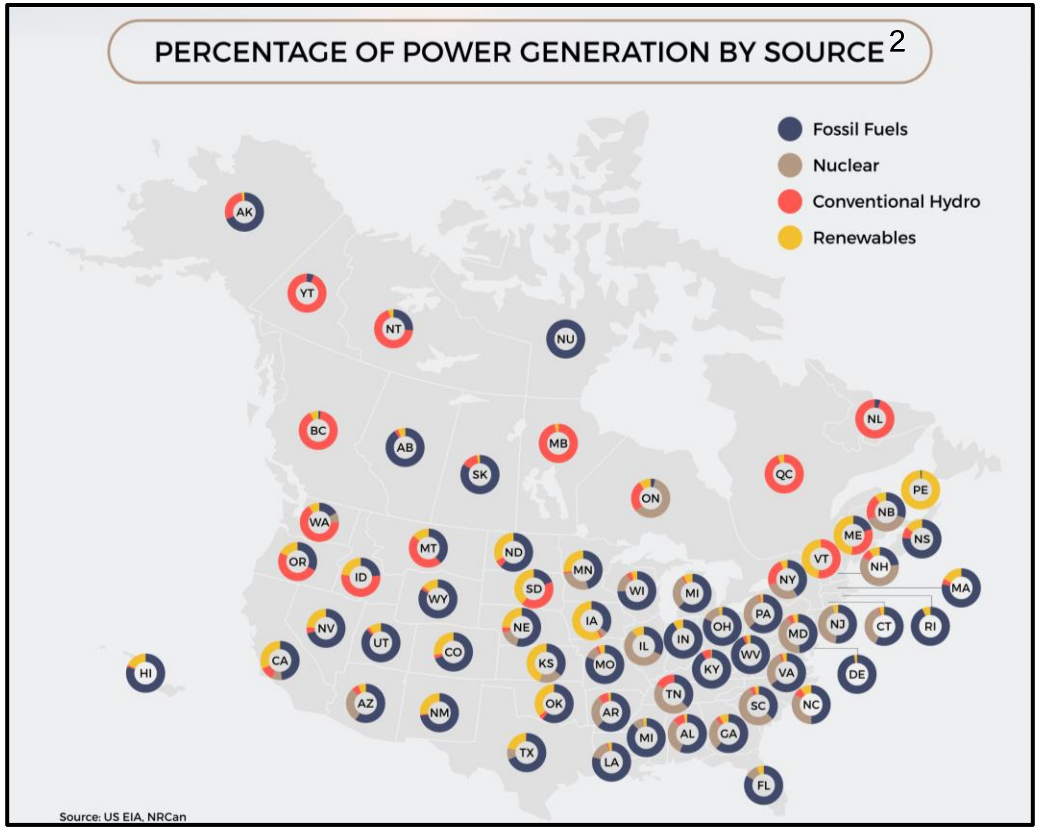
Akshay

Emissions

Electrifiction is only the first step to decarbonization

For emission-free UAM, we must support a diverse mix of clean energy sources[1]

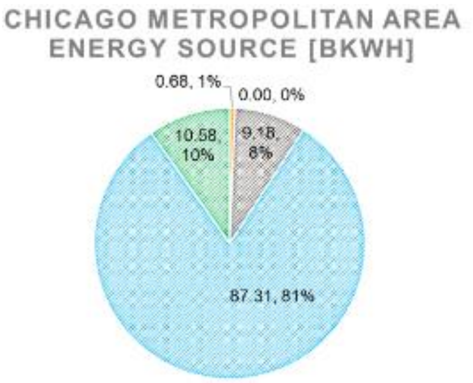


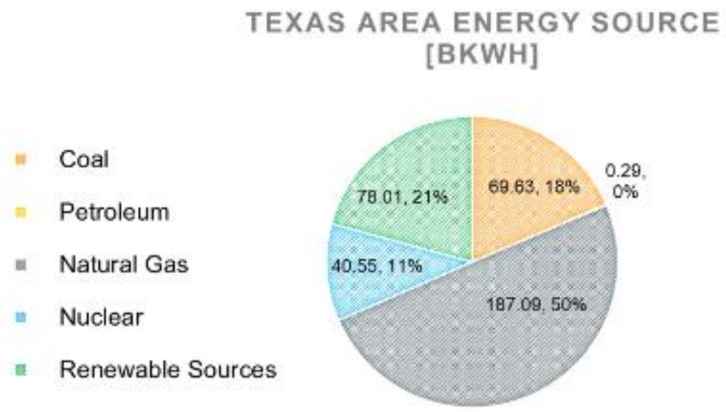


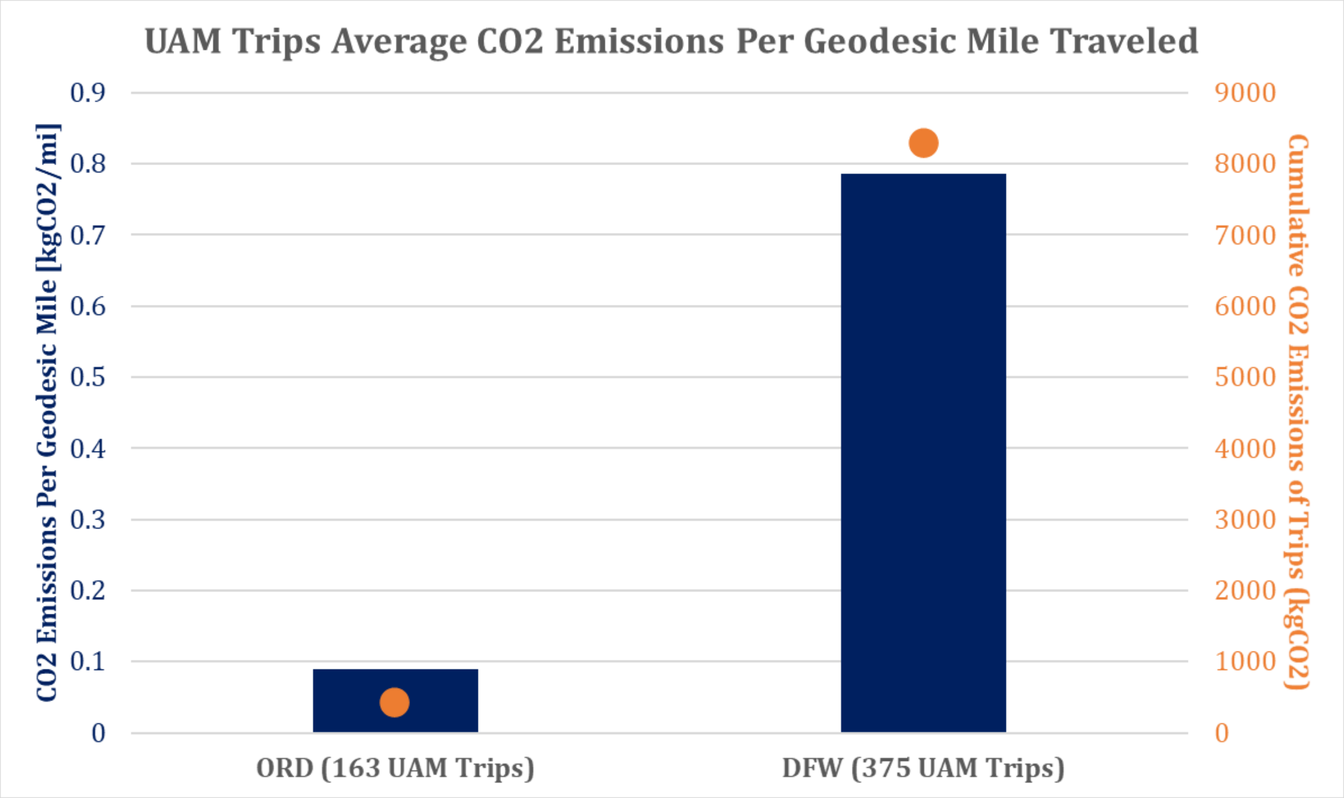
[1] Meckling, J., Sterner, T., & Wagner, G. (2017). Policy sequencing toward decarbonization. *Nature Energy*, *2*(12), 918-922.
[2] *M. Heath & A. Foyer (2022) North American Electricity Mix by State and Province. EnergyMinute.*

Emissions Study

- Chicago 2020 Grid Emissions Index: 0.0470 kgCO2/kWh
- Dallas 2020 Grid Emissions Index: 0.4090 kgCO2/kWh







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Charging UAM Vehicles from the Grid Releases CO2 Emissions!
CO2 Emissions from a purely Solar Power would be Zero!

Example system initialization with solar PV

Sizing assumptions with sensitivity

Parameter	Range of values
Number of vehicles	$4 - 50$
Onsite energy requirement to fleet battery storage ratio	$0.5 - 1.5$
Onsite battery power to fleet battery power ratio	$0.1 - 1$

Fixed parameter assumptions

Parameter	Value
Power density (Solar)	$0.15 \frac{\text{kW}}{\text{m}^2}$
Power density (Hydrogen)	$1.55 \frac{\text{kWh}}{\text{L}}$
Power density (Diesel)	$0.50 \frac{\text{kWh}}{\text{L}}$
Solar panel efficiency	22 %

Solar panel power equations

Initial sizing: $$\text{Area} = \frac{\text{Onsite energy} * \text{daylight hours}}{\text{Power density}}$$

Per-timestep: $$\text{Energy} = \text{Area} * \text{Irradiance} * \text{Efficiency}$$

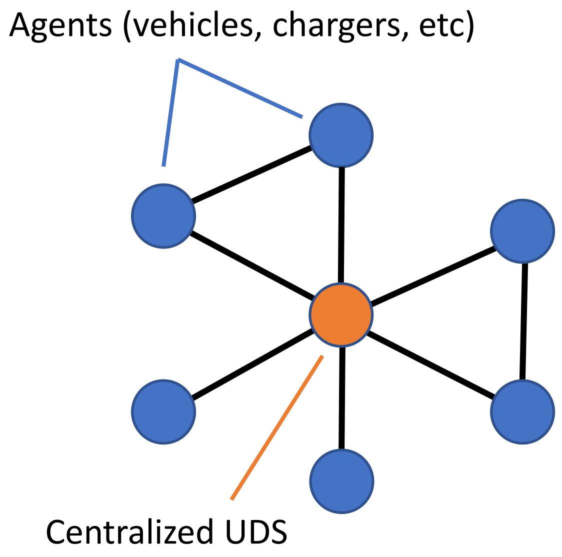
Systems Safety & Reliability

Systems Safety & Reliability

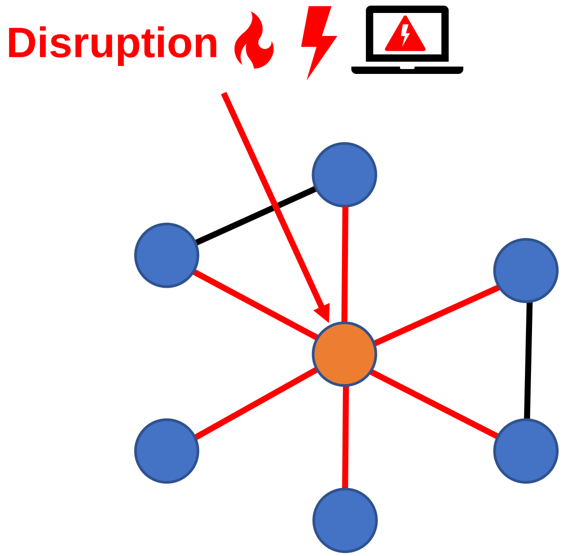
UDS does not have control over flight-critical systems

Scope	Failure Mode	Causes	Effects	Mitigation
Internal	Unexpected system shutdown	Cyber-attack, Physical system failure, Server failure	Long-term operation disruption, Revenue loss	Decentralized control mode, Secure and robust software
	Communications failure	Server delays, Physical system failure	Unintended predictions and dispatches	Regular maintenance, Redundant systems
	...	...	...	...
External	Loss of Power	On-site power failure, Grid blackout	Loss of control, Operational delays, Revenue loss	Localized computing
	Inaccurate data transmitted	Abnormal system operation, communication disruption	Unintended predictions and dispatches, loss of optimal control	Regular maintenance, Nominal operation monitoring
	...	...	...	...

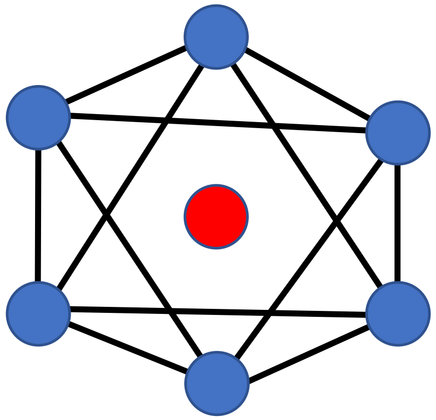
Multi-agent operating mode for centralized failure.



Nominal operating mode with centralized UDS



Disruption on UDS – e.g. cyber attack, physical damage



Decentralized UDS protocol when central UDS is inactive

Commercialization – Business Model Canvas

Key Partners	Key Activities / Key Resources	Value Propositions	Customer Relationships / Channels	Customer Segments
• Airports • UAM Manufacturers • Grid Service Providers • Computational Service Providers • Governing Bodies	**Key Activities** • Optimize **Key Resources** • Data	• Reduce Emissions • Increase operational	**Customer Relationships** • Operators **Channels** • Email, IM • Publications	• UAM Operators • UAM Manufacturers

Cost Structure	Revenue Streams
• Value Driven	• Partnerships with operators, utility providers, • Consulting Engineering

Stakeholder Discussion / Analysis

Stakeholder Identification for Customer Needs

Stakeholder Category	Example Stakeholders
Passenger	Businesspeople, Children, Families, Adults including Mobility, Visually, and Hearing Challenged
Airport Authority	Decision Makers, Dispatch
UAM Operators	Ground Crew, Engineering, Aircraft Maintenance Technicians, Dispatch
Airside Operations	Aircraft Cleaning Crew, Aircraft Charging Crew
Air Traffic Control	Departure Controllers, Flight Data Controllers, Arrival Controllers
Regulatory Agencies	FAA, EASA, etc.
Local Communities	Local government, community organizers, citizens
Suppliers	Renewable Power Assets Suppliers, Aircraft Acquisition Suppliers (OEM)
Unions (Airline & Airport)	Maintenance Unions, Ground Crew Unions, Airport Workers' Unions, Grid Operators' Unions
Grid Power Suppliers	Independent System Operators (ISOs), Mechanical and electrical contractors, construction entities

Stakeholders Interviewed:

SAN DIEGO INTERNATIONAL AIRPORT LET'S GO.

NORMAN Y. MINETA SAN JOSE INTERNATIONAL AIRPORT

American Airlines

GE Aviation

Unnamed UAM Operators

System-of-Systems Stakeholder Interviews

Stakeholders Interviewed:

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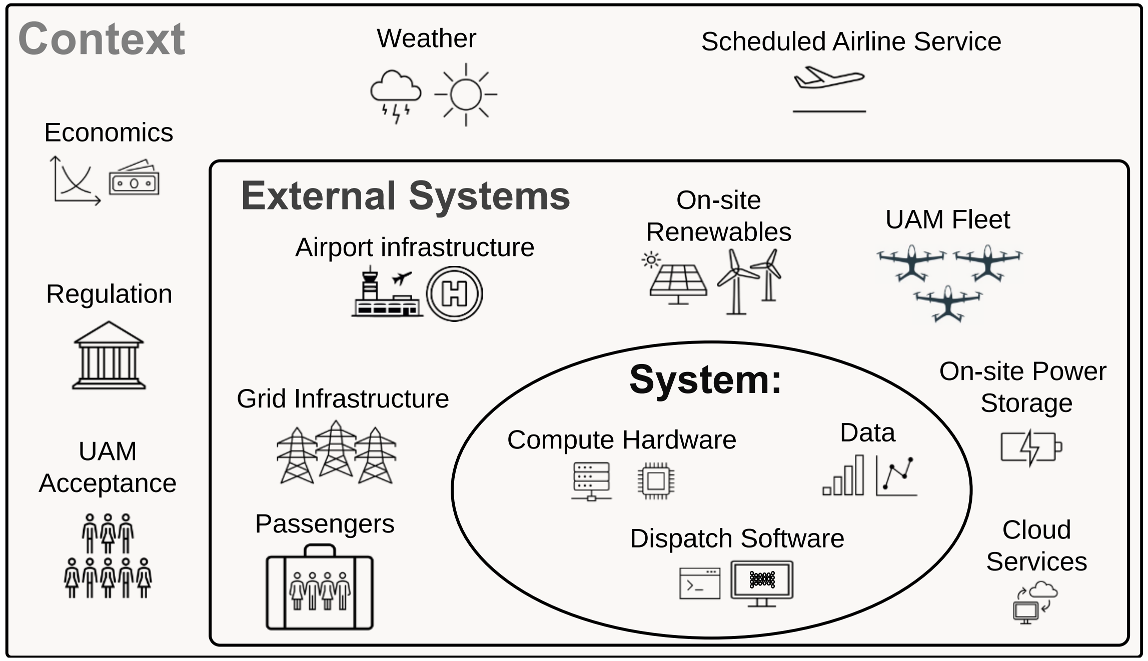
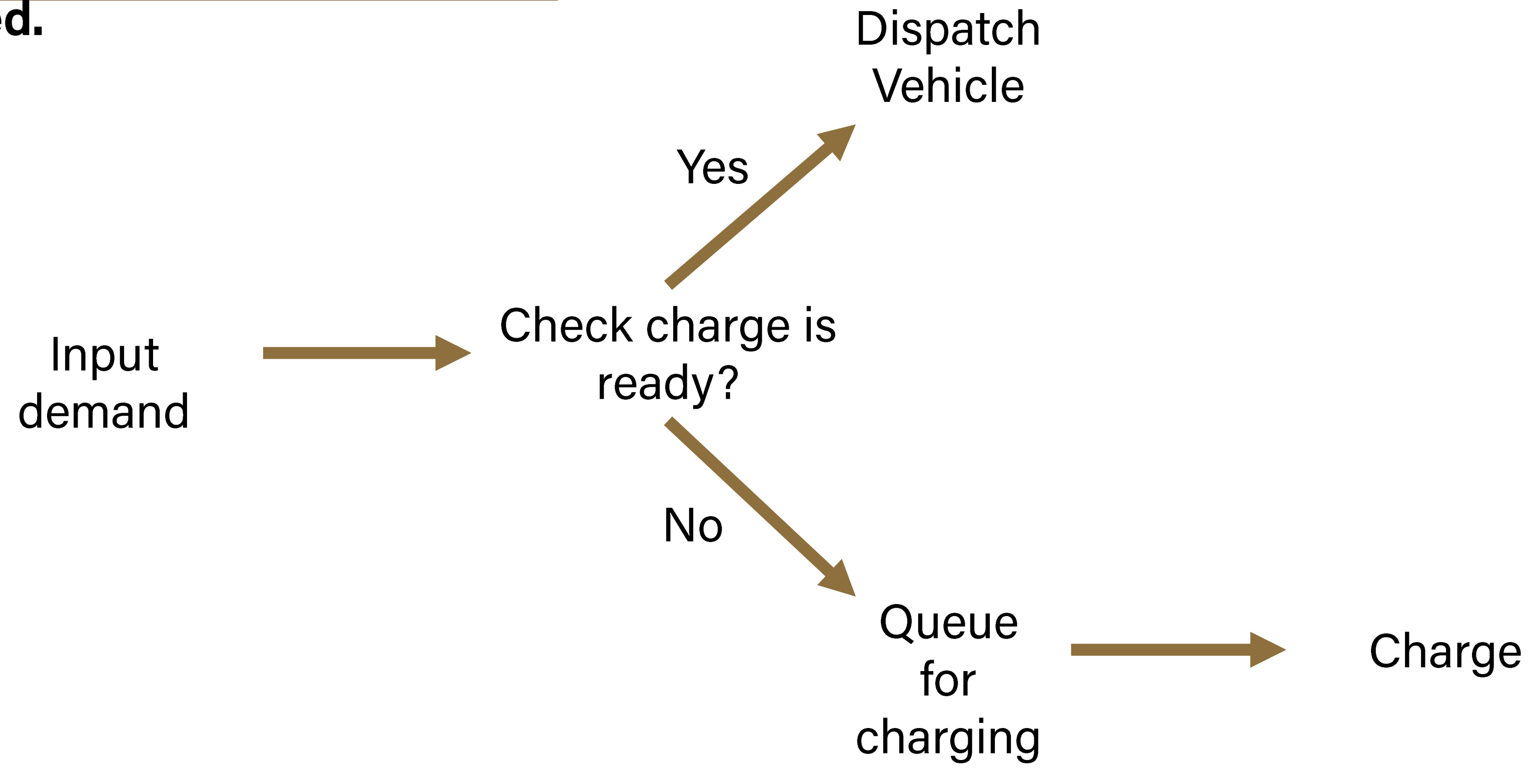


Infrastructure for future UAM operations will likely be the responsibility of the UAM operator, not the airport.

M. W. Maier, "Architecting principles for systems-of-systems," *Systems engineering*, vol. 1, pp. 267–284, 4 1998

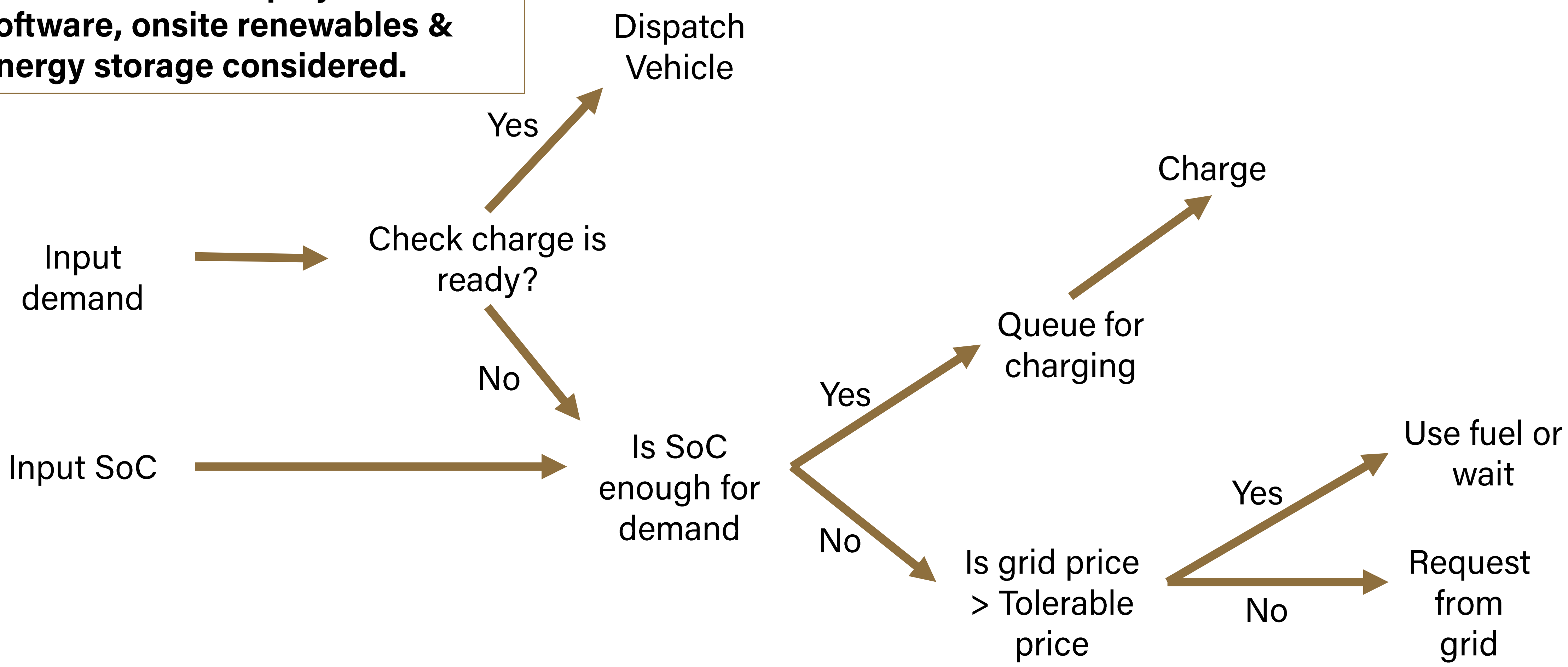
Controller Mk 1

First MVP of deployment software, no renewables considered.

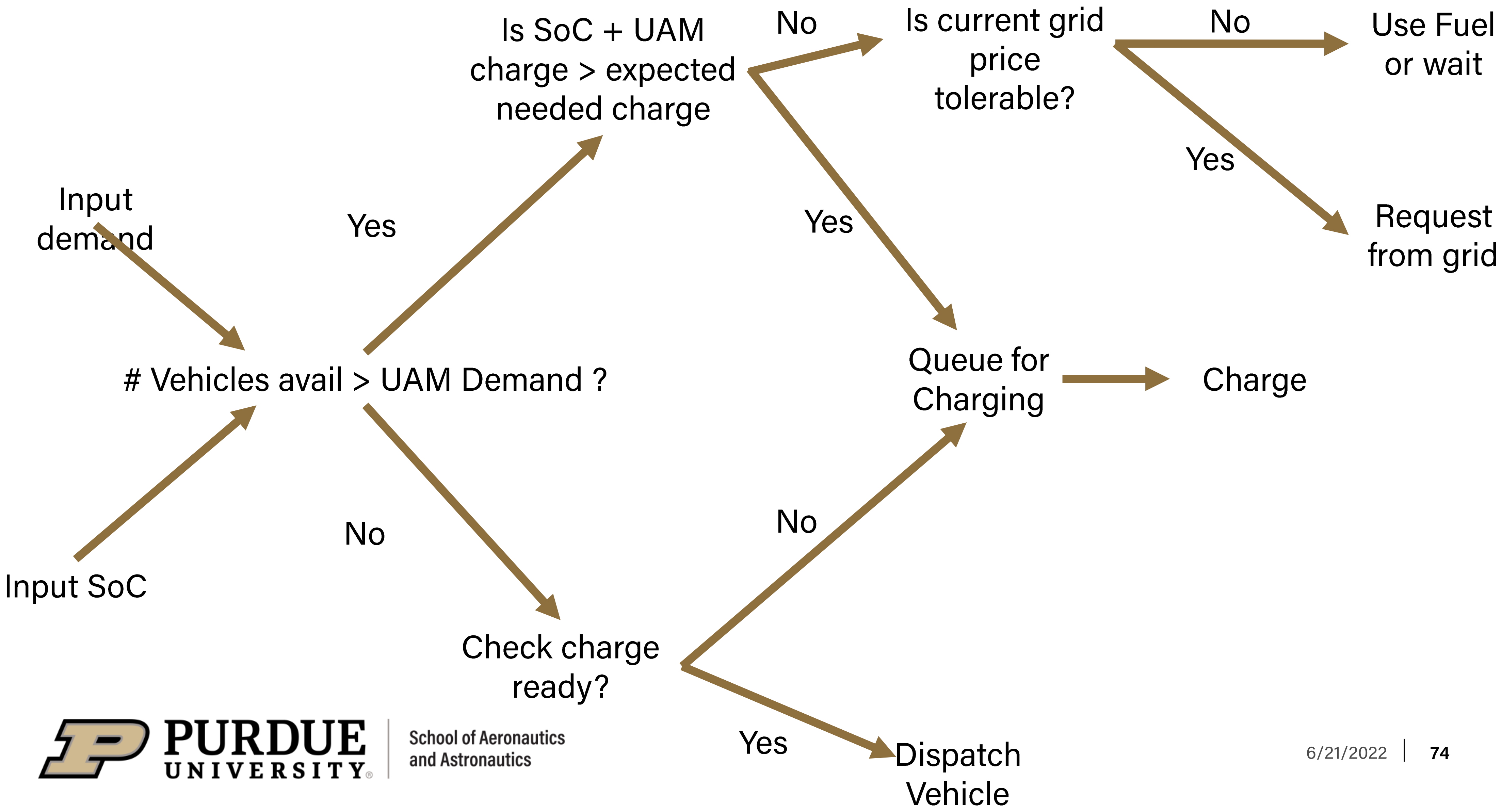


Controller Mk 1.2

Second MVP of deployment software, onsite renewables & energy storage considered.

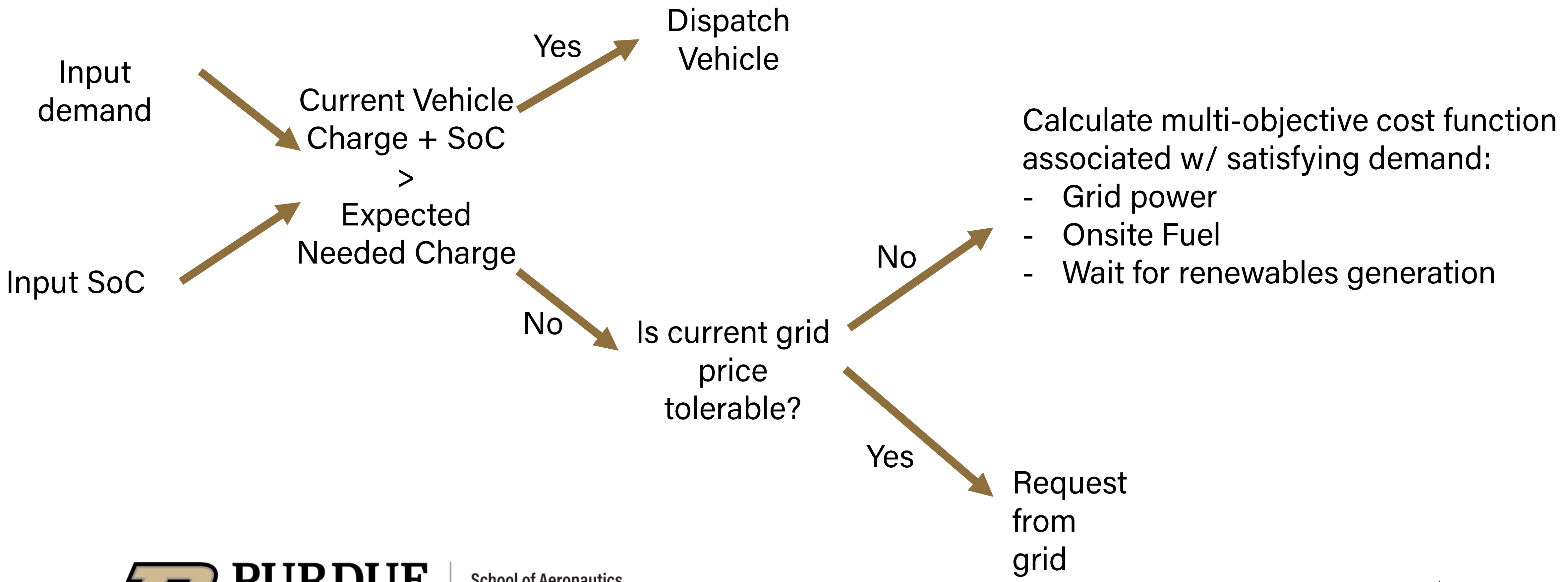


Controller Mk 3.1 – Throughput Focus



Controller Mk 3.2 – Renewables Focus

For all vehicles, prioritize dispatch of vehicles that have highest current charge



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