INL/CON-23-76011-Revision-0

# Droning on to Delivery: Examining the Energy Impacts of Using Drones for Moving Goods

February 2024

Changing the World's Energy Future

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Idaho National Laboratory

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**February 2024**

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**U.S. Department of Energy**
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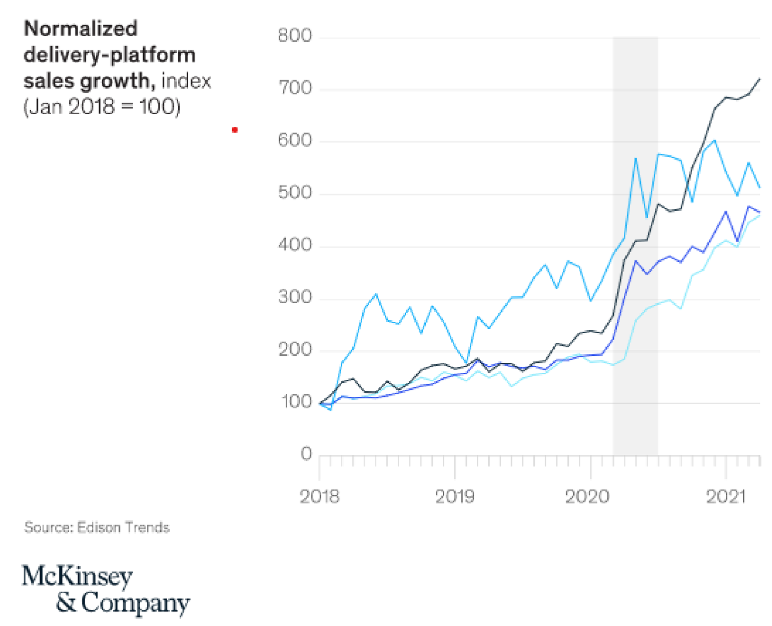
# Droning on to Delivery

## Examining the Energy Impacts of Using Drones for Moving Goods

## Approach

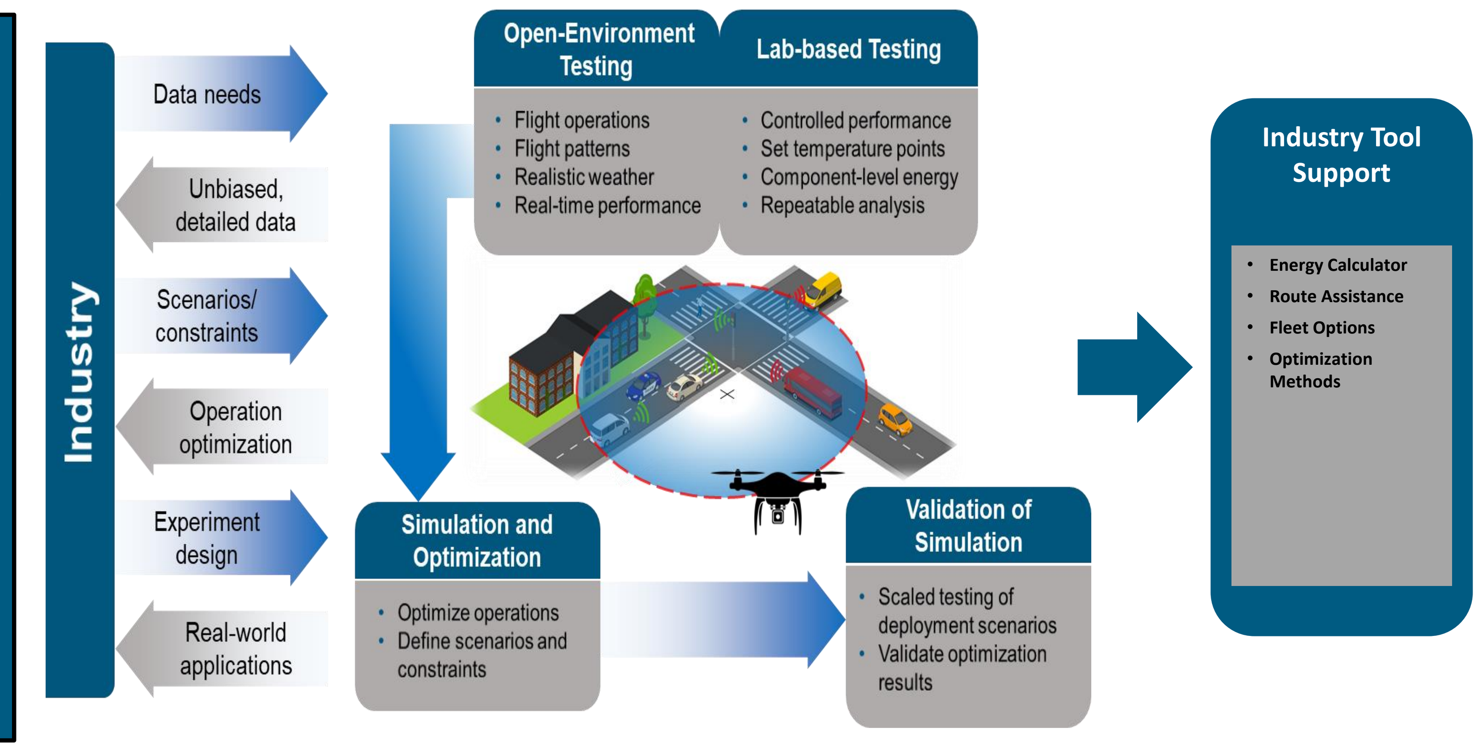
- Provides a solution for "Microfreight"
  - Localized delivery of items such as *prepared food, groceries, prescriptions, Cheez-its.* (five-fold increase in *food delivery* since 2018).
  - Industries include *Healthcare, Restaurants, Grocery, Home Goods, Distribution, etc.*
  - Business to Consumer or Business to Business.
- Solution offers "air advantages" to local delivery.
  - Better direct routing without road network
  - Faster local speeds with reduced congestion
  - Increased autonomous capabilities
- Drone delivery can apply to urban and rural environments

Since pandemic-related lockdowns started in March 2020, the growing food-delivery business has spiked to new heights in the most mature markets.




Inhibiting S's:
- Standards (Regulation)
- Safety
- Secrecy (Privacy)
- Sound

New Technologies → several uncertainties & unknowns
Industry & public interest → need for unbiased information
Opportunities → need for understanding of impacts
Complicated deployment → understand connections
Technology differences → drone studies
Large scale deployment → large scale energy impact
Innovation → begins by identifying problem or opportunity
Expansion → expanding potential application areas




## Comparing different drone types

**Drone 1 – Large Rotary**
- DJI Matrice 600 Pro
- Hexacopter (6 Propellers)
- 21 pounds w/ battery
- Payload up to 13 lbs.
- Max speed 40 mph
- ~10 Mile range
- 5.4 x 5.0 x 2.4 ft

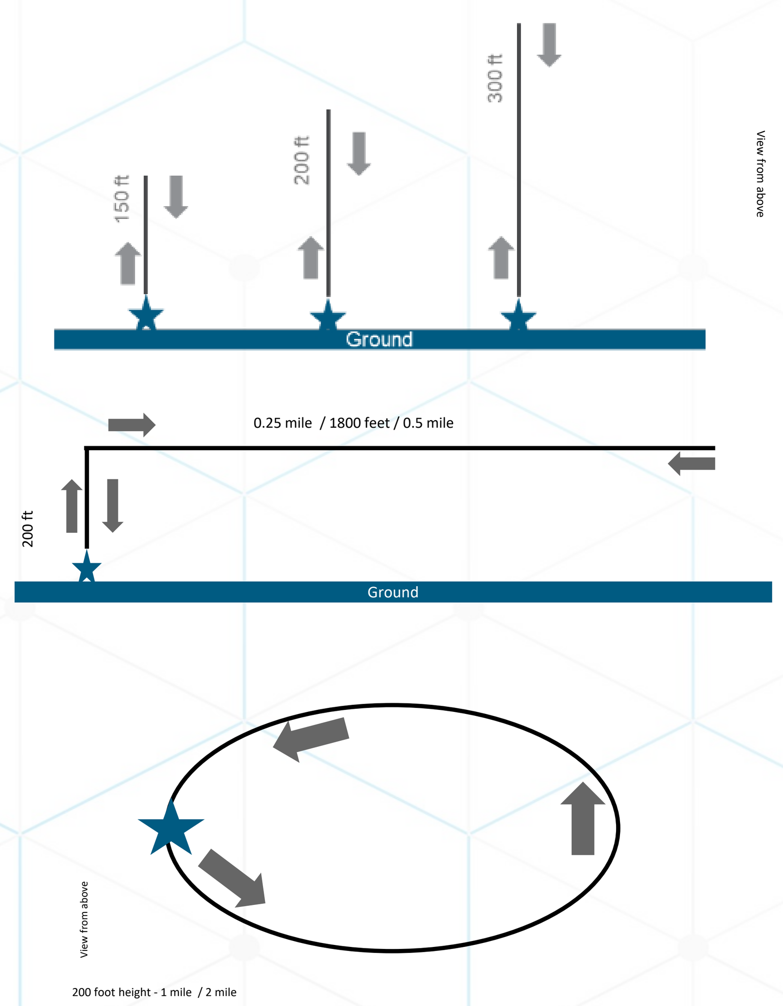
**Drone 2 – Small Rotary**
- Tarot 650
- Quadcopter (4 Propellers)
- 7.8 pounds w/ battery
- Payload up to 3.3 lbs.
- Max speed 32 mph
- ~2.5 mile range
- 1.7 x 1.7 x 1.1 ft

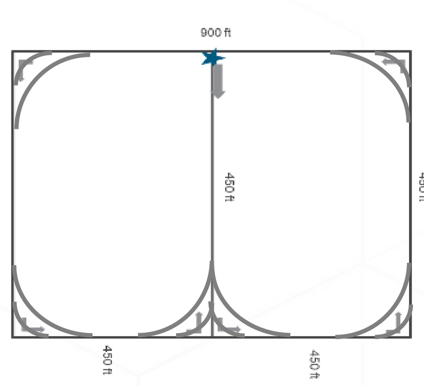
**Drone 3 – Large VTOL**
- Wingcopter 198
- 8 propellers – 4 rotating
- ~44 pounds w/ battery
- Payload up to 13 lbs.
- Cruising speed 60 mph
- ~60 Mile range
- 6.5 x 5.0 ft

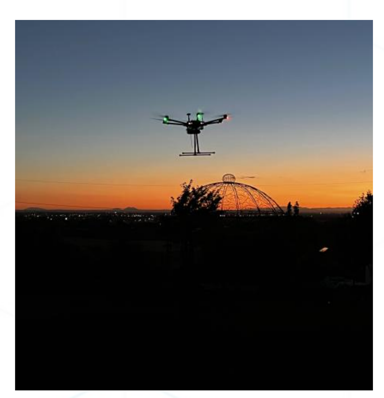
**Drone 4 – Small VTOL**
- Wing Drone1
- 12 hover propellers – 2 forward
- ~11.4 pounds w/ battery
- Payload up to 3 lbs.
- Cruising speed 55 mph
- ~12 Mile range
- 4.3 x 3.3 ft

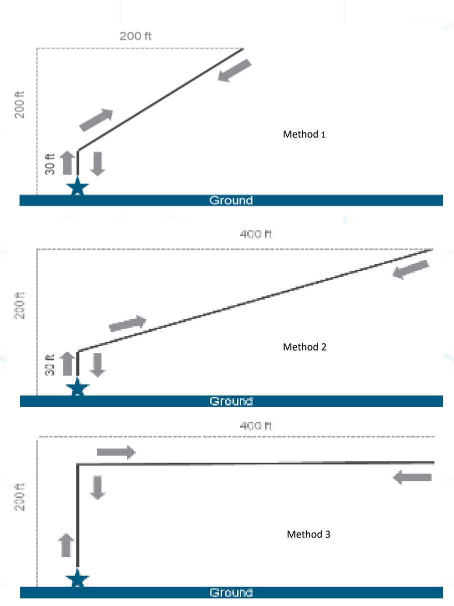
## Methods

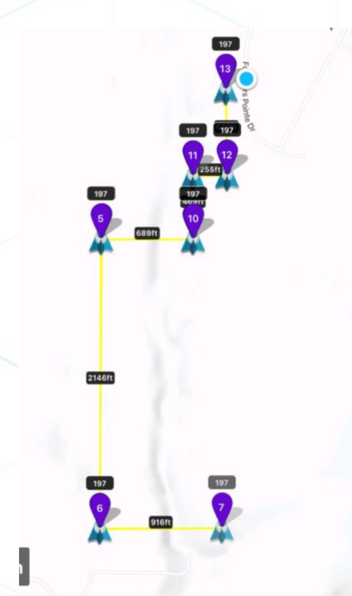
### Outdoor Testing



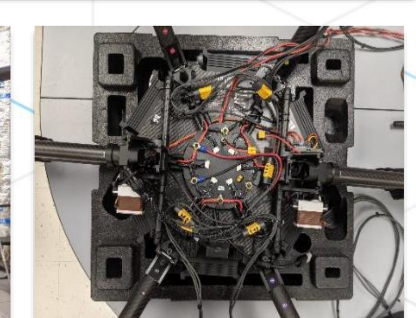







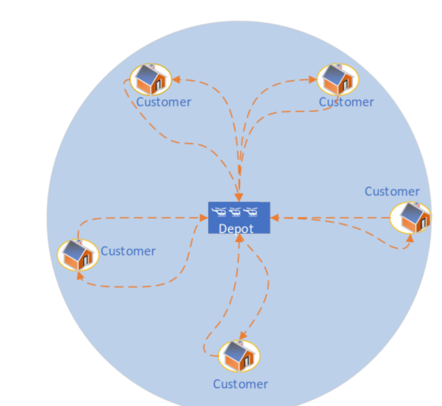
### Lab Testing

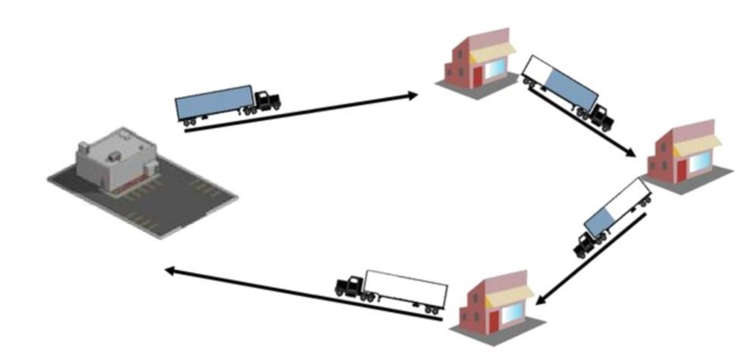


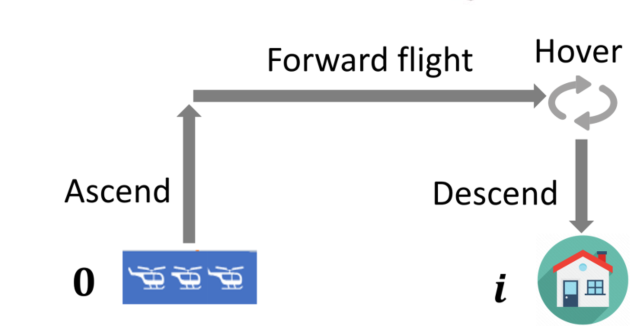
- **Force Sensor**
  - Nordbo Robotics NRS-6050-D80 sensor for lift force feedback
- **HIOKI Power Analyzer and Current Clamps**
  - Total battery power output
  - Accessories power consumption
- **Lab Environmental Conditions**
  - Temperature
  - Pressure
  - Humidity

### Modeling

- Novel data-driven mixed-integer programming models for routing drone-only and mixed drone-vehicle fleets
- Accounts for real-life aspects: release and due times, endogenous drone battery replacement
- Valid inequalities to remove inferior candidate routes
- Machine learning (Agglomerative clustering) algorithm to efficiently solve the fleet optimization problems
  - Three features: latitude, longitude, and package ready time.









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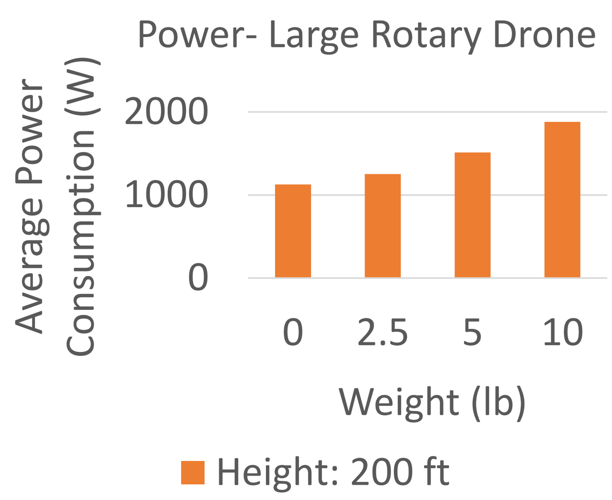
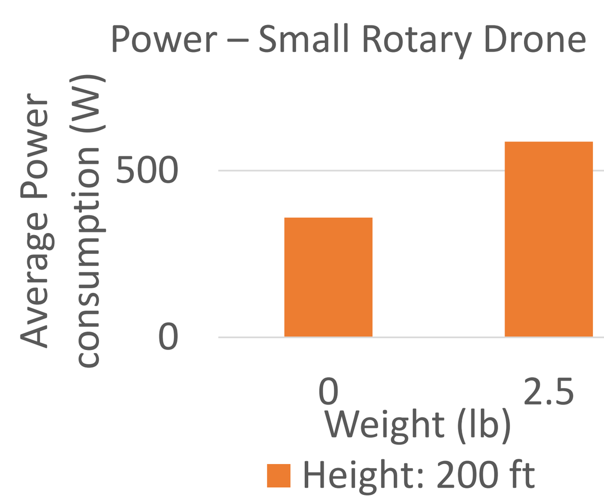
# Droning on to Delivery

## Examining the Energy Impacts of Using Drones for Moving Goods

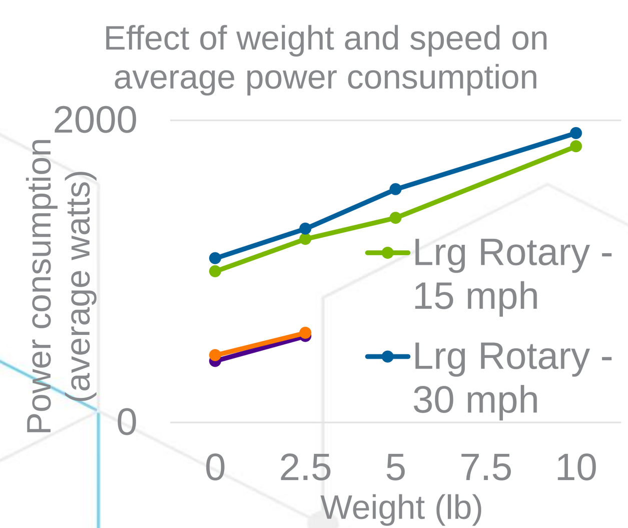
## Insights

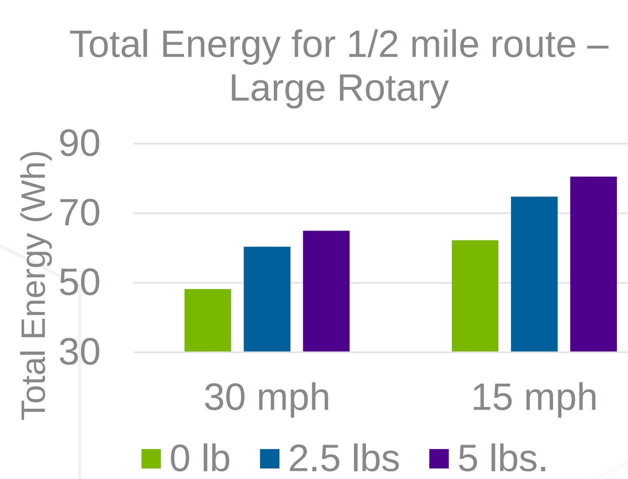
### Power consumption increases linearly with package weight.



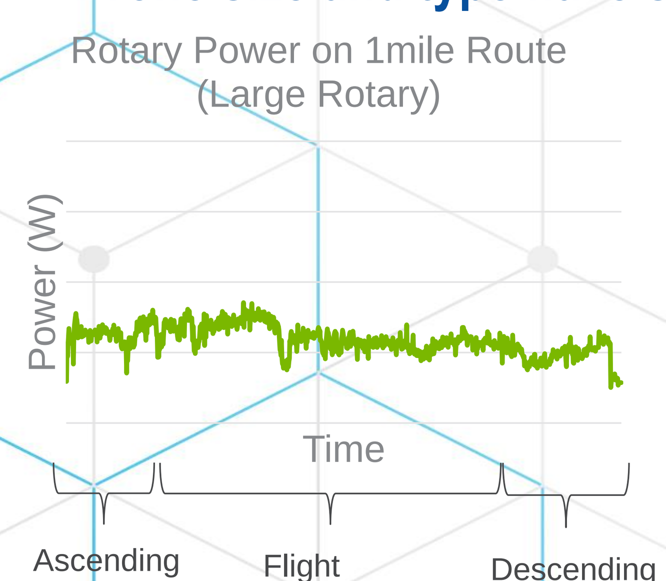



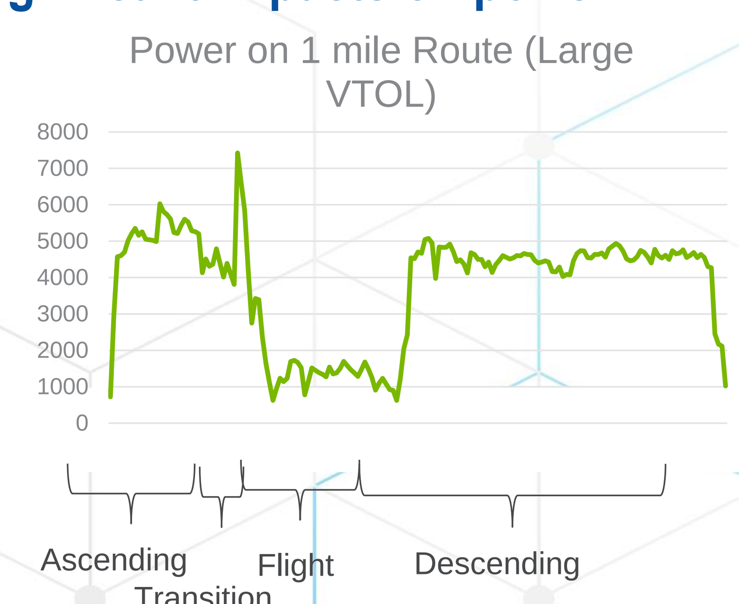

### Rotary drones use more power but less total energy with speed

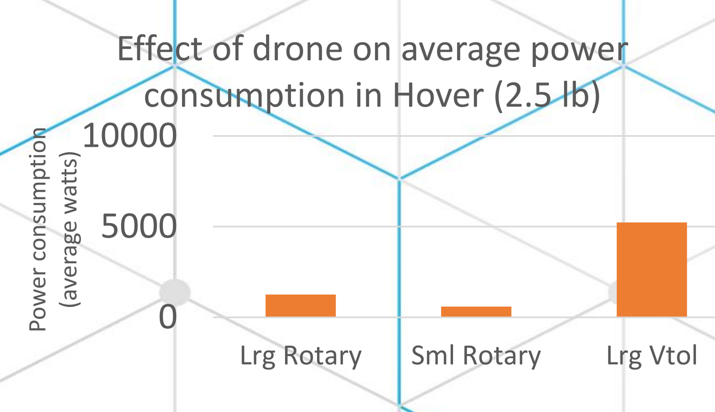


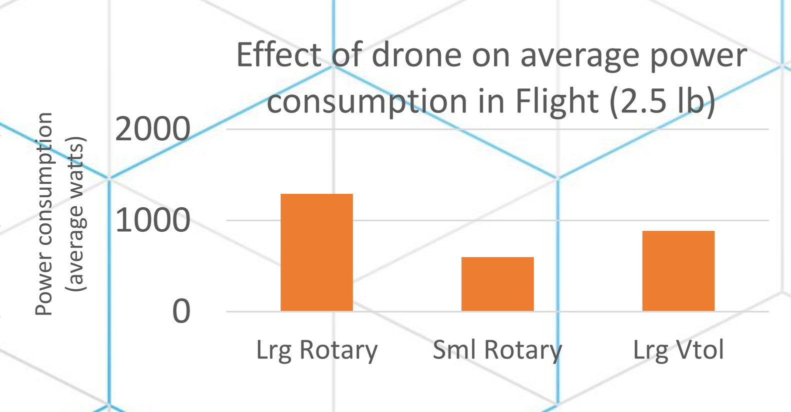




### Drone size and type have significant impacts on power

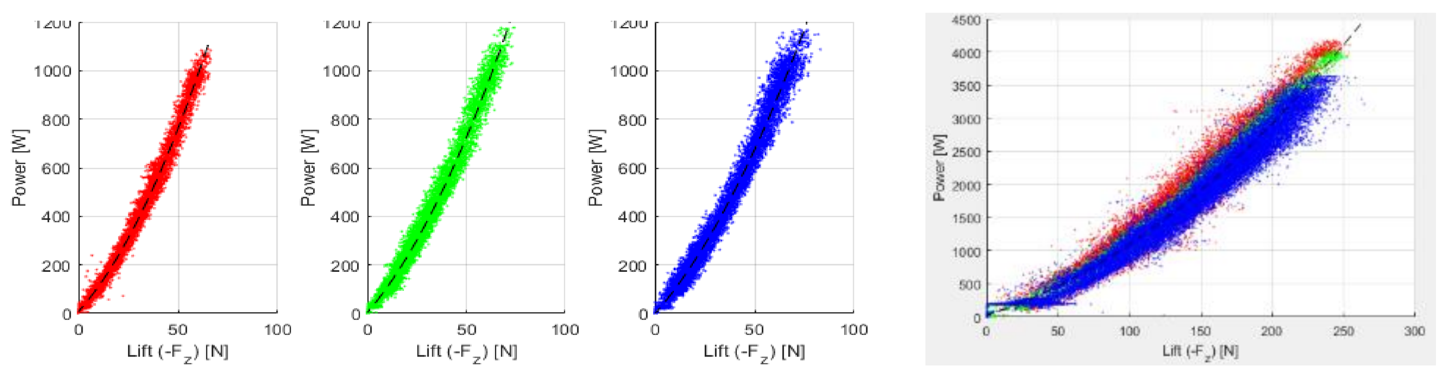


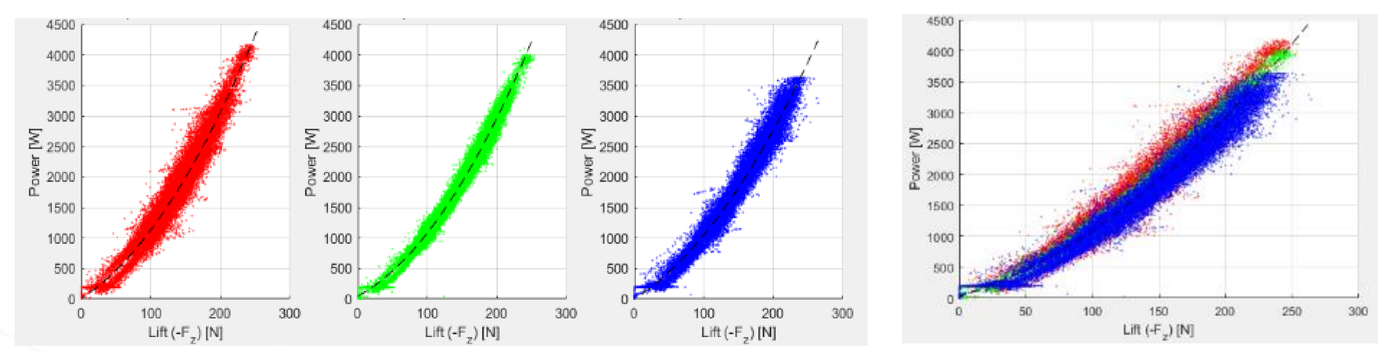




### Temperature influences power

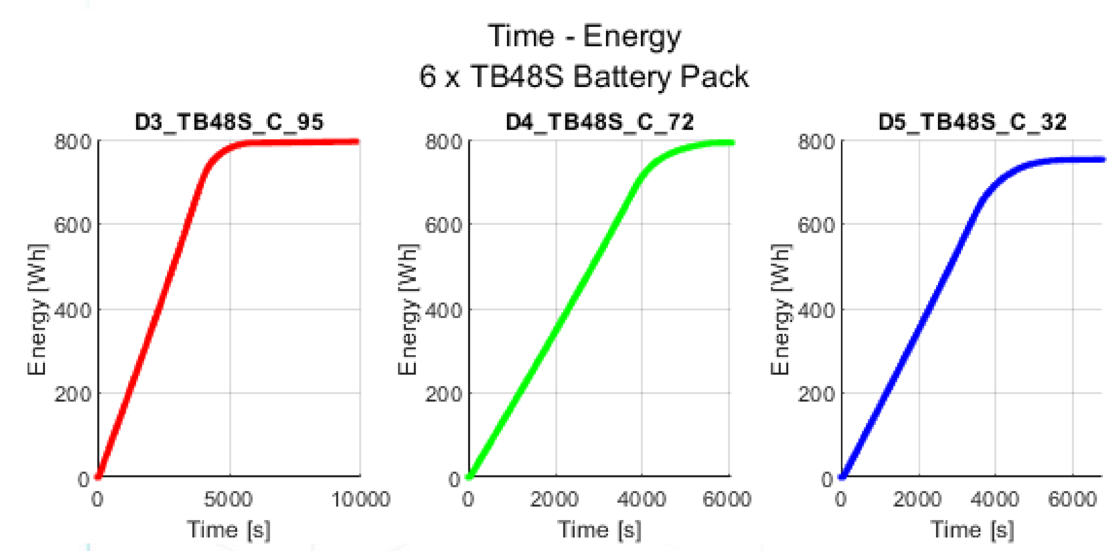


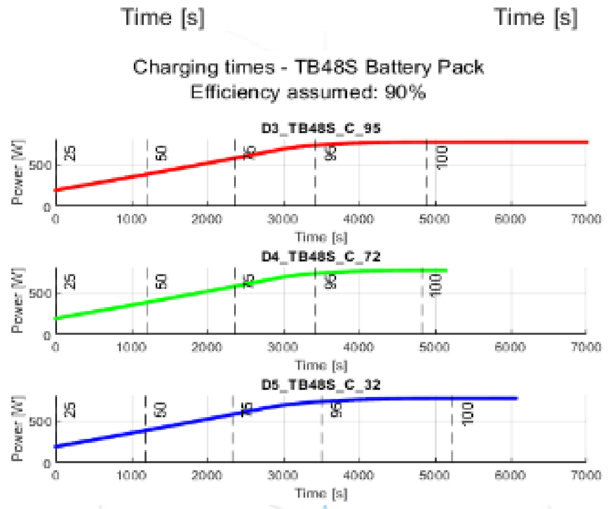
Small rotary drone force by temperature



Large rotary drone force by temperature

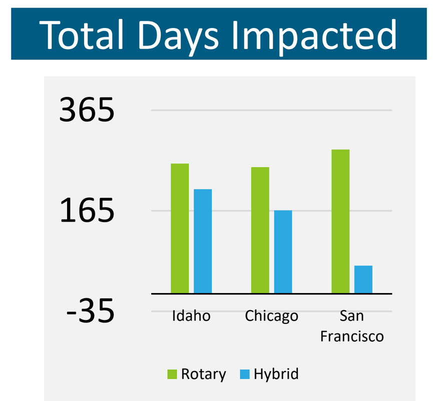
### Charging models provide detailed prediction of charge times

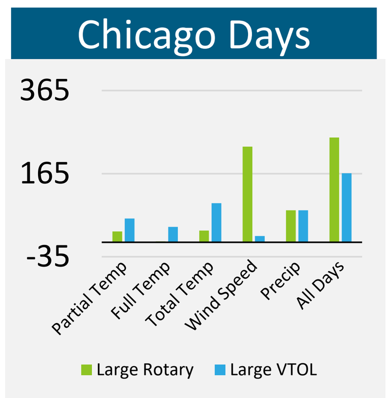


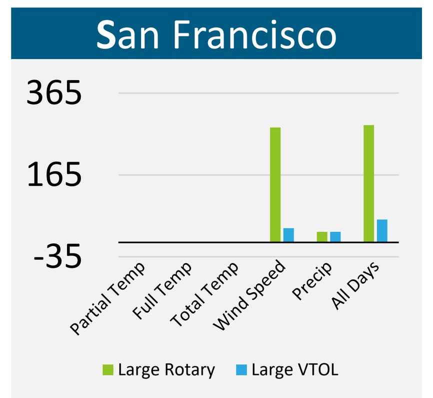



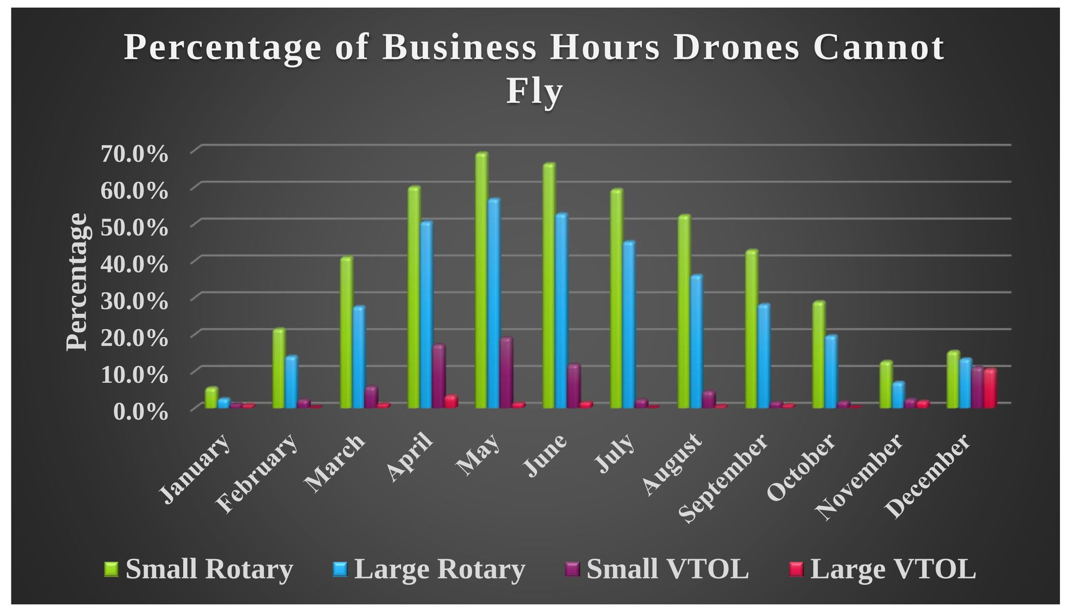

### Weather can have significant impact on drone operations and impacts drones differently

| Drone | Low temp | High temp | Max Wind | Precipitation |
|---|---|---|---|---|
| Small Rotary | *25 | *100 | *15 | Light rain |
| Large Rotary | 14 | 104 | 17.9 | Light rain/snow |
| Small VTOL | *32 | *105 | *25 | No icing / light rain only |
| Large VTOL | 32 | 113 | 33 | No icing / no heavy rain, etc. |

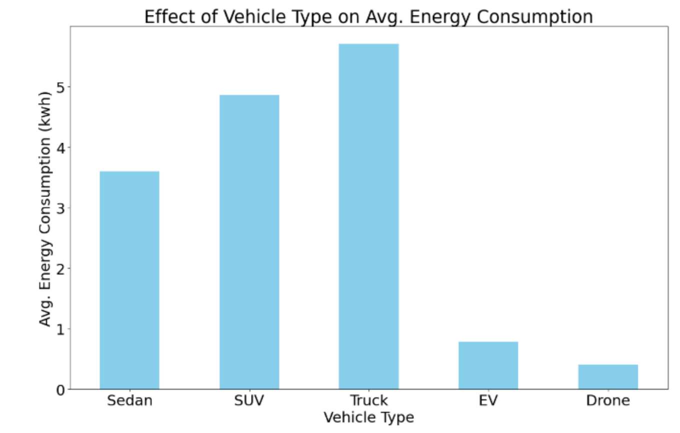



### Drones can use much less energy than larger ground vehicles




Percentage increase in average energy consumption compared to using drone

| Vehicle Type | % Increase in Energy Consumption |
|---|---|
| EV | 92.16 |
| Sedan | 782.35 |
| SUV | 1091.18 |
| Truck | 1299.51 |

- Large rotary.
- Speed: 15 mph
- Package 10 lb.
- Over Road Network
- Number of deliveries: 44 (excluding 82 out of range)
- Vehicle data from (https://fueleconomy.gov/)

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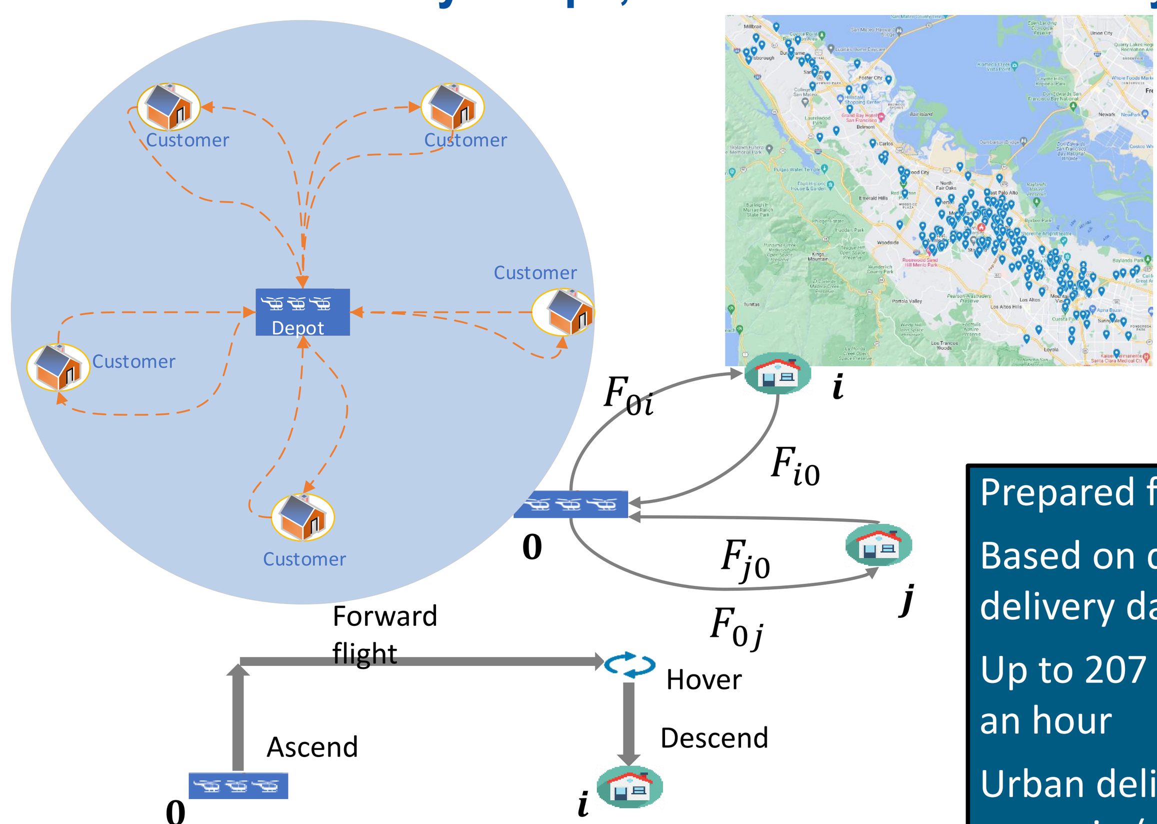
## Insights

### Models look at full energy picture, including delivery windows and battery swaps, urban and rural delivery




$F_{0i}$ = Ascend energy + Forward flight energy + Hover energy + Descend energy

Prepared food delivery

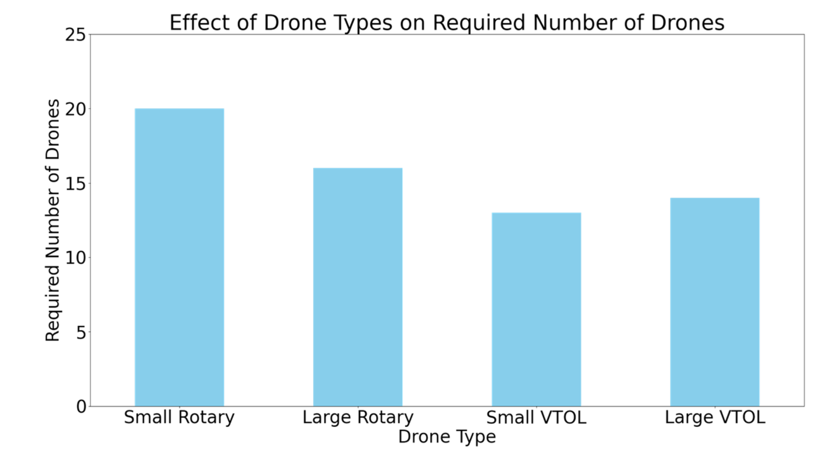
Based on dense delivery dataset

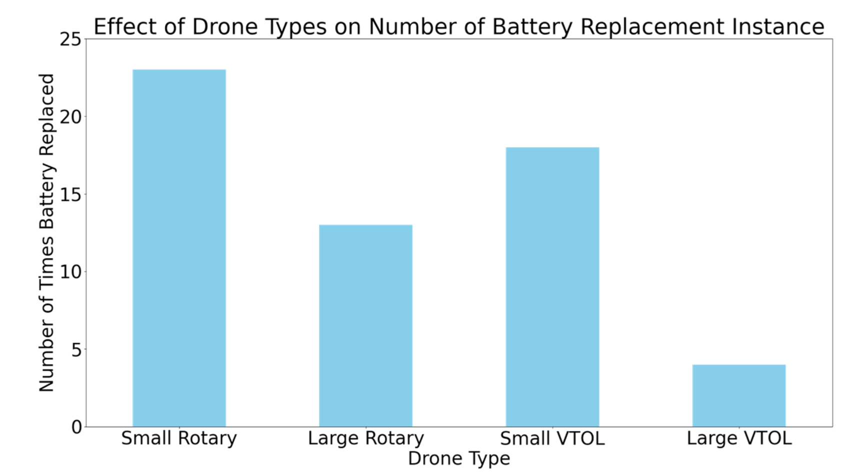
Up to 207 deliveries in an hour

Urban delivery scenario (near San Francisco)

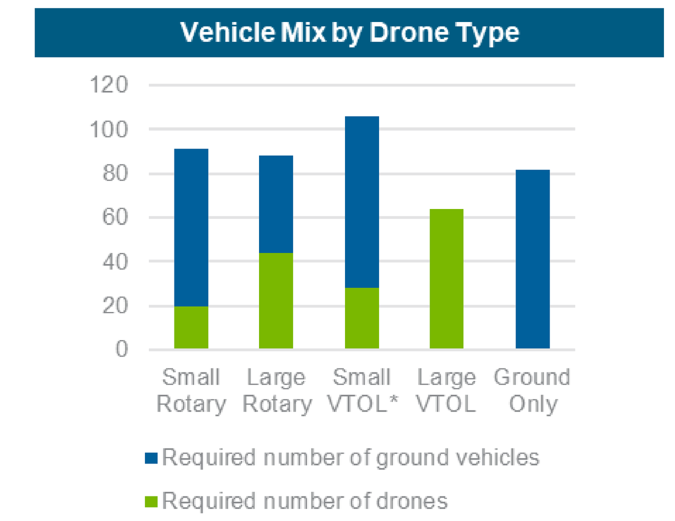
### Each drone type requires different management (homogenous fleet)

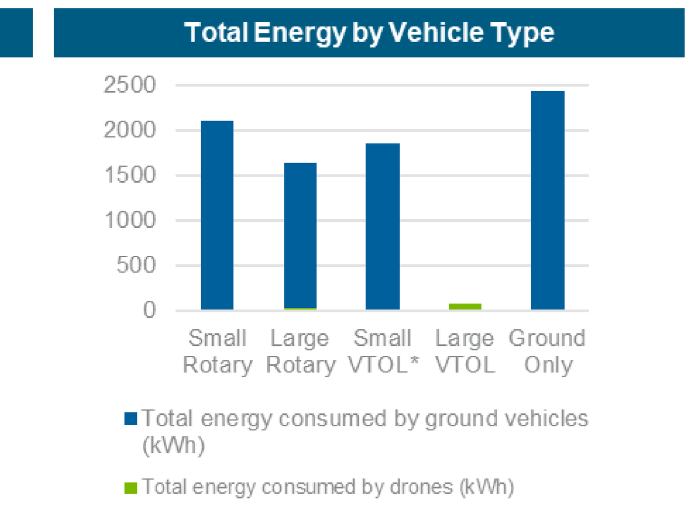
| Drone types | Total energy (kWh) | # of Drones | Delivery time (min) | Battery change time |
|---|---|---|---|---|
| Small Rotary | 4.6 | 20 | 1070.7 | 115 |
| Large Rotary | 12.6 | 16 | 1020.7 | 65 |
| Small VTOL* | 6.5 | 13 | 808.5 | 90 |
| Large VTOL | 14.9 | 14 | 752.4 | 20 |



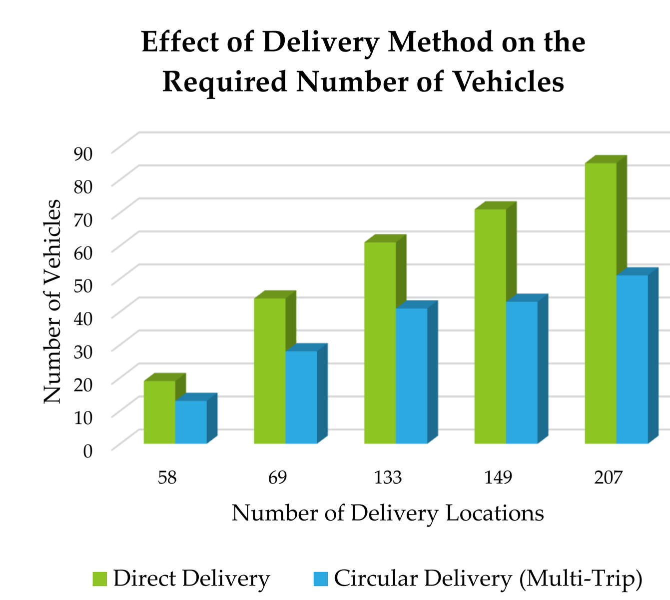



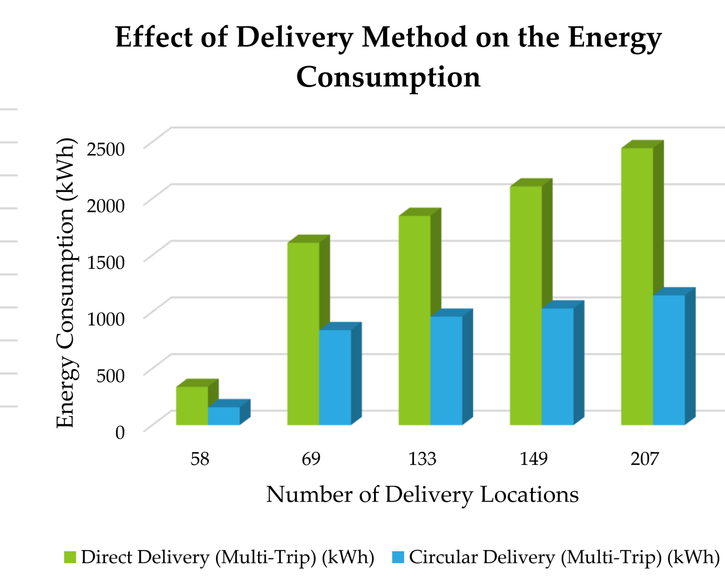

### Combination of ground and air vehicles extend capabilities



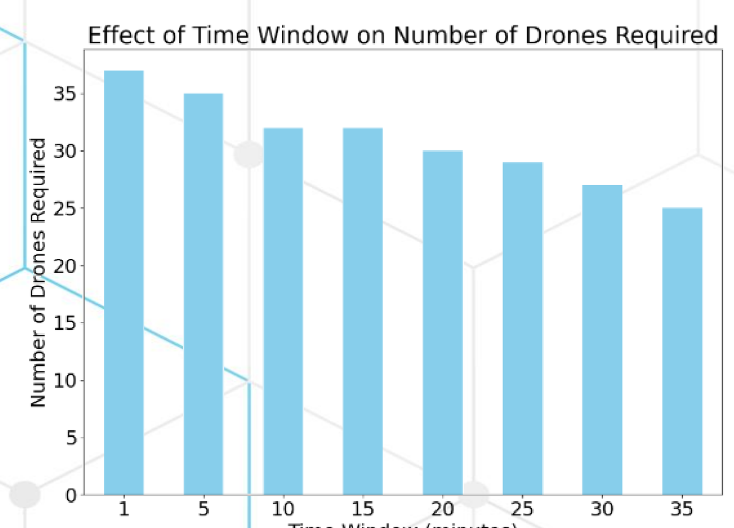




### Using circuit deliveries for ground vehicles can lower energy



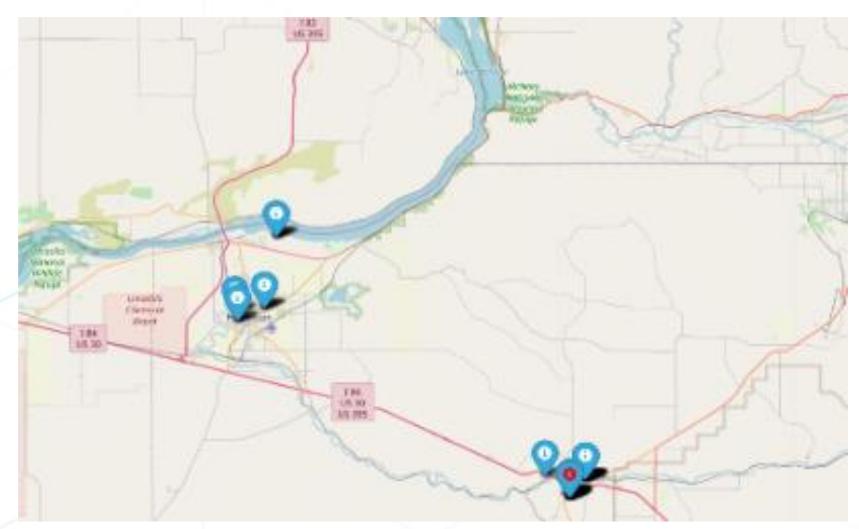




### Delivery window has big impact on the required number of drones




| Time Window | % Reduction |
|---|---|
| 5 minutes | 5.4 |
| 10 minutes | 13.51 |
| 15 minutes | 13.51 |
| 20 minutes | 18.92 |
| 25 minutes | 21.62 |
| 30 minutes | 27.02 |
| 35 minutes | 32.43 |

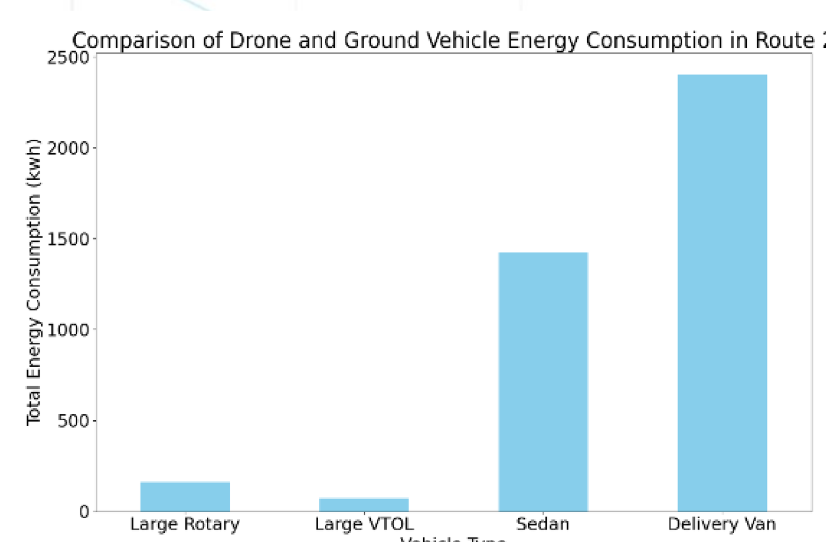
### Large VTOL is more efficient in remote rural deliveries

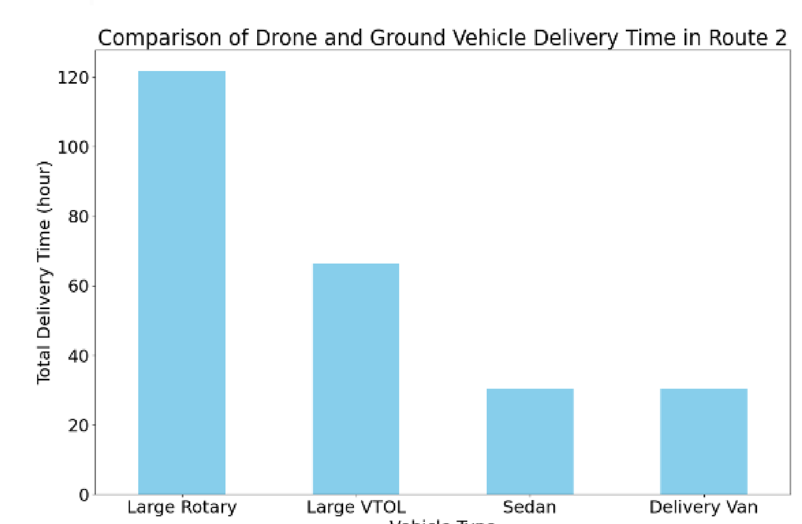


Medical sample deliveries over a large area (up to 45 miles)

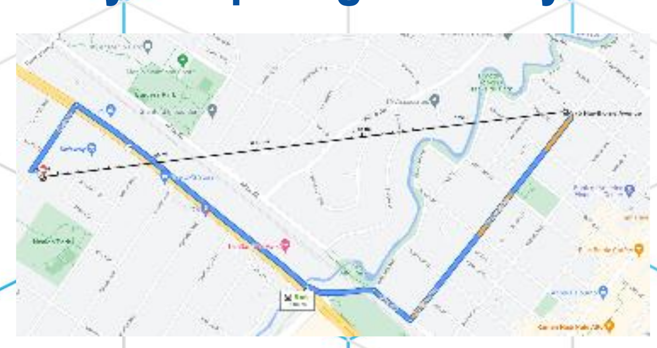
Partnership with Spright and Interpath

Enables reach to rural and under-served community




### Flight path avoiding no-fly zones increases energy, fleet size, and battery swaps significantly compared to flying in a straight path



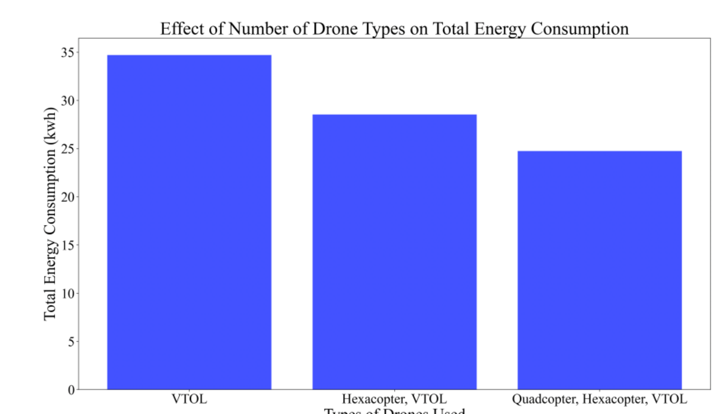
Rural delivery data. Package weight distribution:

1.0 - 2.5 lbs: 88%
2.5 - 3.5 lbs: 6%
3.5 - 4.5 lbs: 6%

| | No-fly zone detour | Flying over the road networks |
|---|---|---|
| Fleet size (mixed fleet) | 18.75% | 26.67% |
| Battery swaps | 15.31% | 32.94% |
| Total energy | 21.77% | 28.43% |

### Using a mixed-fleet of drones can lower overall energy

- Number of deliveries: 58




| # of drone types in the mixed fleet | % decrease in total energy from a pure VTOL fleet |
|---|---|
| Hexacopter, VTOL | 18 |
| Quadcopter, Hexacopter, VTOL | 30 |

## Acknowledgments


This work is supported by the U.S. Department of Energy's Vehicle Technologies Office under Contract No. DE-AC07-07ID14517



Bhuiyan, T.H., Roni, M. and Walker, V., 2022. Drone Deployment Optimization for Direct Delivery with Time Windows and Battery Replacements, *Transportation Research Part C: Emerging Technologies (Under Review).*



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