System-Level Urban Air Mobility Transportation Modeling and Determination of Energy-Related Constraints

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Outline

- Background
- Motivation
- Modeling Approach
- Energy Source Comparison
  - Fuels vs. Battery
  - Deep Dive: LNG vs. Battery
- Conclusions

Background

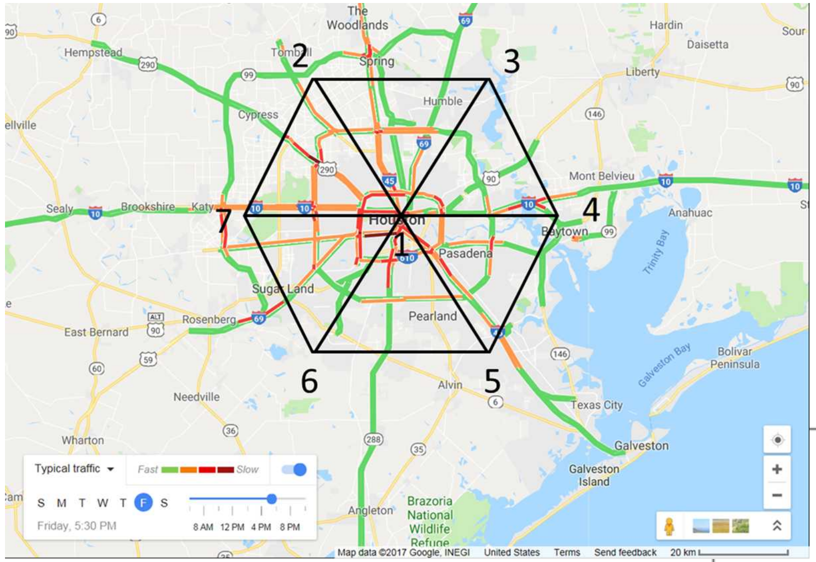
- Urban Air Mobility (UAM) refers to the transportation of people and cargo by air in a metropolitan area
- This new emerging market has the potential to transform the way people and cargo move within the urban environment
- Smaller, unconventional configurations will be needed to operate in these systems
- Emissions, noise and costs will be key to the success of these systems

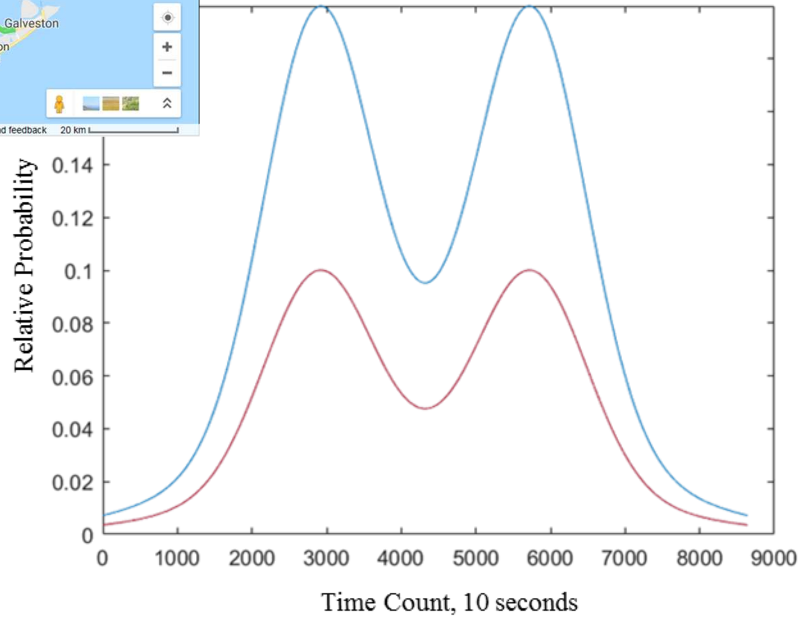
Motivation

- To better understand how choices in vehicle design and power system architecture affects network operations
- To evaluate the viability of potential energy storage and conversion systems for primary electric propulsion of UAM aircraft

Modeling Approach

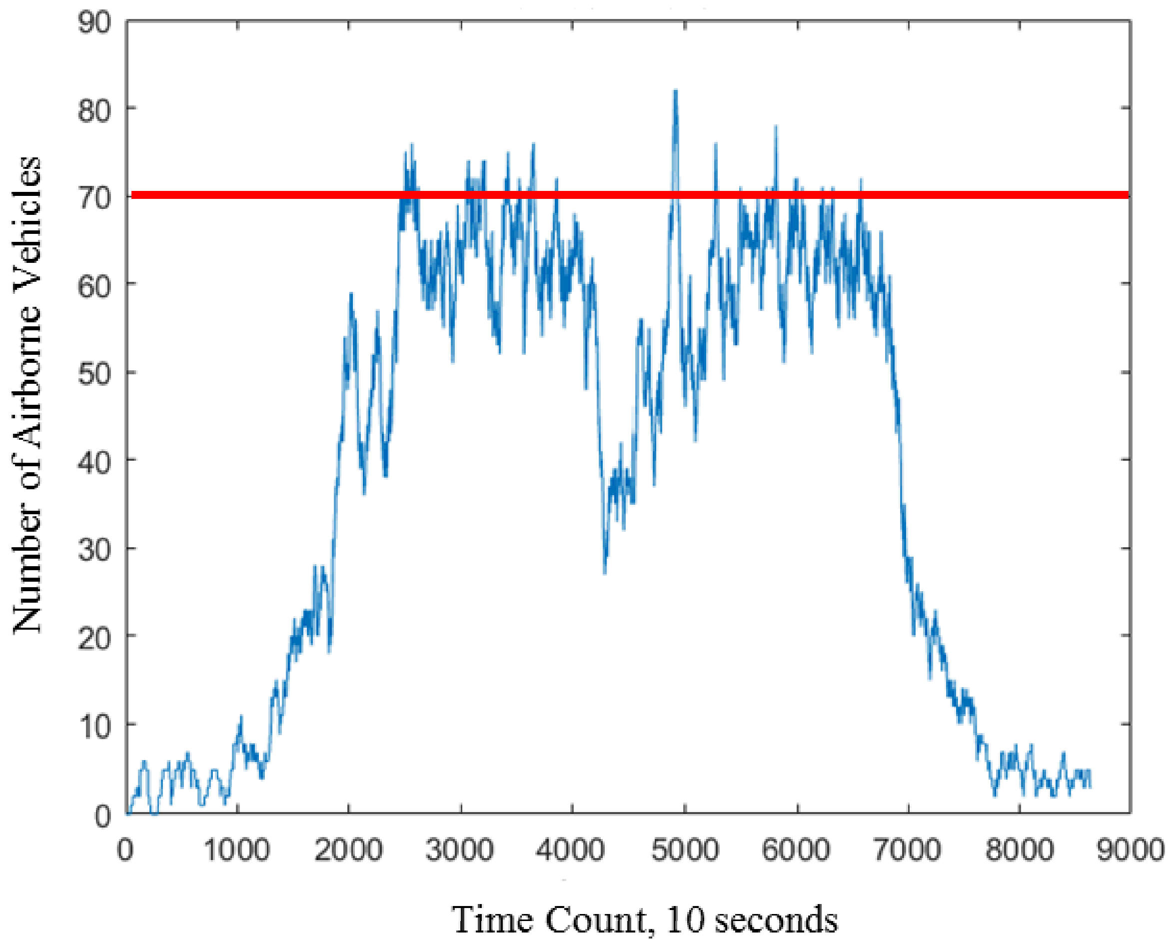
- 7 vertiport, hexagonal model for sensitivity studies
- 5 vertiport, hexagonal model for Dallas-Fort Worth/Uber parameters
- Scale model 30-50 aircraft per vertiport
- Full scale model 300-500 aircraft per vertiport
- Demand model: discrete events generated from probability curve
- More information available in the paper





Saturating Replenish Stations

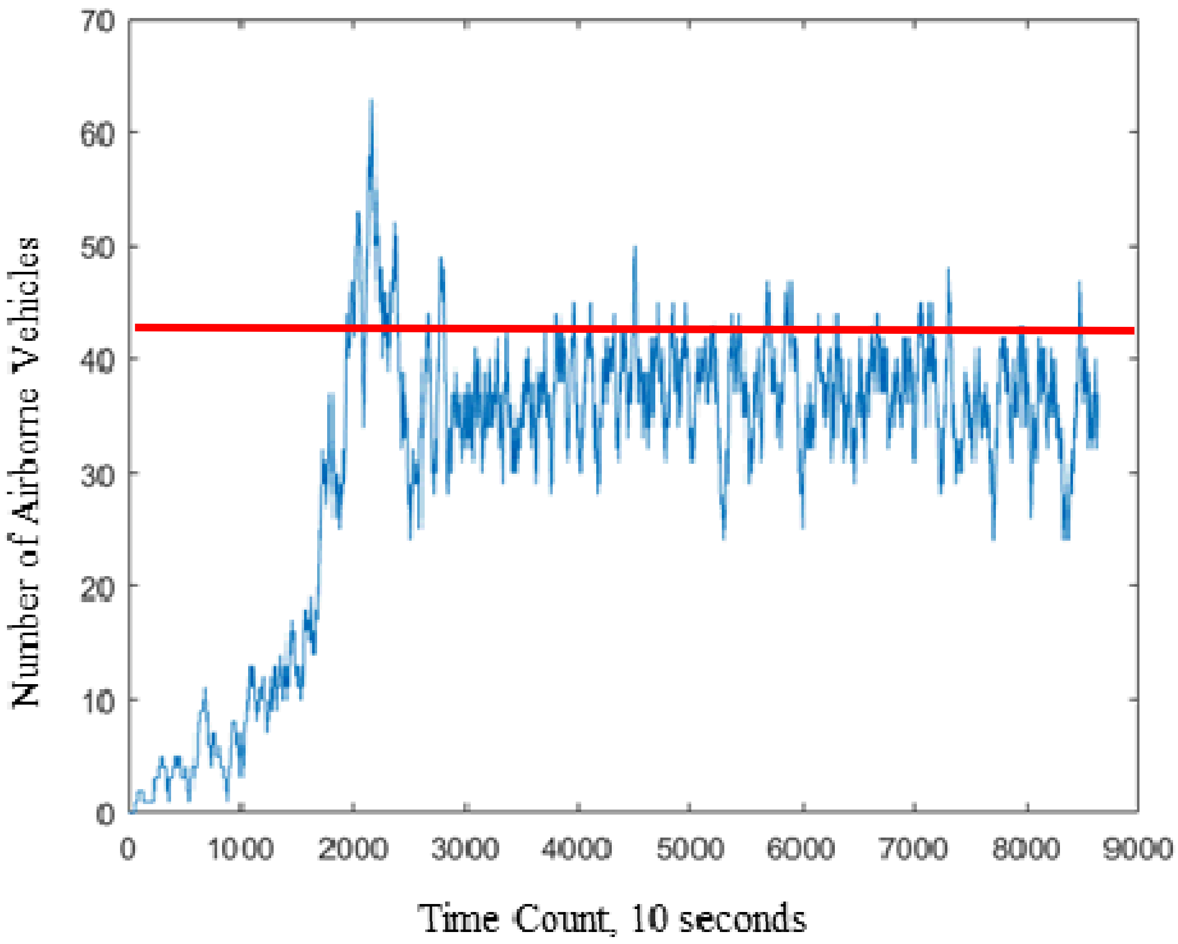
Baseline



30 aircraft per vertiport

Saturated Replenish, Impacting Ops

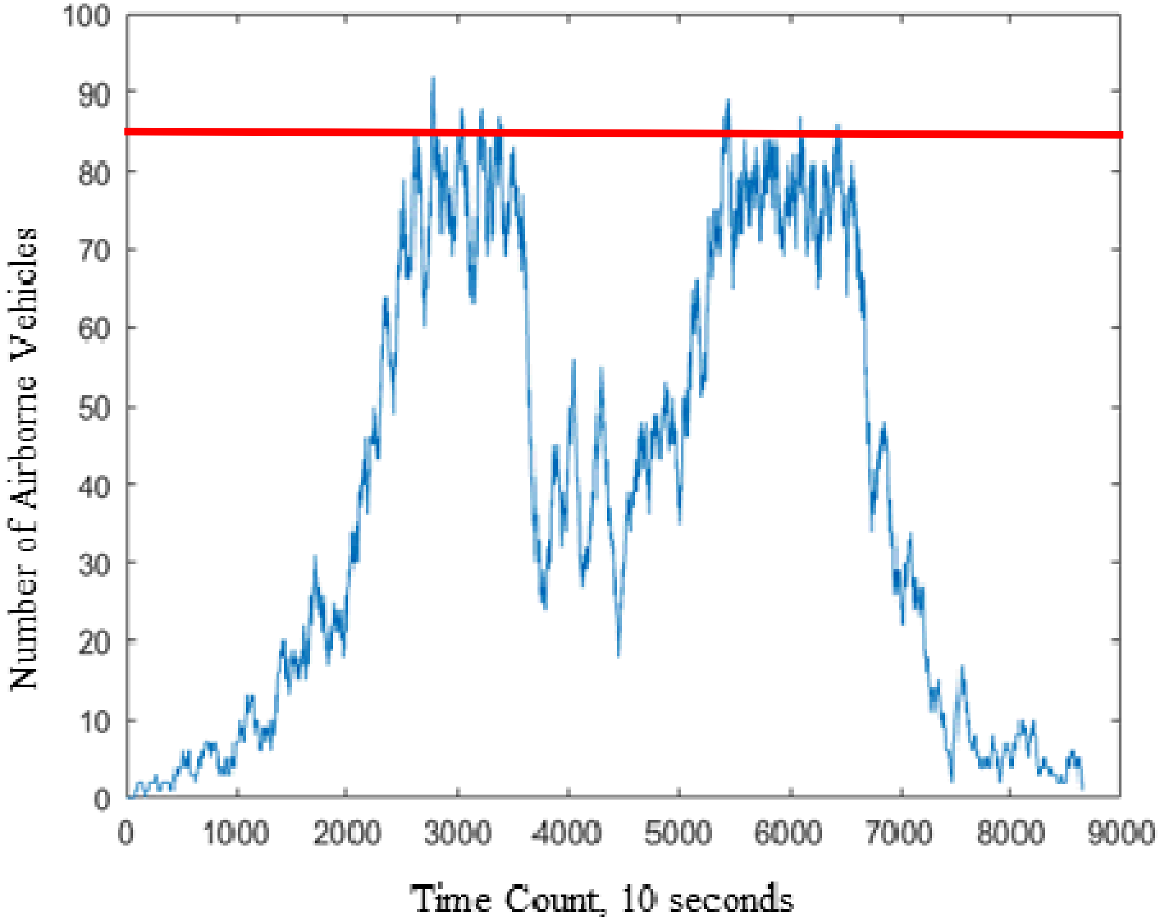
Half Replenish Rate



30 aircraft per vertiport

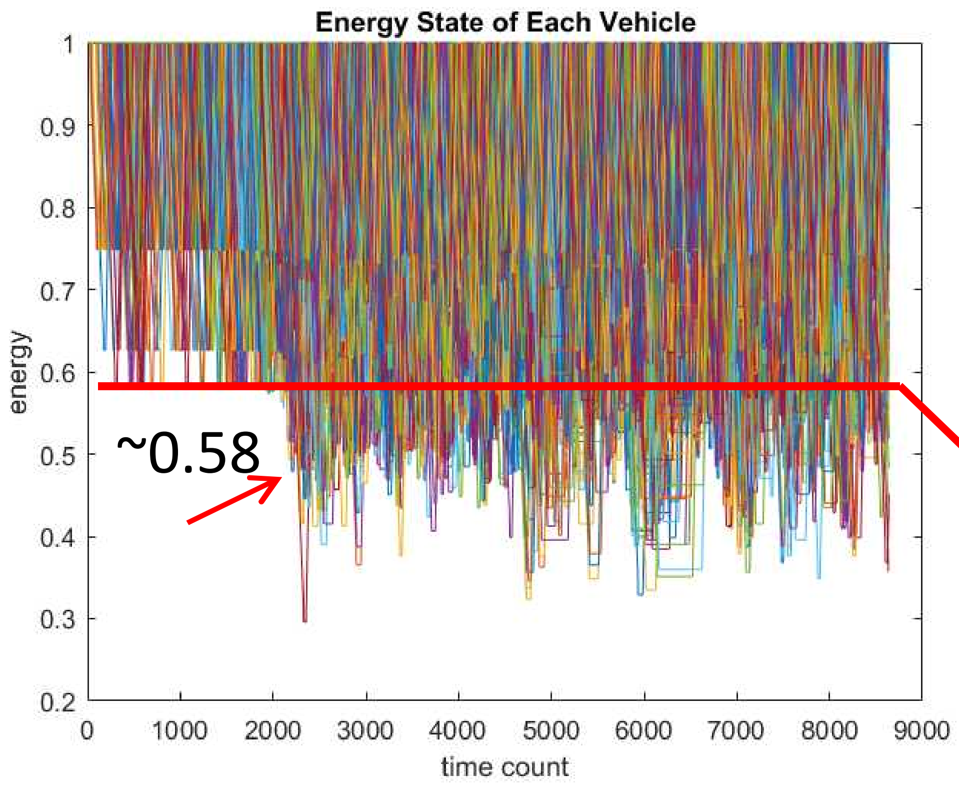
Unsaturated Ops

Double Replenish Rate

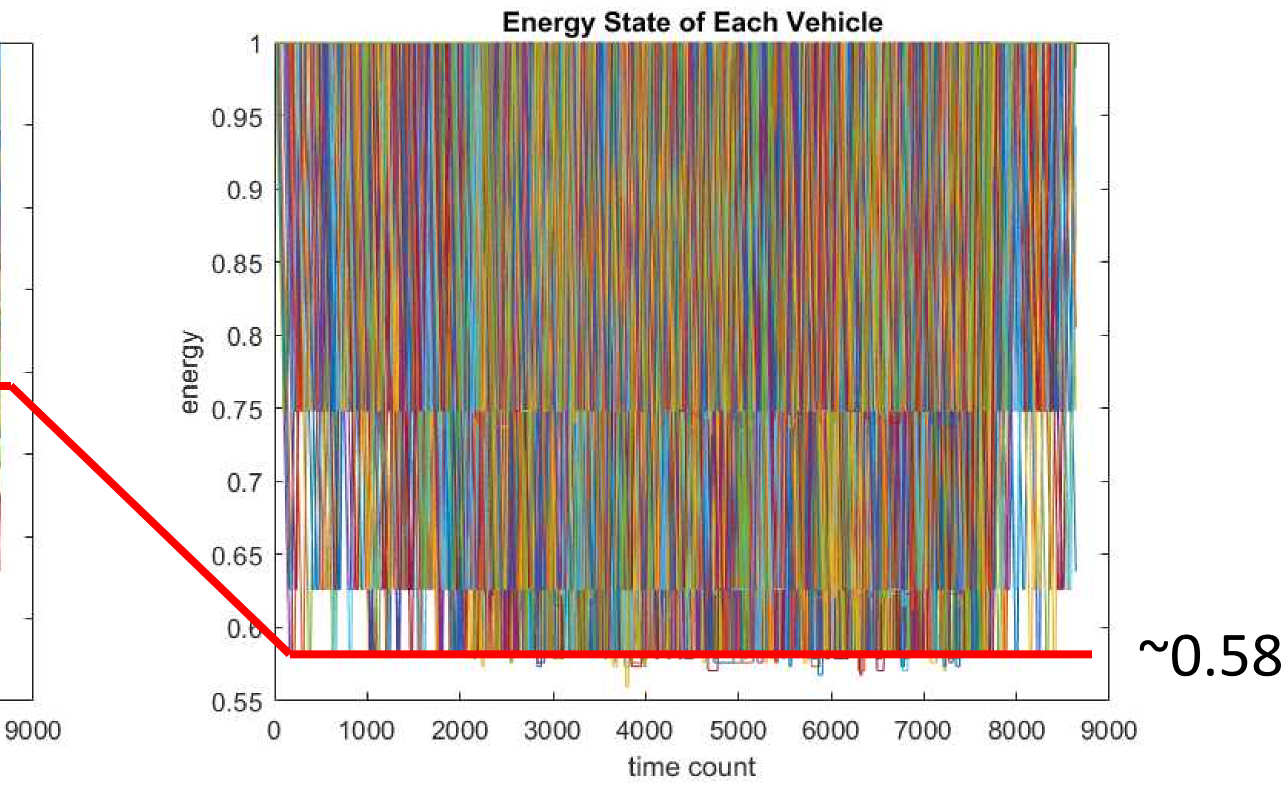


30 aircraft per vertiport

Number of Landing Pads



Baseline

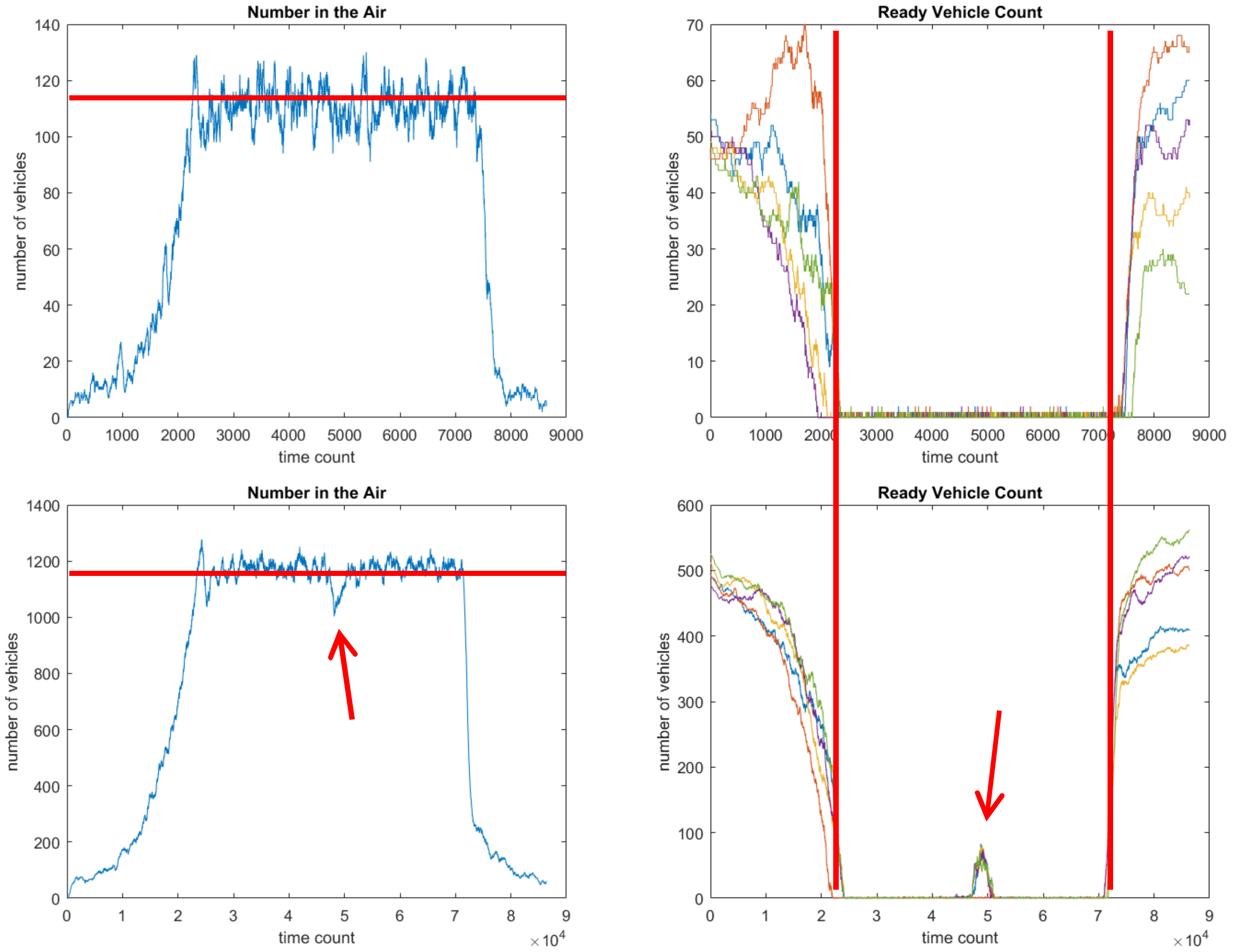


Doubled Landing Pads

Scaling Comparison

1/10th Scale

Full Scale

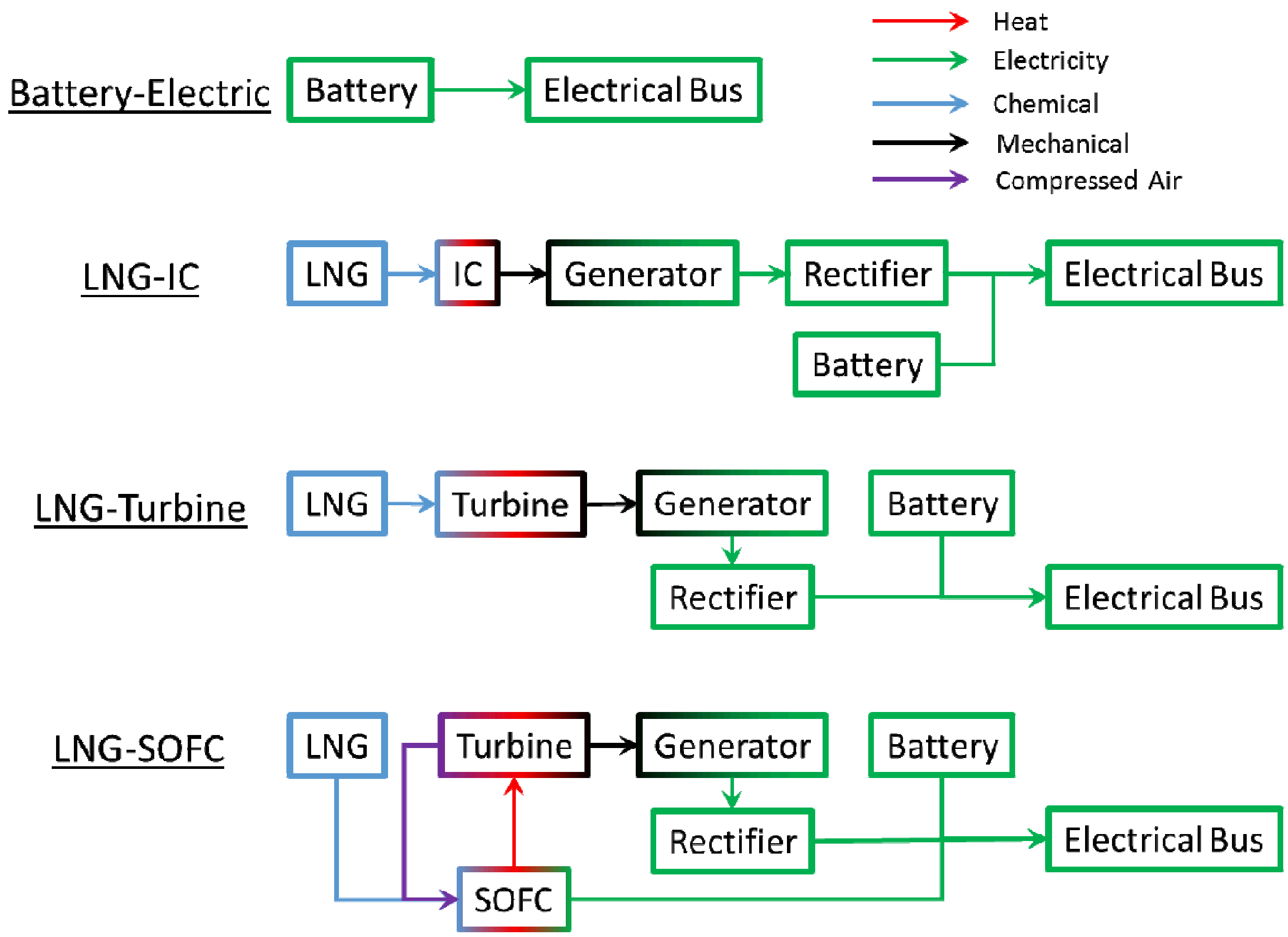


40 aircraft per vertiport

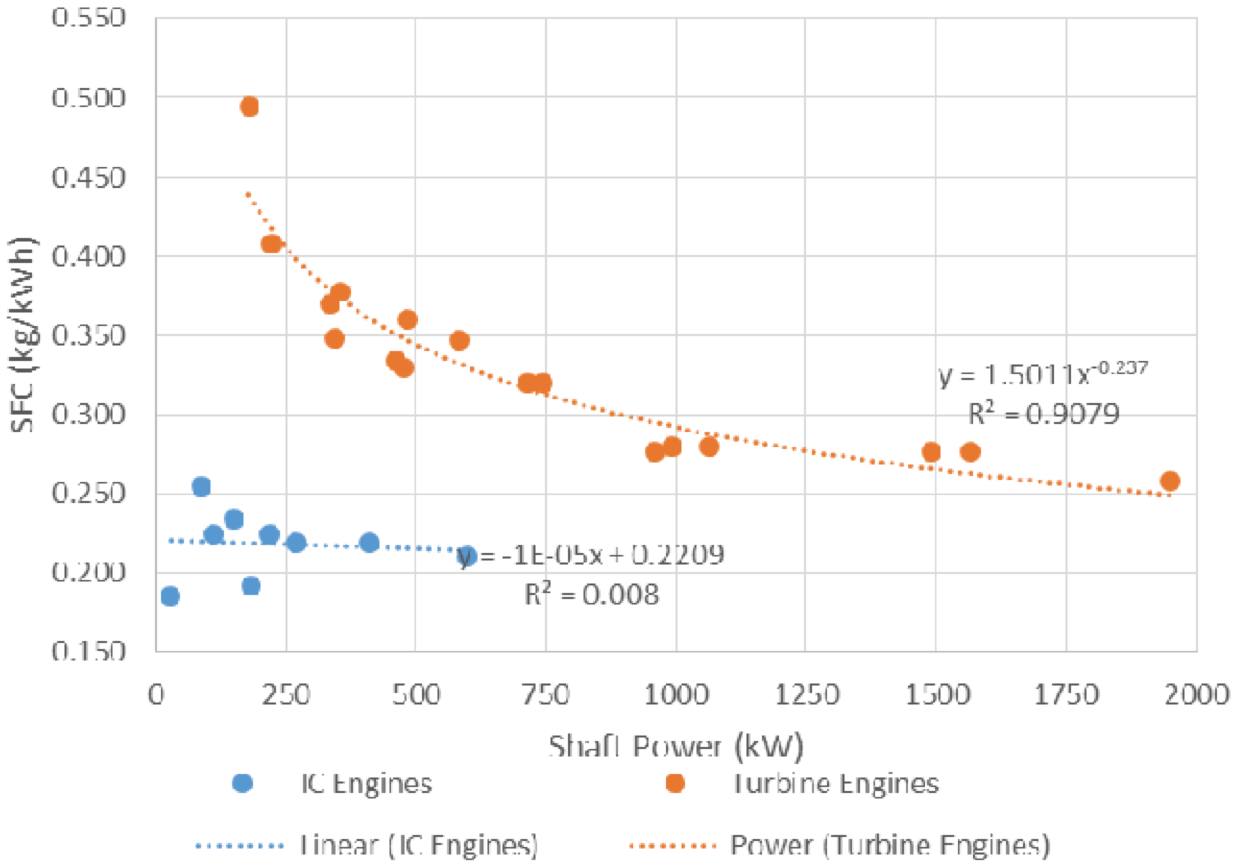
400 aircraft per vertiport

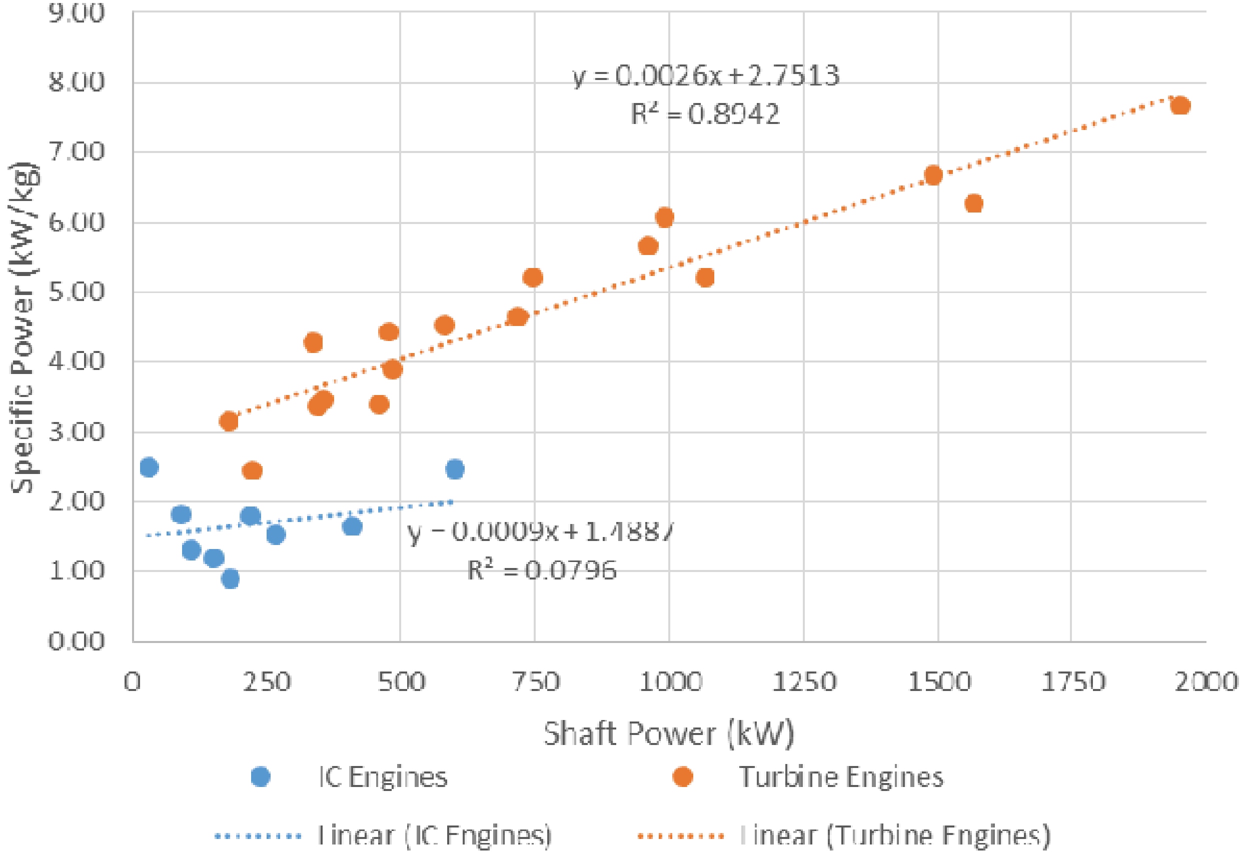
Energy Source Comparison: Fuel vs. Battery

UAM Power Sources: Battery vs. Hybrid



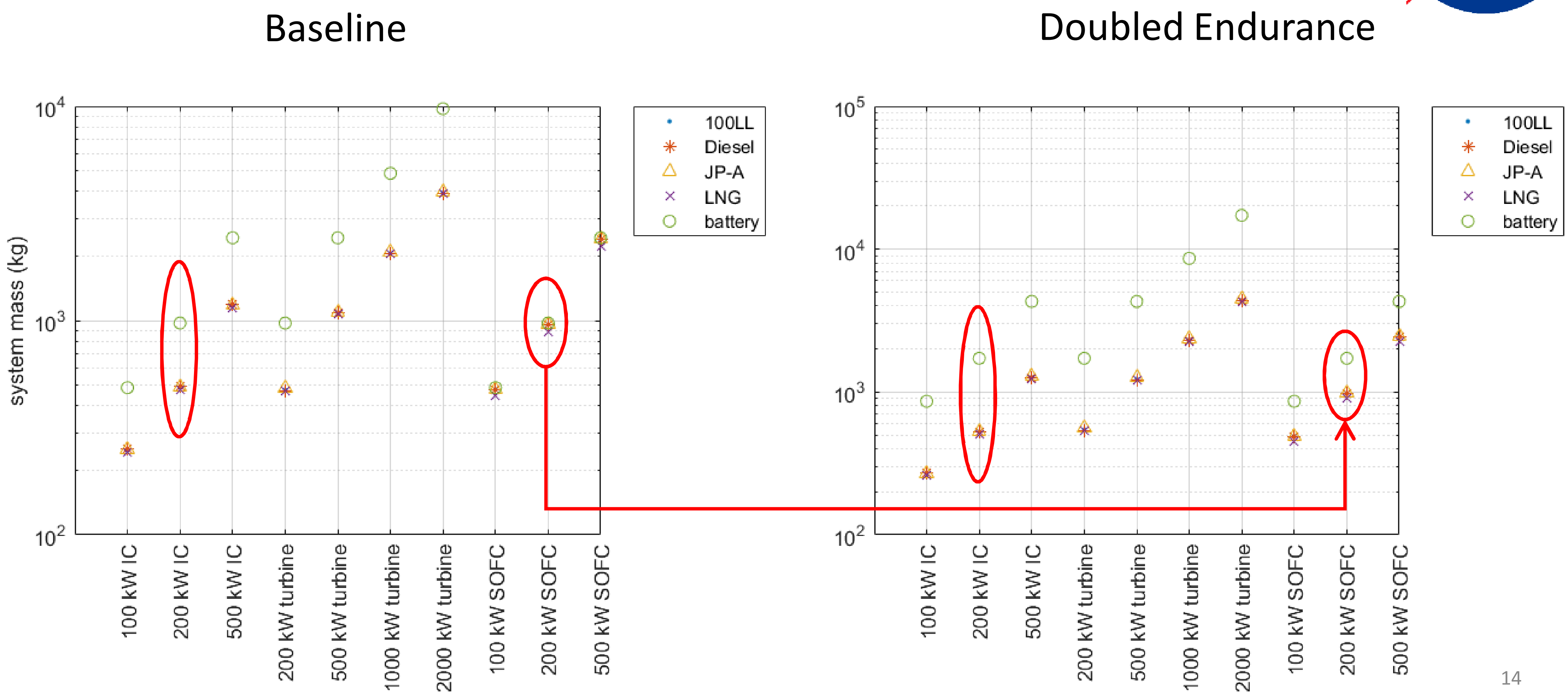
Engine/Turbine Modeling



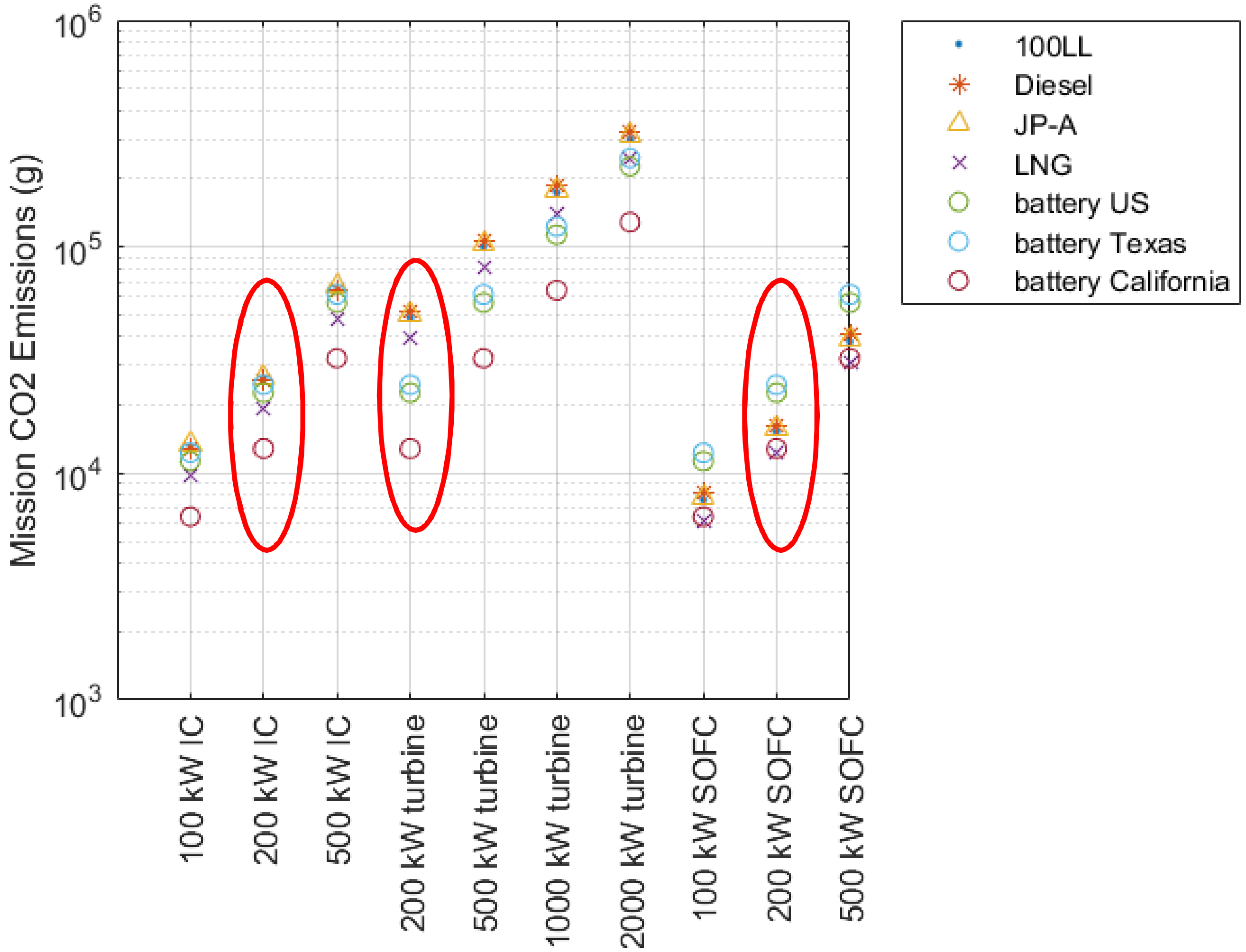


Data provided by Jim Felder, NASA Glenn Research Center

System Mass: Doubling Endurance



CO2 Emissions



Modeling Results: Fuel and Electricity Usage

	100 kW IC	200 kW IC	500 kW IC	200 kW Turbine	500 kW Turbine	1000 kW Turbine	2000 kW Turbine	100 kW SOFC	200 kW SOFC	500 kW SOFC
100-LL (L)	5.47	10.92	27.21	20.52	42.31	73.14	126.4	3.22	6.43	16.1
Diesel (L)	4.83	9.65	24.05	19.60	40.42	69.87	120.8	3.07	6.15	15.4
JP-A (L)	5.00	9.99	24.88	18.76	38.69	66.88	115.6	2.94	5.88	14.7
LNG (L)	7.79	15.56	38.79	31.61	65.18	112.7	194.8	4.96	9.91	24.8

	100 kW	200 kW	500 kW	1000 kW	2000 kW
Battery Energy (MJ)	78	156	390	780	1560

System Fuel Usage

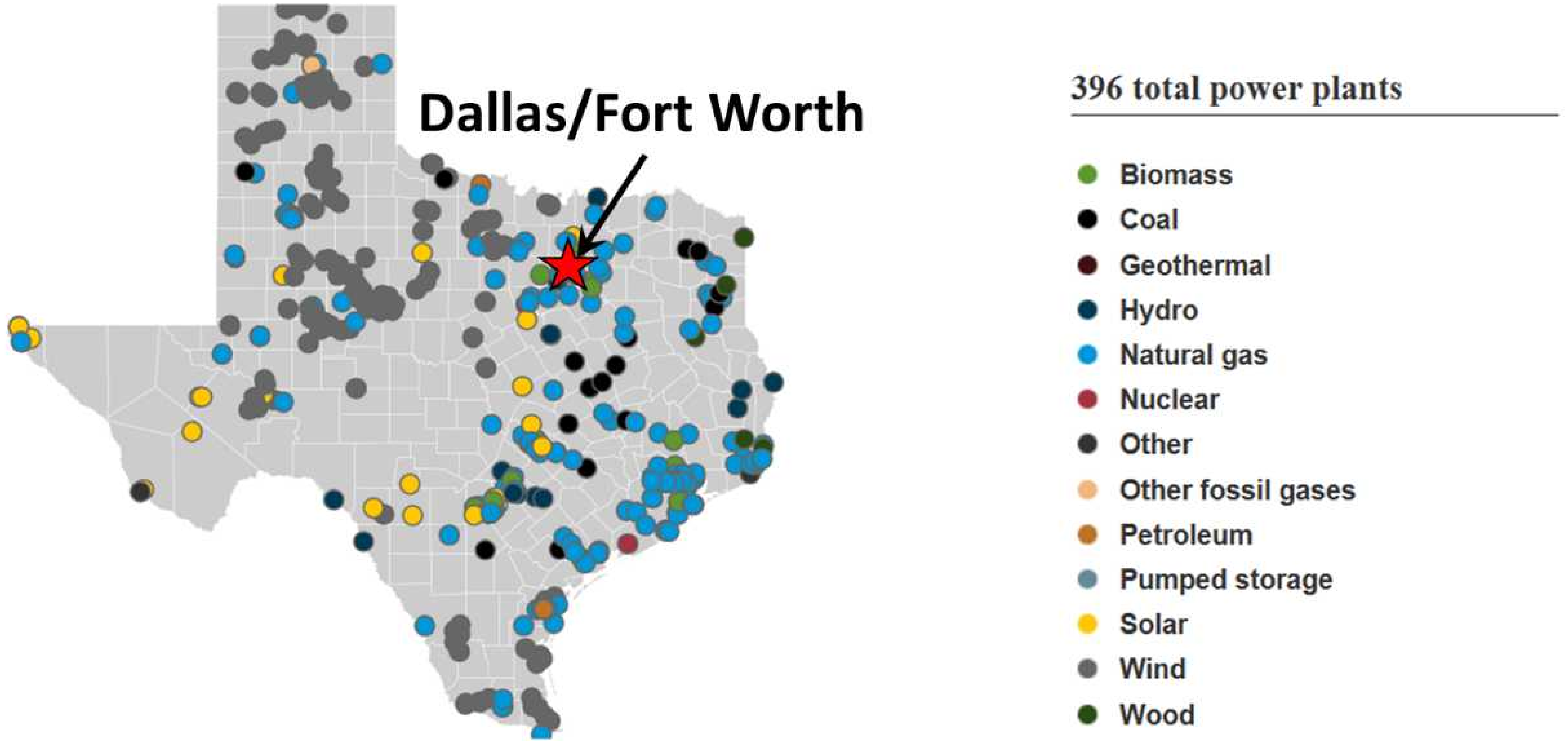
	AvGas 100LL	Ultra-Low Sulfur Diesel	JP-A	LNG	Electricity
200 kW IC 40 km mission fuel volume/energy (L/MJ)	10.92/373	9.65/345	9.99/374	15.56/345	209/156
Average mission volume/energy (L/MJ)	13.61/465	12.03/431	12.45/466	19.39/430	260/194
Energy used for 15,000 missions	53,931 Gal	47,670 Gal	49,334 Gal	76,834 Gal	808,333 kWh
Energy used for 75,000 missions	269,655 Gal	238,350 Gal	246,670 Gal	384,170 Gal	4,041,665 kWh
Number of 9000 Gallon Tanker Deliveries	30	27	28	43	--
Price per Unit ($/Gal, $/kWh)	$2.99 [28], premium	$2.93 [28]	$2.83 [28]	$1.50 [26], [27], [29]	$0.13 [26]
Energy Operating Cost per Day	$806,268	$698,365	$698,076	$576,255	$525,416
CO_2 per Day (kg)	2,419,235	2,393,470	2,496,940	1,811,150	2,178,455

LNG: slightly higher cost (%9.7), lower CO_2 (17%)

[26] Alternative Fuels Data Center, "Fuel Prices," [Online]. Available: https://www.afdc.energy.gov/fuels/prices.html. [Accessed 27 November 2017].
[27] Alternative Fuels Data Center, "Clean Cities Alternative Fuels Price Report," [Online]. Available: https://www.afdc.energy.gov/uploads/publication/alternative_fuel_price_report_july_2017.pdf. [Accessed 29 November 2017].
[28] U.S. Energy Information Administration, "Data, Weekly Retail Gasoline and Diesel Prices," [Online]. Available: https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm. [Accessed 1 December 2017].
[29] Prometheus Energy, "LNG Quick Facts," [Online]. Available: http://www.prometheusenergy.com/_pdf/LNGQuickFacts.pdf. [Accessed 1 December 2017].

Energy Source Comparison: Deep Dive LNG vs. Battery

Existing DFW Power Sources

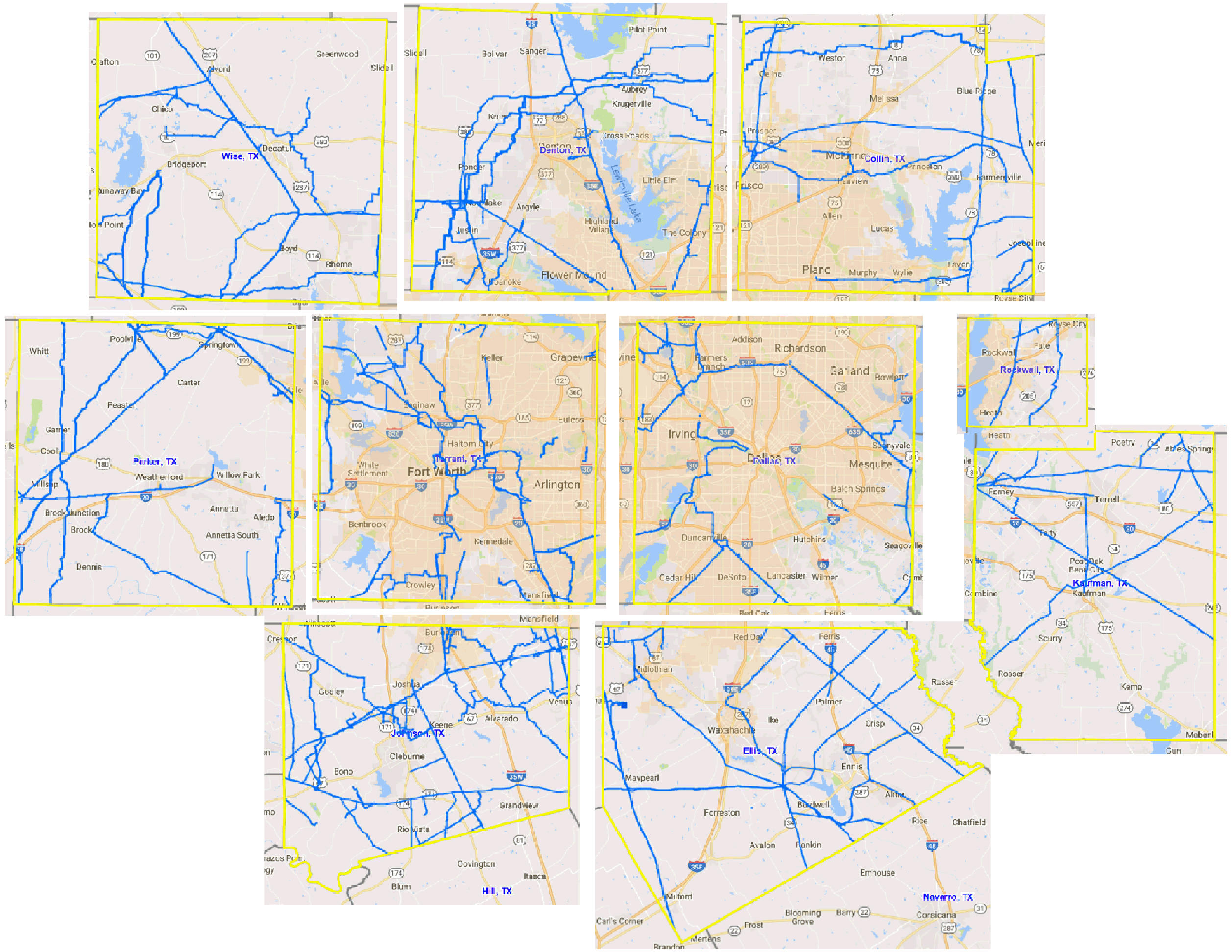


U.S. Energy Information Administration, "Electricity Data Browser," [Online]. Available: https://www.eia.gov/electricity/data/browser/. [Accessed 1 December 2017].

Cost of New Electricity Generation

Vehicle Cruise Power	100 kW	200 kW	500 kW	1000 kW	2000 kW
Lm Length (40 km) Mission Energy (MJ)	78	156	390	780	1560
Power for five minute recharger (kW)	260	520	1300	2600	5200
Power for one vertiport with 160 five minute rechargers(MW)	41.6	83.2	208	416	832
Total power for five vertiports (full model) each with 160 five minute rechargers (MW)	208	416	1040	2080	4160
Number of additional 237 MW Advanced Combined Cycle Natural Gas (NG) Plants	1	2	5	9	18
Total NG Installation Cost ($M 2016)	$159M	$319M	$795M	$1431M	$2862M
Number of additional 100 MW wind power installations	2	4	11	19	37
Total Wind Installation Cost ($M 2016)	$337M	$674M	$1854M	$3202M	$6235M

Natural Gas Pipelines in Dallas/Fort Worth



Cost of LNG Plant

Capacity	Pretreatment and Liquefaction	Construction, Installation, Storage	Total Installed Cost
10,000 gallons/day[m]	$5-8M	$5-12M	$10-20M
50,000 gallons/day*[m]	$12-15M	$12-22.5M	$24-37.5M
75,000 gallons/day[c]	$20M	$20M	$42M
150,000 gallons/day^[m]	$22-25M	$22-37.5M	$44-62.5M
250,000 gallons/day[c]	$42M	$33-38M	$75-80M
375,000 gallons/day	$63M (est.)	$57M (est.)	$120M (est.)
*minimum recommended size, ^minimum recommended economic size [m]numbers provided by MicroLNG (Ref. [40]) [c]numbers provided by Chart Industries (Ref. [38])			

[38] L. Hallas, Interviewee, *Chart, LNG Refueling Correspondence.* [Interview]. 8 January 2018.
[40] W. Livingston, Interviewee, *President of MicroLNG: Email Conversation on LNG Production.* [Interview]. 11 December 2017.

Cost of LNG Fuel

Cost Component	Price $/Gal (High)	Price $/Gal (Low)	Used in Calculation
Natural Gas 375,000 Gal/day	$0.70	$0.32	$8.48 commercial/$3.89 industrial per 1000 cu feet [41] 82.6 cu feet/Gal [29]
Amortized Installation 5 year, 10% interest, 95% utilization	$0.40	$0.22	Ref. [42], estimate from page 7
Electricity @ 1 kWh/Gal	$0.1043	$0.0533	High estimate: US average commercial price, Low estimate: Texas industrial [40]
Labor (two workers 24 hrs/day and two workers 12 hrs/day at $30/hr)	$0.03	$0.03	Estimate (LNG plant only, not refueling pumps)
Maintenance and operations	$0.073	$0.037	Estimate high $2M/year, low $1M/year
Total Near Term	$1.31	$0.66	
Total Long Term	$0.91	$0.44	Remove Amortization
Current Retail	$1.50		See Table 7

[29] Prometheus Energy, "LNG Quick Facts," [Online]. Available: http://www.prometheusenergy.com/_pdf/LNGQuickFacts.pdf. [Accessed 1 December 2017].
[40] W. Livingston, Interviewee, *President of MicroLNG: Email Conversation on LNG Production.* [Interview]. 11 December 2017.
[41] U.S. Energy Information Administration, "Natural Gas," [Online]. Available: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm. [Accessed 11 December 2017].
[42] MicroLNG, *Kilotherm Natural Gas Processing, MicroLNG Natural Gas Liquefaction,* Athens, Georgia, 2017.

Energy Cost for 200kW System

Region	Residential	Commercial	Industrial	Transportation
National	12.55	10.43	6.76	9.63
Texas	10.99	8.26	5.33	7.92
California	17.39	15.07	11.92	9.80
New York	17.58	14.45	6.03	12.05

Cents/kWh

200 kW Power System	Electricity High	Electricity Low	LNG High w/ IC	LNG Low w/ IC	LNG High w/ SOFC	LNG Low w/ SOFC
Mission use	43.3 kWh[A]	43.3 kWh[A]	4.11 Gal[B]	4.11 Gal[B]	2.62 Gal[B]	2.62 Gal[B]
Price per unit	$0.15/kWh[C]	$0.05/kWh[D]	$1.31/Gal[E]	$0.44/Gal[F]	$1.31/Gal[E]	$0.44/Gal[F]
Mission Price	$6.53	$2.31	$5.38	$1.81	$3.43	$1.15
Mission length (km)	40	40	40	40	40	40
Cents/km	16.3	5.77	13.46	4.52	8.58	2.88

[A] from Table 4, 200 kW vehicle, includes conversion from MJ to kWh
[B] from Table 3, 200 kW vehicle, includes conversion from L to Gal
[C] from Table 10, highest average of “Commercial” (California)
[D] from Table 10, lowest average of “Industrial” (Texas)
[E] from Table 9, high estimate with amortization
[F] from Table 9, low estimate without amortization

Charging vs. Refueling

Replenish Type	Recharge	Refuel
Rate	450 kW	50 Gal/min
Time to replenish vehicle	5.8 min	1.47 min (IC)
Cruise Flight Time	10 min	180 min
State of Development	In development	Commercially available
Preferred operational model	Distributed	Centralized Depot
Unit Cost Estimate	$450k/charger [46]	$2.25M for 15 pump station [38]
Units Required	~160	1 (2)
Total Cost Per Vertiport (500 Vehicles)	$72M	$2.25M ($4.5M)

Conclusions

- Network modeling is critical to understanding the impact of vehicle design choices on the overall system operation
  - Replenishment rate and frequency will have a large impact on availability of aircraft
  - Takeoff and landing pads are critical potential bottlenecks in the system
- LNG is a competitive option for energy storage onboard UAM aircraft
  - The CO2 emissions are potentially lower than battery
  - The energy cost is potentially lower than battery
  - The technology has been developed to TRL 9 in ground transportation
  - The infrastructure costs are lower than for battery

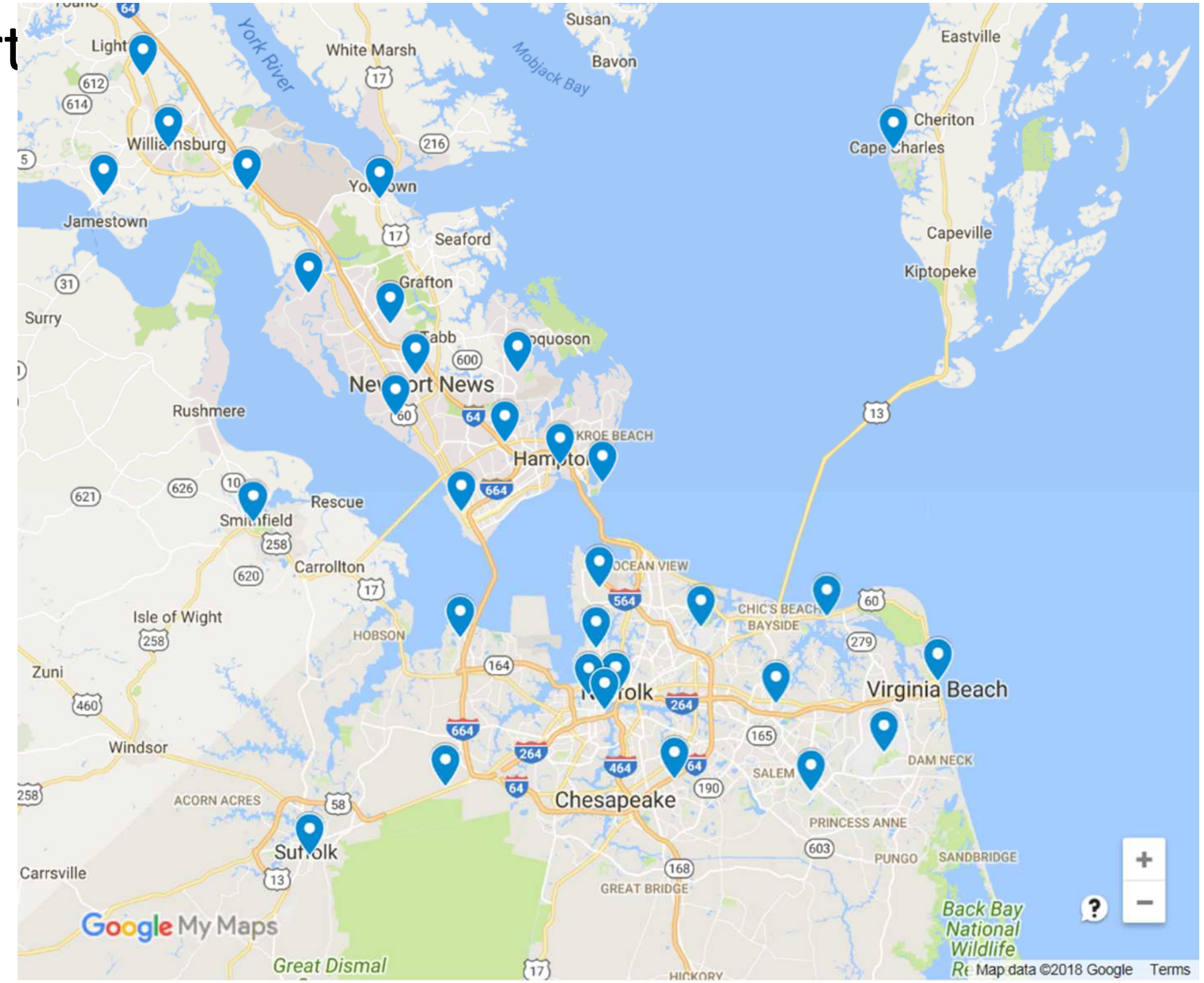
Acknowledgements

- We would like to acknowledge the Revolutionary Vertical Lift Technologies project and the FUELEAP project for supporting this work.

The End.

New Model Capabilities

- KML GPS coordinate file import
- Distributed replenish and depot based replenish



New Demand Models

- A person object “lives” at one port and “works” at another
  - A request is generated in the morning from “live” to “work”
  - A request is generated in the afternoon from “work” to “live”
- A person object originates at one port and requests a flight to a random port
- A person is either located at an airport or wants to travel to an airport, the non-airport end of the trip is randomly selected.
- Both churn (random movement of people) and flow (bulk movement in a similar direction) can be simulated

Model Structure