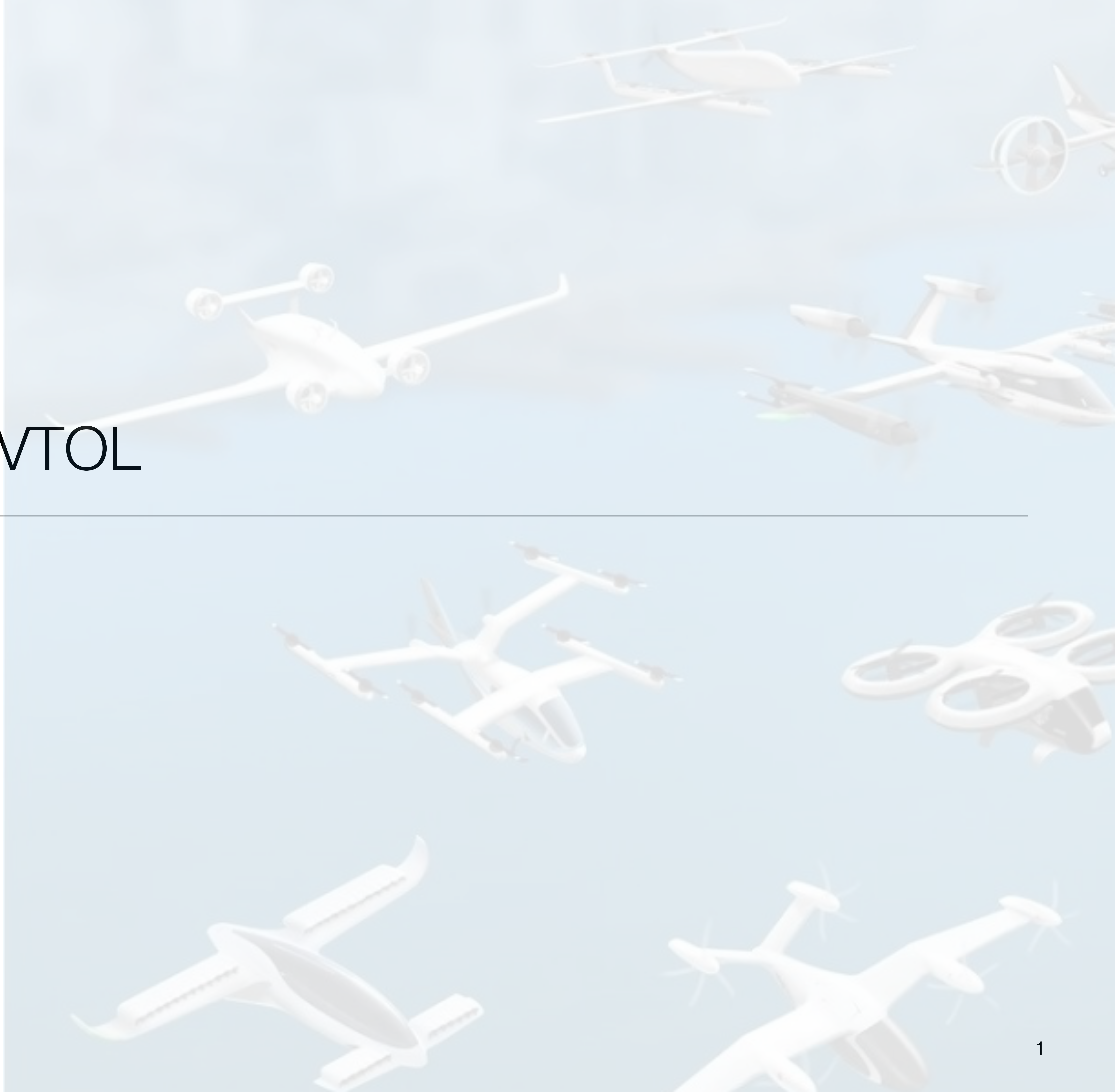
UAM Team Project :
Conceptual Design of Cargo eVTOL



FLY

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2021. 8. 3.

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  - Market Needs
  - Environment
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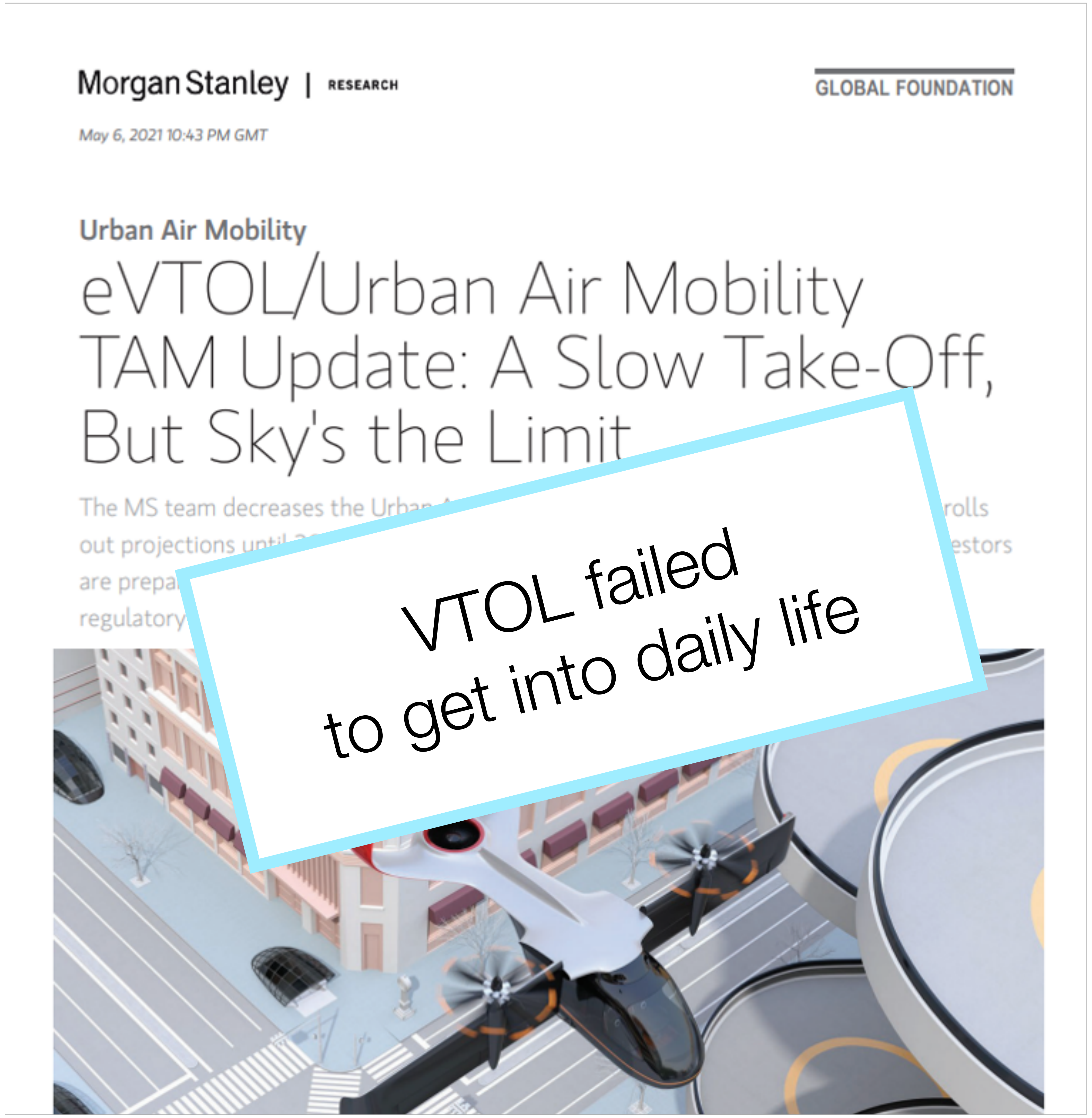
Motivation

Motivation


Morgan Stanley | RESEARCH

GLOBAL FOUNDATION

May 6, 2021 10:43 PM GMT

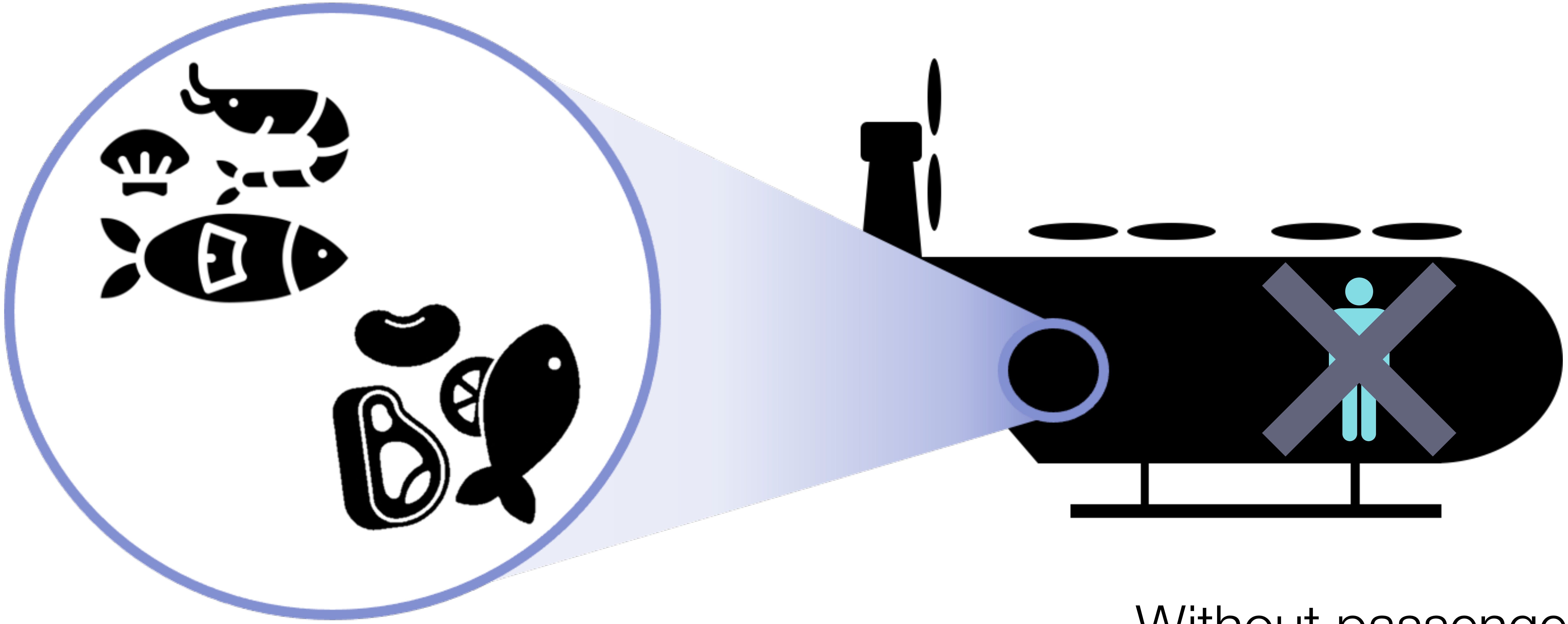
Urban Air Mobility

eVTOL/Urban Air Mobility TAM Update: A Slow Take-Off, But Sky's the Limit

VTOL failed
to get into daily life

Reliability

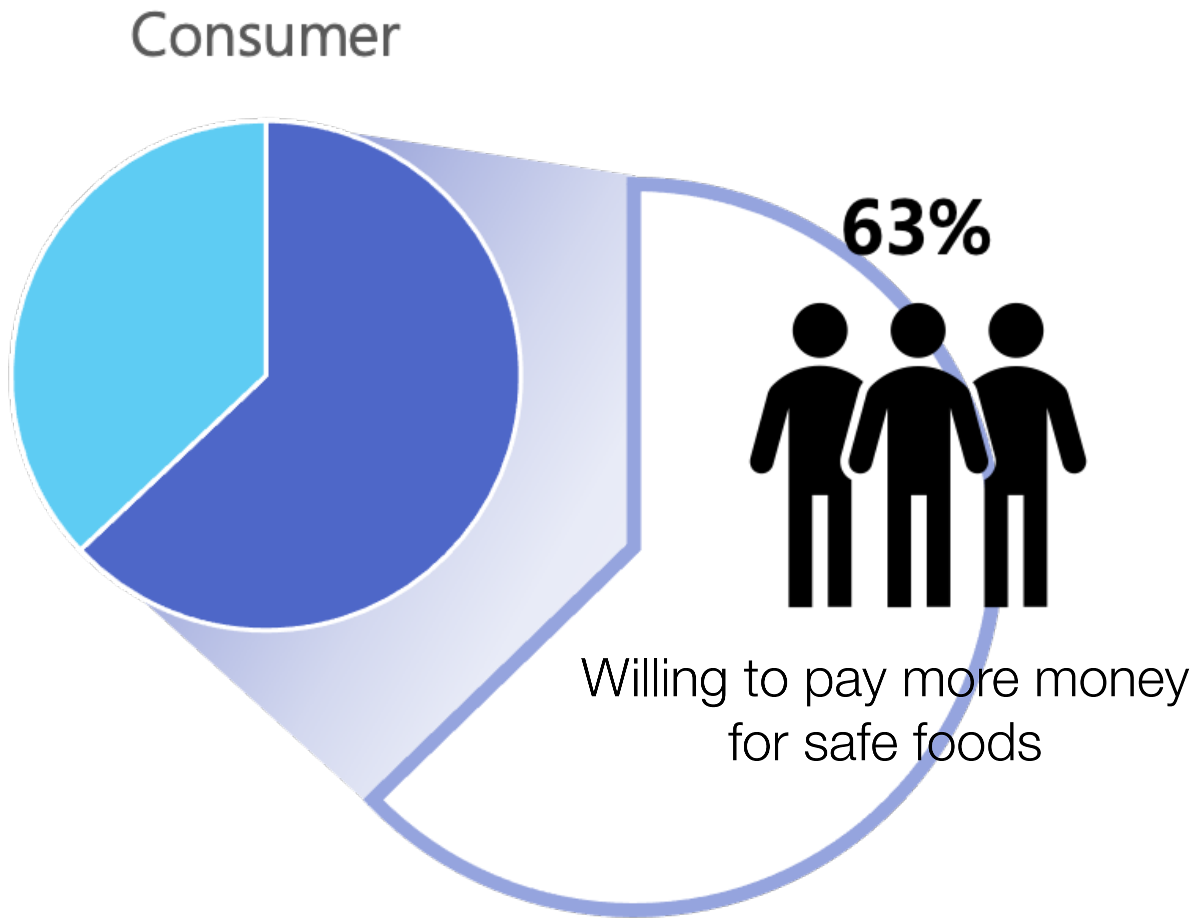
Motivation



Without passengers -> Less risky

Market Needs

- Consumer



- Government

Over 50% of the retail price

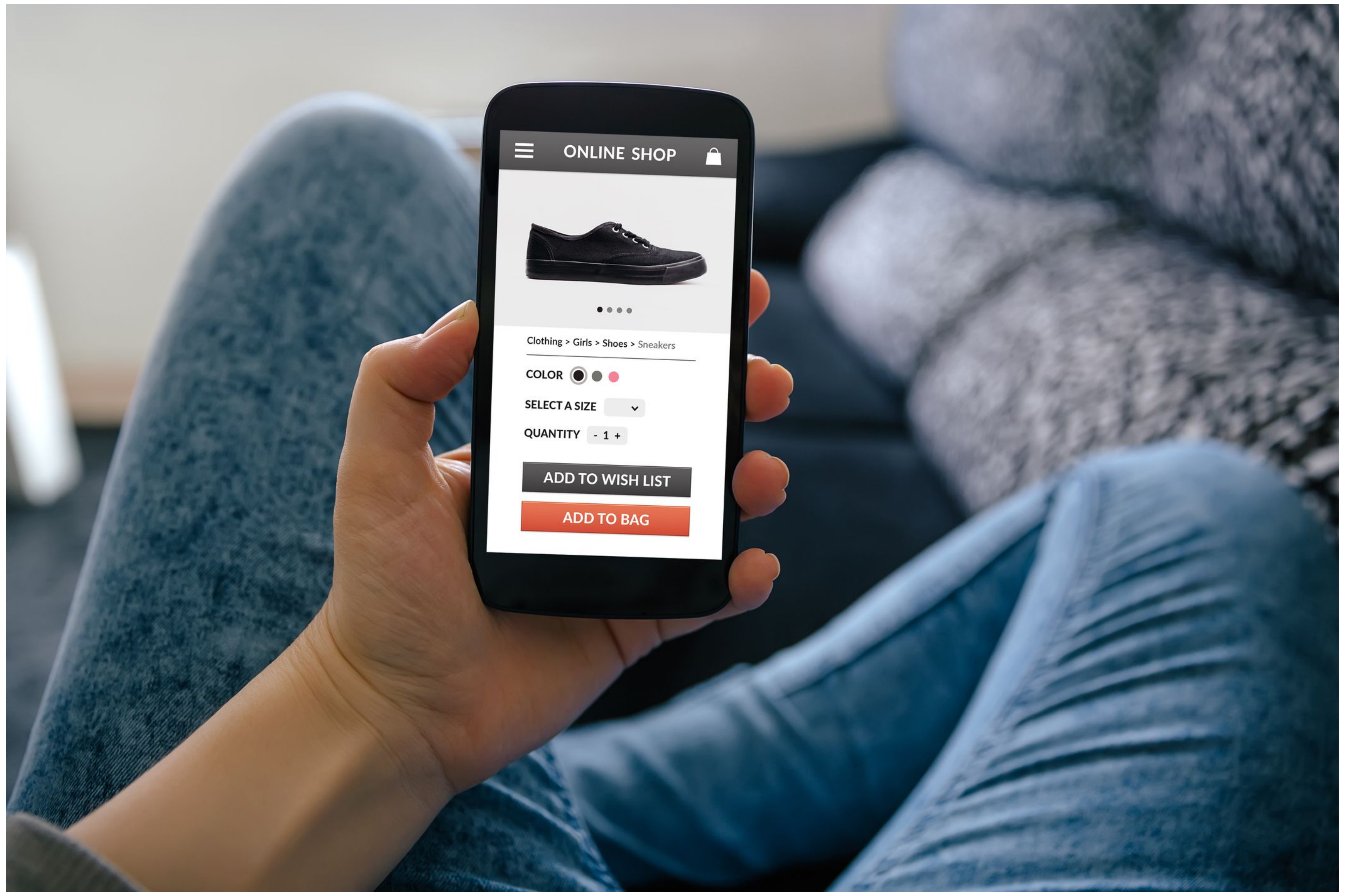
Consistently try to improve marine products distribution system

Environment

- Housing

http://www.koreaherald.com/view.php?ud=20210228000213

- Technology



https://www.oprahdaily.com/life/work-money/g28937971/best-shopping-apps/

Summary

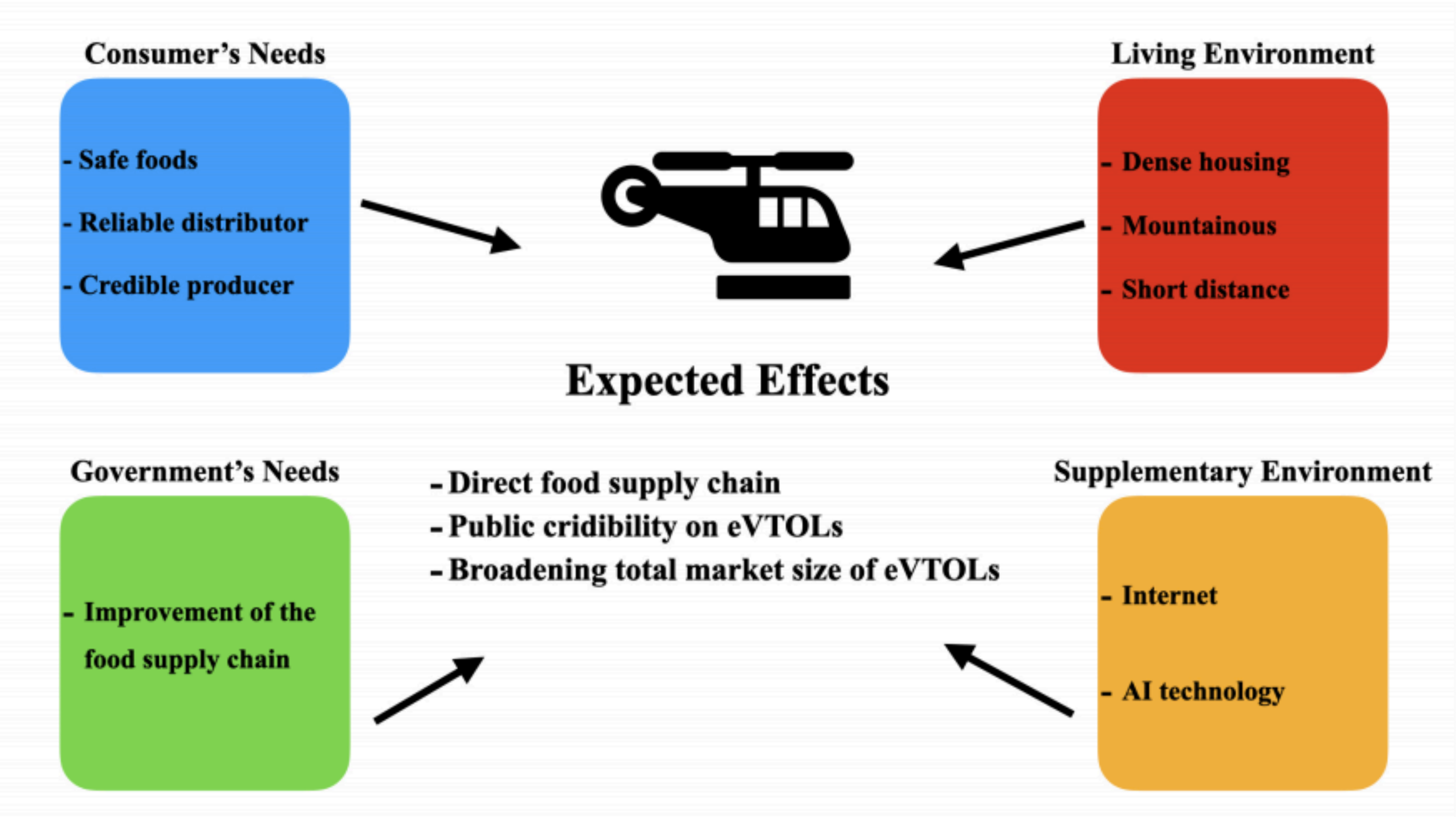
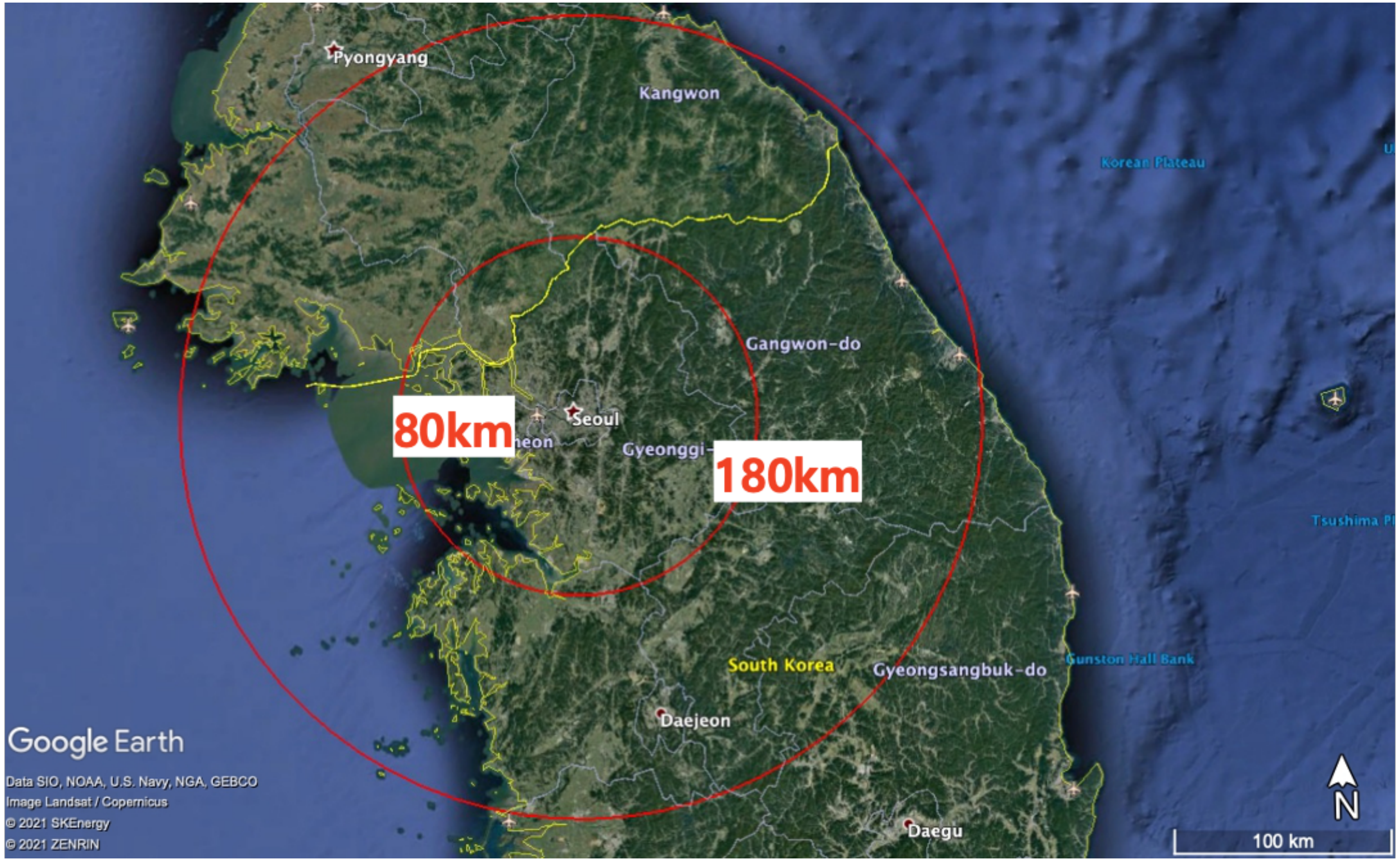


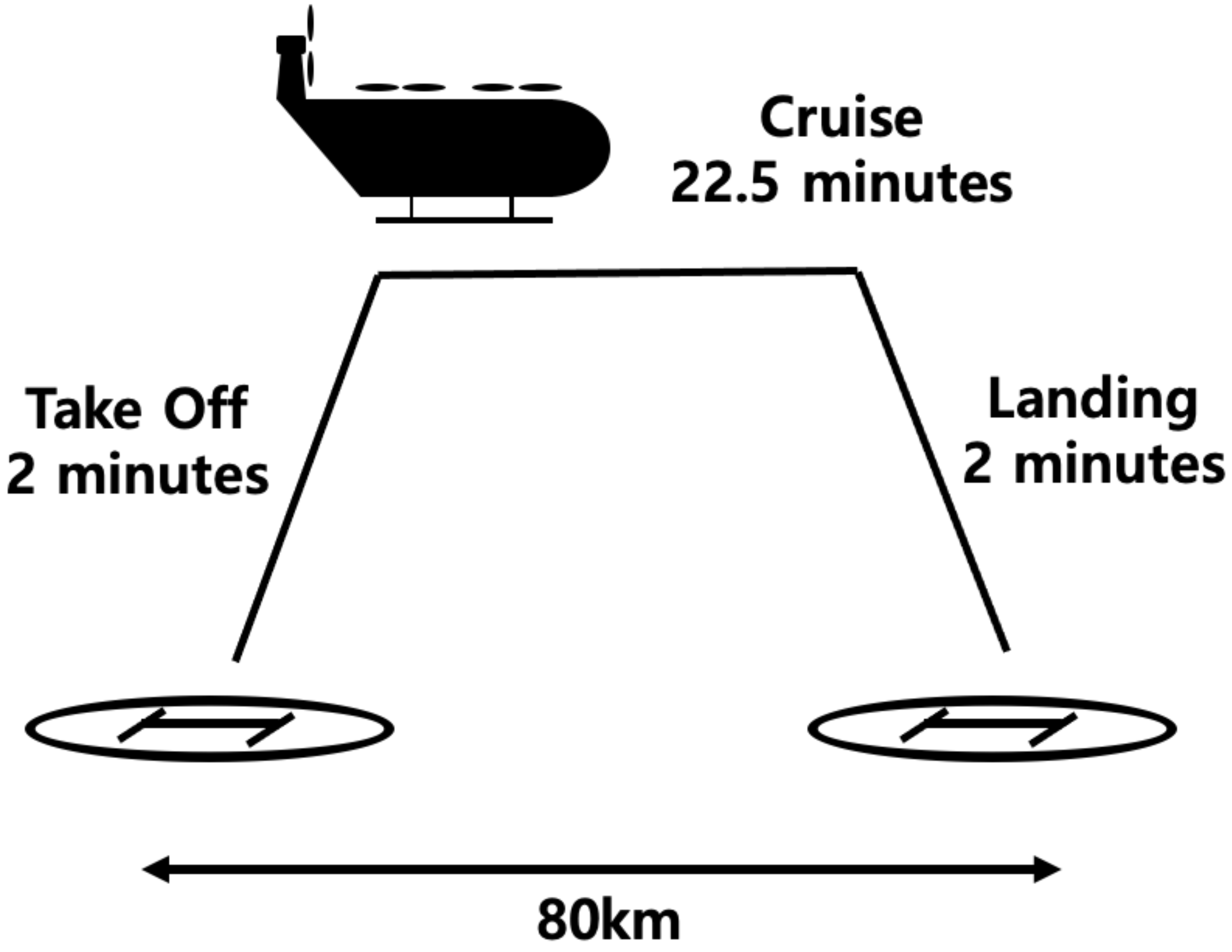
Fig. 2 Overall Motivation

Mission Profile

Mission Profile



Mission Profile



- Total Gross Weight < 3000kg
- Tip Speed < 0.49M
- Battery : 5C, 200Wh/kg
- Payload : 500kg
- Range > 80km
- Cost < $9/kg (=$30 * 0.3)

Aircraft Sizing

Wing

- The higher wing aspect ratio, the higher maximum lift to drag ratio
- Cruise speed at maximum lift to drag ratio can be calculated from the given AR, S_{ref}

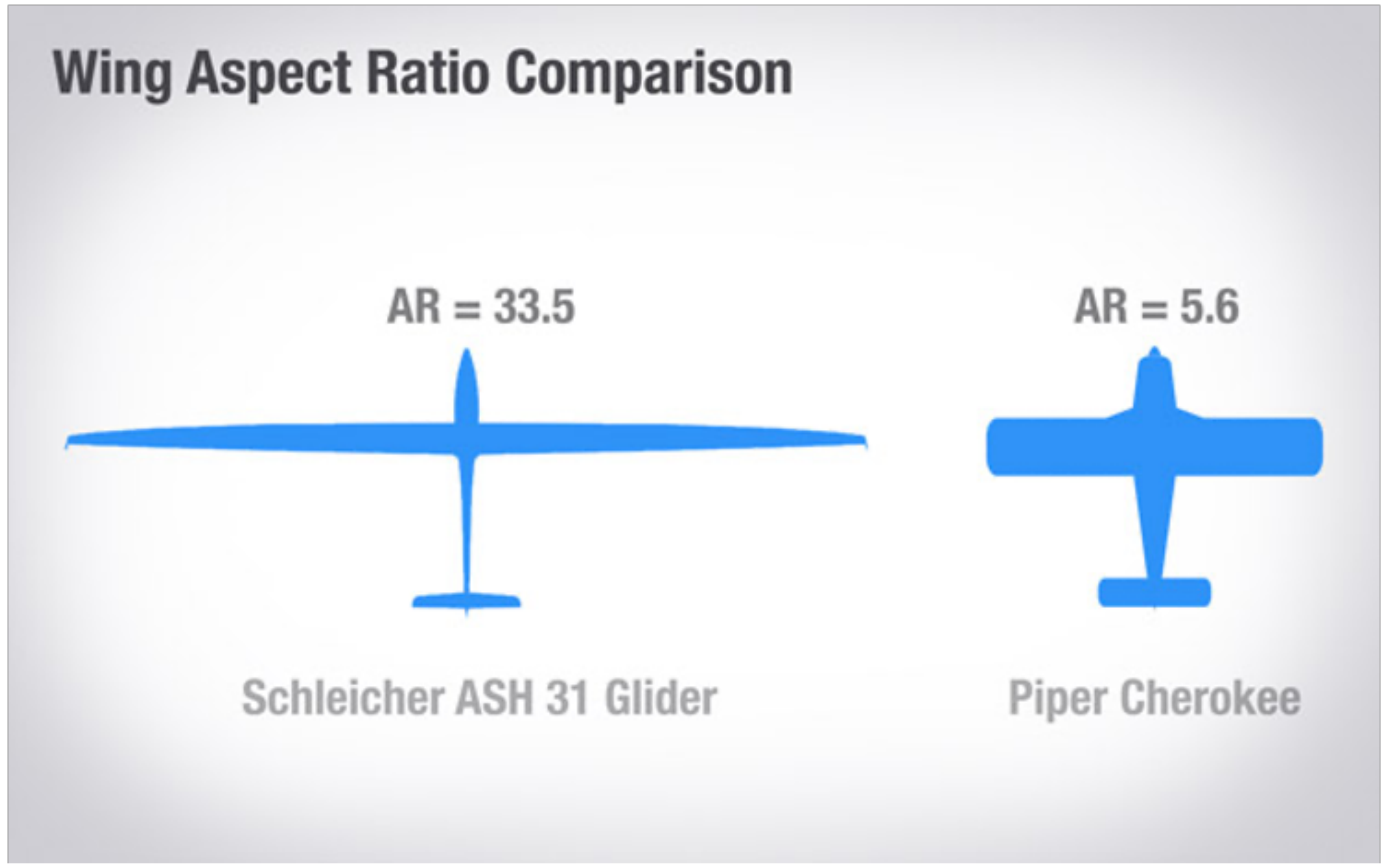
e: Oswald span efficiency

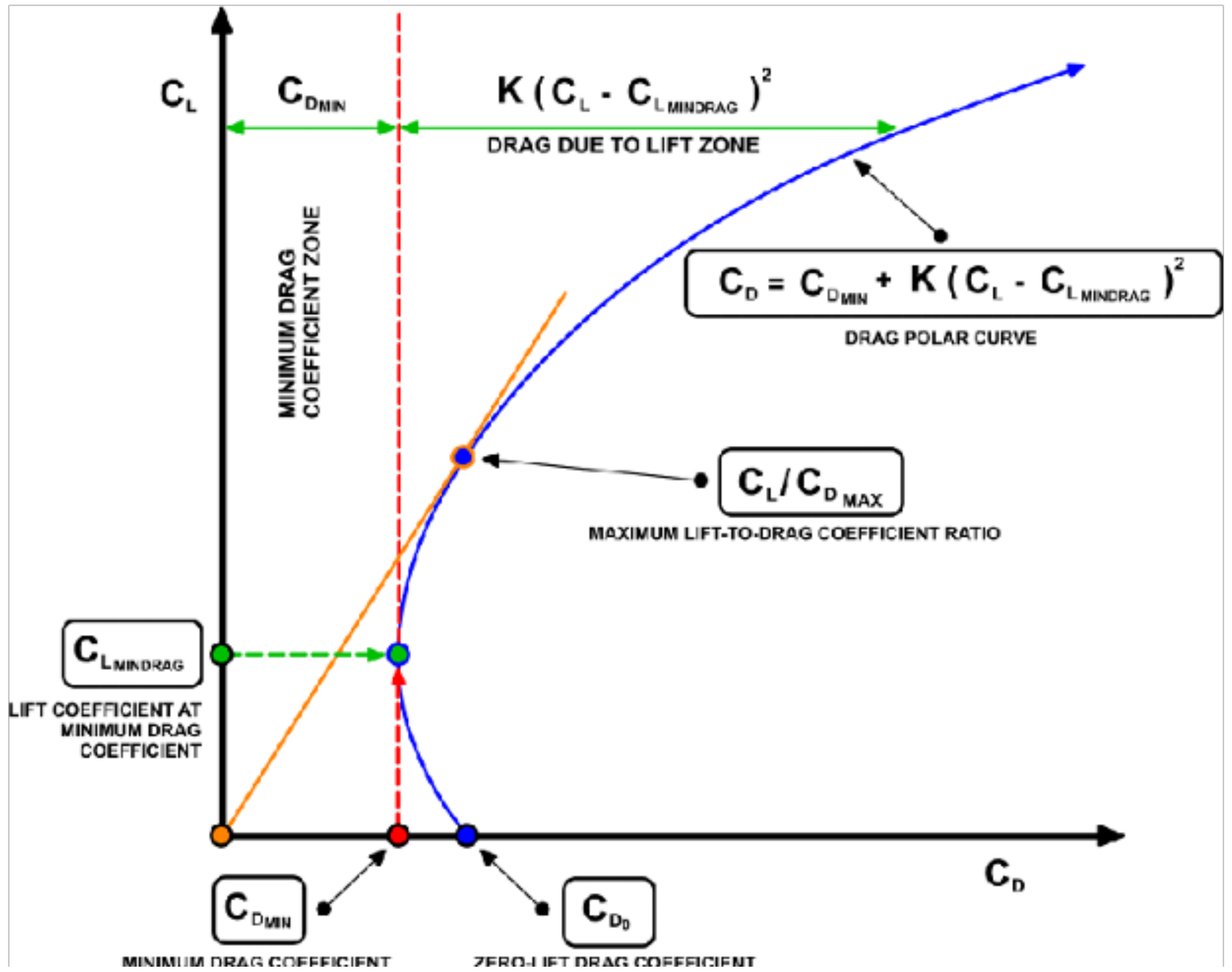
$$C_D = C_{D_0} + \frac{C_L^2}{\pi e AR}$$

- $$W = \frac{1}{2}\rho_{air} V_{cruise}^2 S_{ref} C_L$$

C_L at maximum lift to drag is determined by the given AR

$$\left(L/D\right)_{max} = \frac{1}{2}\sqrt{\frac{\pi e AR}{C_{D_0}}}$$





Battery

- How much power do eVTOL need?
- We connected 800V batteries to each rotor and 120V battery to the refrigerator.
- We also designed the battery by checking wether discharging C rate exceeds 5C

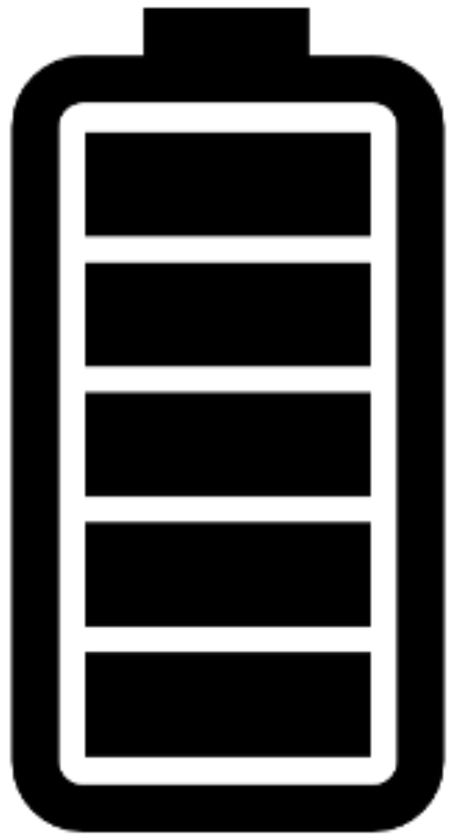
$$P_{hover} = \frac{(W_{gross}g)^{1.5}}{M}\sqrt{\frac{DL}{2\rho_{air}W_{gross}}} = 563.5kW$$

$$P_{cruise} = \frac{W_{gross}gV_c}{LD \times M} = 101.68kW$$

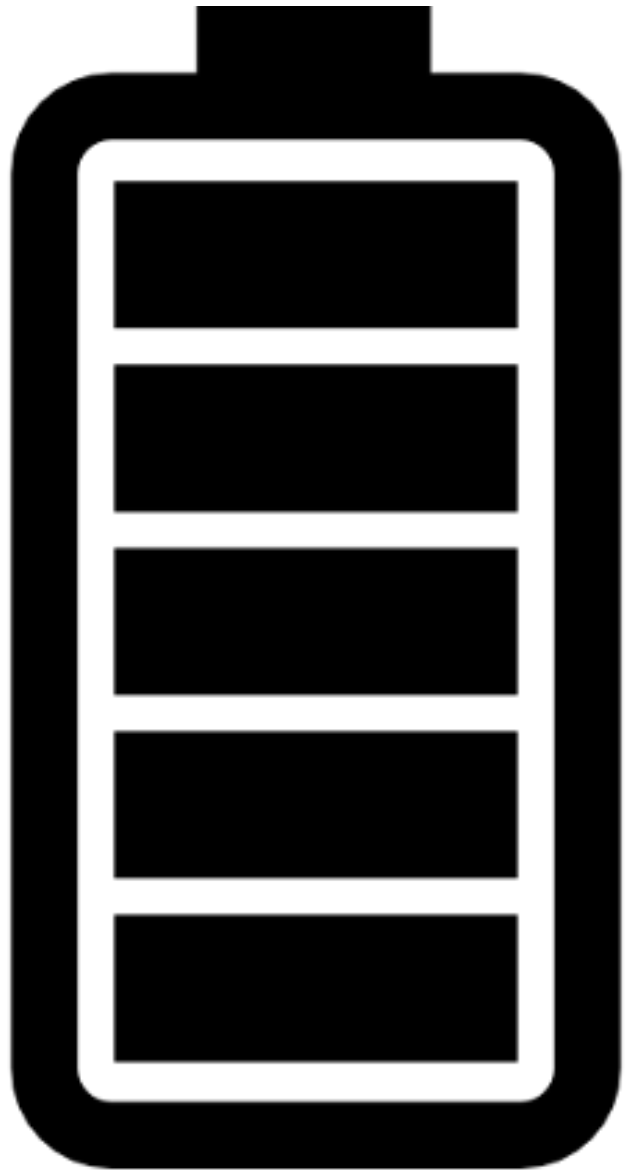
$$P_{AC} = 0.26kW$$

	# of rotors	Discharging C rate
P_{hover}	12	4.66C
P_{cruise}	2	0.93C
P_{AC}		2.2C

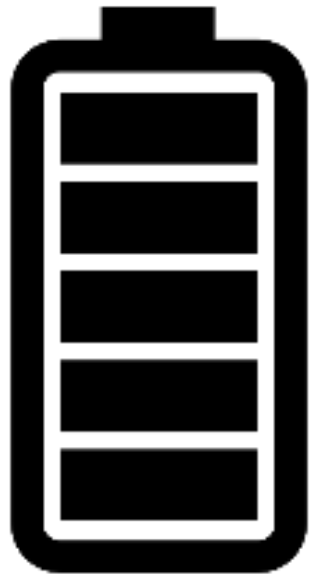
Battery



X 12



X 2



Each Lift Rotor

9.6kWh, 800V
200S12P

Each Cruise Rotor

54.4kWh, 800V
200S68P

Refrigerator

54.4kWh, 800V
200S68P

Rotor

$$P_{lift} = \frac{(T_{VTOL})^{3/2}}{\sqrt{2\rho_{air}S_{Disk}}}\frac{1}{M}$$

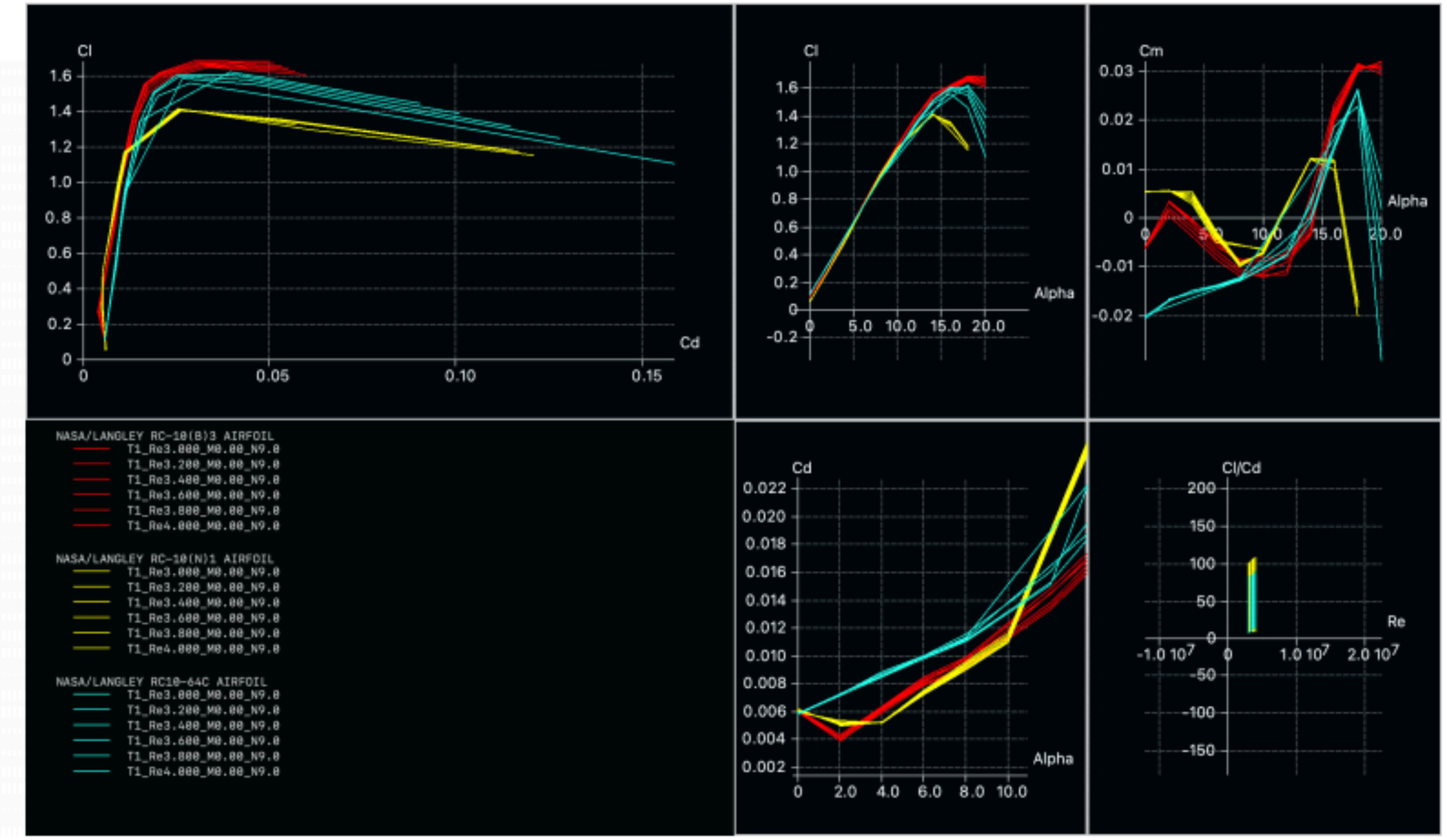
$$P_{cruise} = \frac{W_{gross}g}{LD}V$$

$$R_{lift} = \sqrt{\frac{W_{gross}}{DL\pi N}}$$

- Gross Weight = 3000kg
- Disk Loading = 12lb/ft^2
- # of lift rotors : 12
- # of cruise rotors : 2
- L/D : 20

Rotor

- Solidity = 0.3 (typical to lift + cruise)
- # of blades : 5
- Tip speed ~ 0.49M
- Re = 3e6 ~ 4e6
- NASA/Langley RC-10 series
- **Get a, δ by CFD(characteristic of the airfoil of the blades)**

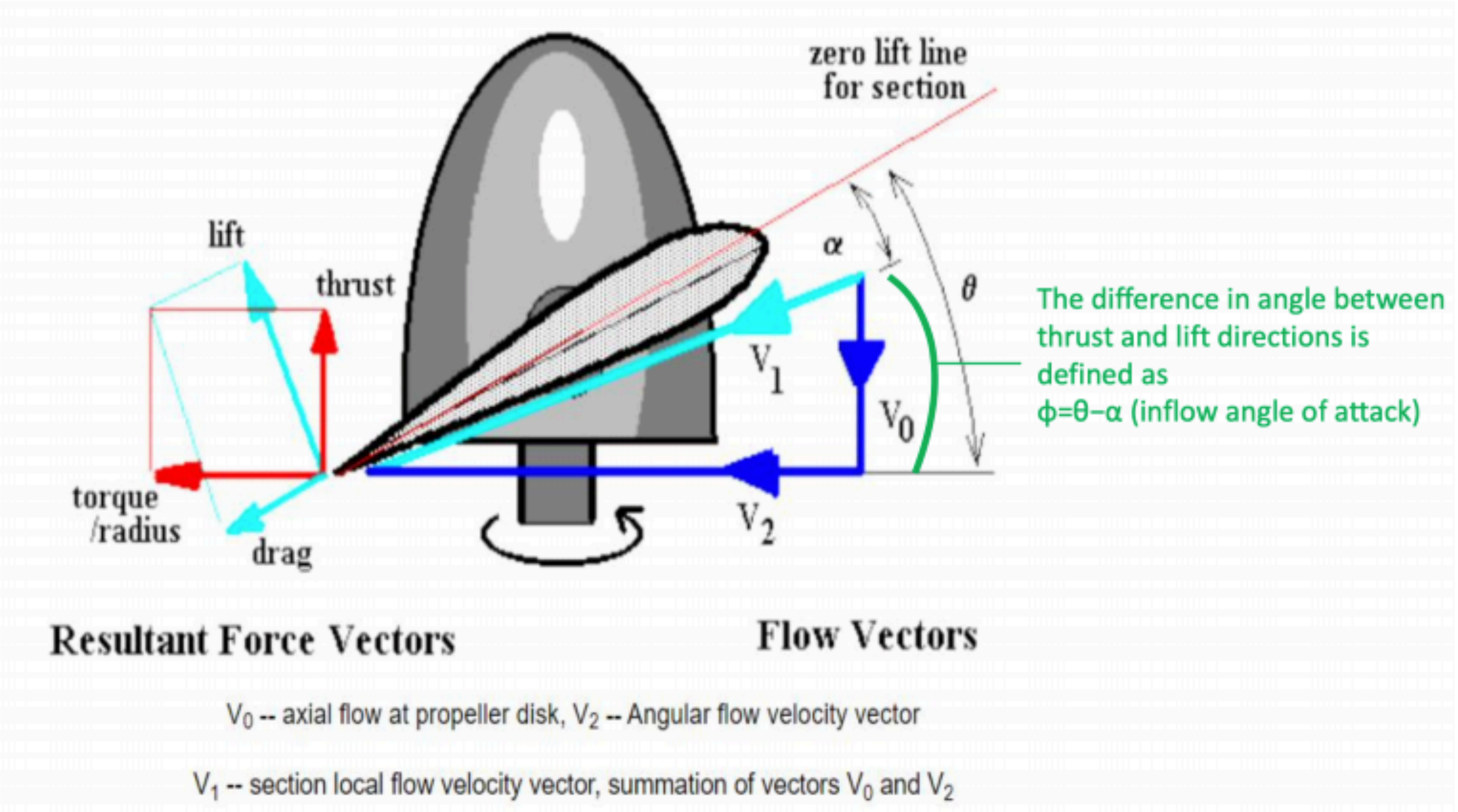


- $C_T = \frac{\delta}{4} a(\theta_t - \phi_t)$
- $C_P = C_Q = \frac{\delta \sigma}{8} + \frac{C_T^{3/2}}{\sqrt{2}}$
- $T = C_T \pi R^2 \rho_{air} (\Omega R)^2$
- $P = C_P \pi R^2 \rho_{air} (\Omega R)^3$
- $M = \frac{1}{\sqrt{2}} \frac{C_T^{3/2}}{C_Q}$

Rotor

- $V_{0,speed=0} = \sqrt{\dfrac{T}{2\rho_{air}\pi R^2}}$

- $V_{0,speed=V} = \dfrac{V}{2}(1 + \sqrt{1 + \dfrac{2T}{\rho_{air}\pi R^2 V^2}})$



Weight Estimation

Weight of each component is estimated by using empirical correlation estimation

- $W_{wing} = 0.0467 W_{gross}^{0.347} S_{ref}^{0.36} N_{ult}^{0.397} AR^{1.712}$
- $W_{empennage} = 0.72 S_h^{1.2} AR_h^{0.32} + 1.05 * S_v^{0.94} AR_v^{0.53}$
- $W_{fuselage} = 6.9(W_{gross}/1000)^{0.49} L_f^{0.61} S_{wet}^{0.25} \eta_{light}$
- $W_{flightcontrol} = 11.5(W_{gross}/1000)^{0.4}$
- $W_{avionics} = 0.0268 W_{gross}$
- $W_{antiicing} = 8(W_{gross}/1000)$
- $W_{furnishing} = W_{landing\ gear} = 0\ (assumption)$

-> The weights of most components are function of gross weight

- $W_{rotor} = 1.763 T_{rotor}^{2.00} \times 10^{-5}$
- $W_{motor} = 0.3225 \tau_c^{0.7476} N_c + 0.3225 \tau_l^{0.7476} N_l$
- $W_{motorcontrol} = 2.20462(49.9/398 * (P_c - 2) + 0.1) N_c + 2.20462(49.9/398 * (P_l - 2) + 0.1) N_l$

-> The weights of the rotor related components are function of motor power, torque or rotor diameter

- $W_{battery} = \dfrac{E_{total}}{BC \times BED}$

Weight Estimation

1) Set design variable

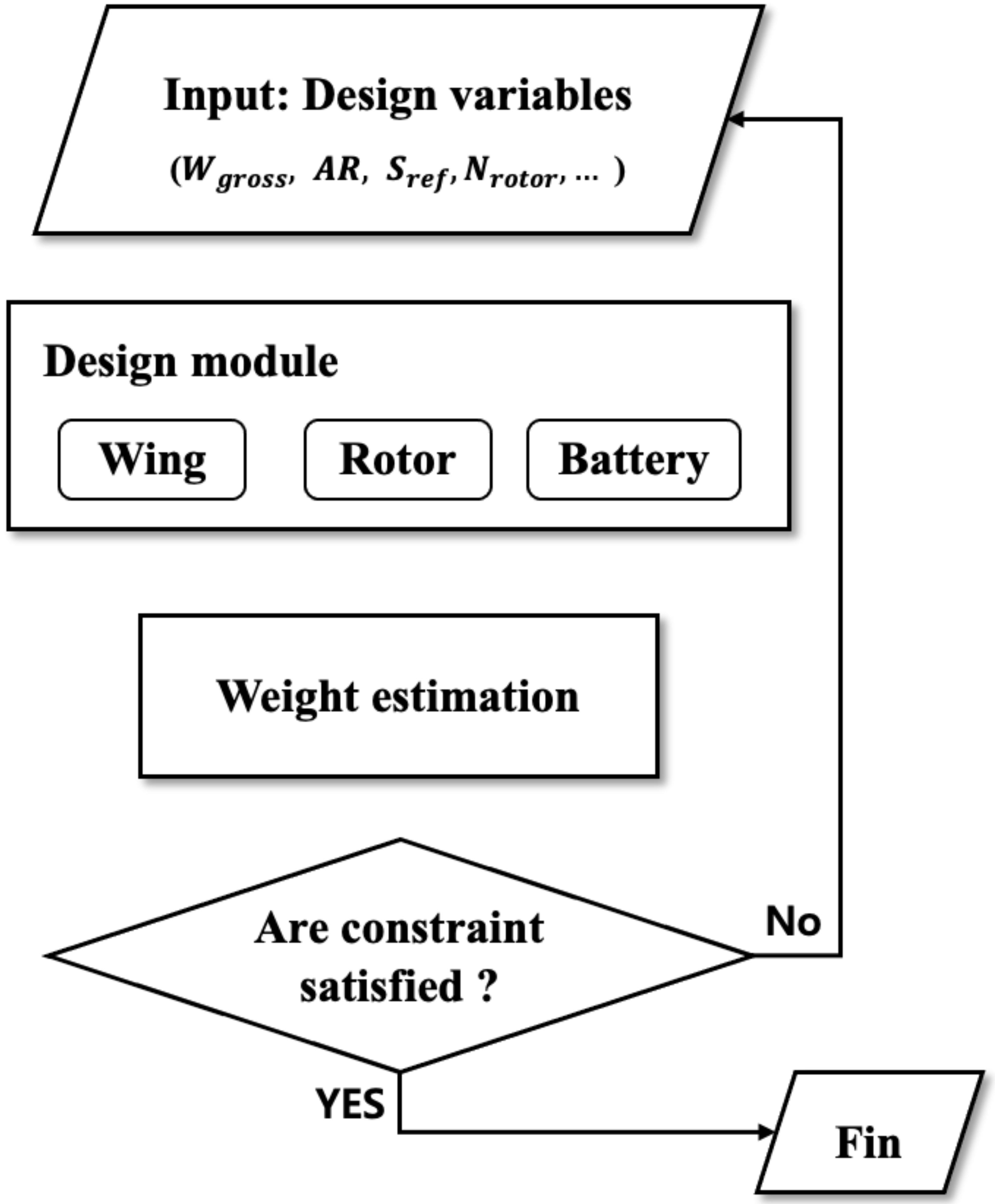
   - Aspect ratio, reference area, the number of the rotors, disk loading, fuselage length, etc.

2) Detail spects are calculated from the design module

   - Optimal crusing speed, rotor diameter, power and torque of the motors, etc.

3) Estimate the weight of each components

4) Repeat 1) to 3) till constraints are satisfied



Weight Estimation

- **Aspect ratio** and **reference area** were regarded as the major design variables

- The domains satisfying specific constraints are plotted

- The design point was selected from the intersection of the domains

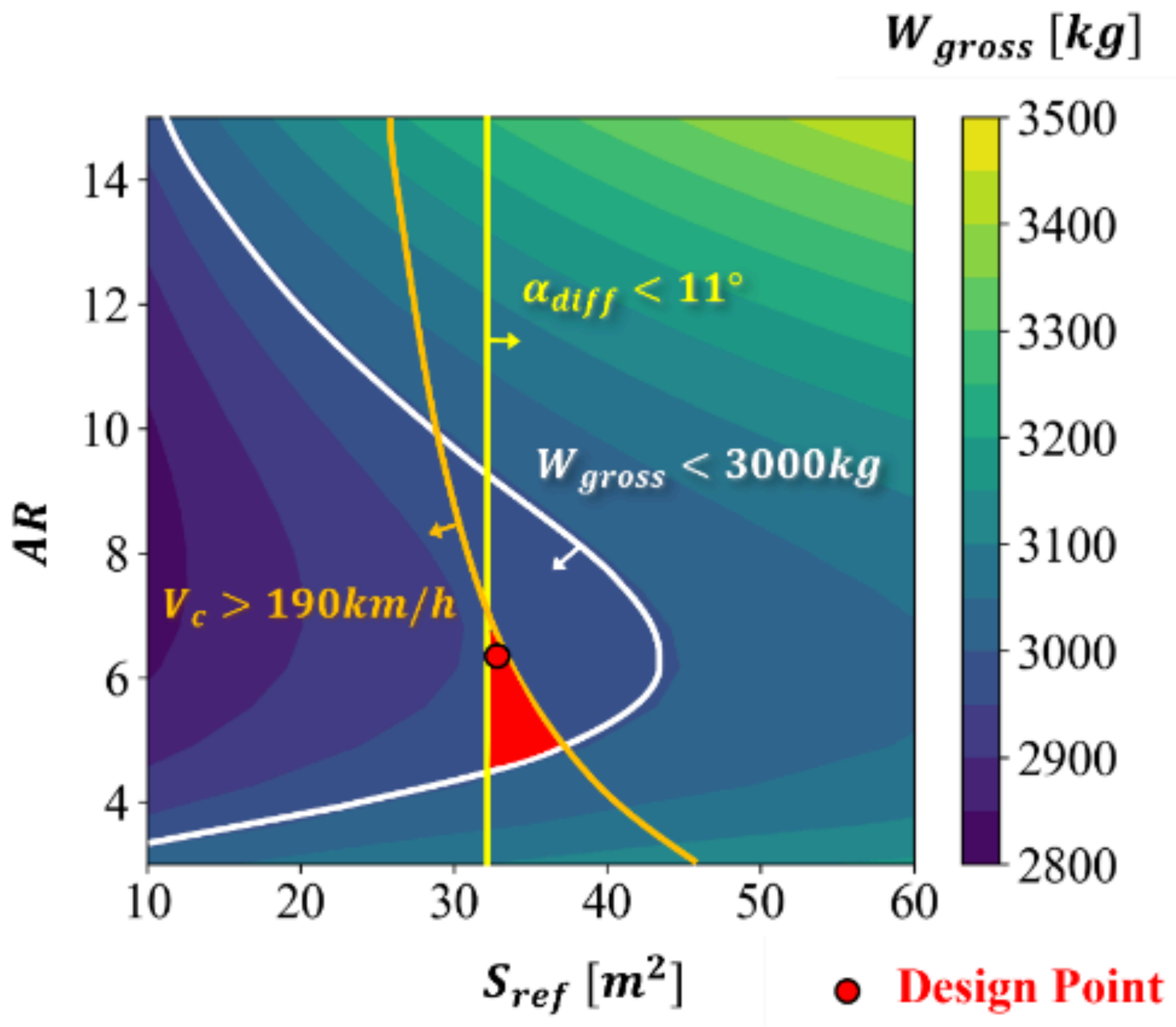


Fig. 6 Design Results of cargo eVTOL

Weight Estimation

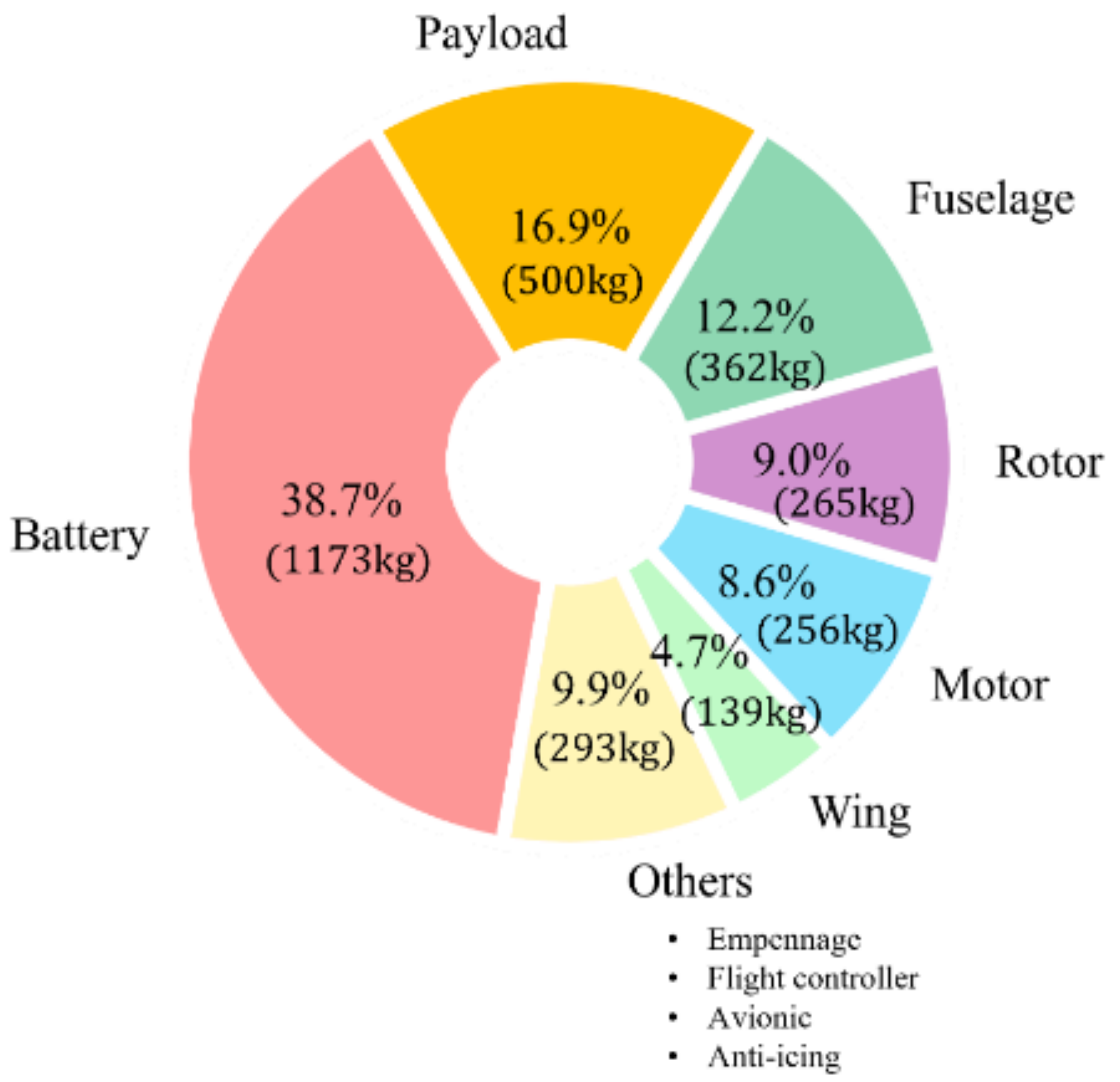


Fig. 7 Estimated mass fraction of each aircraft components

Components	Weight [kg]	Components	Weight [kg]
Wing	**138.9**	**Fuselage**	**361.6**
Main spar	60.2	*Main tube fraom*	188.9
In-plane truss	9.7	*Attachments and fittings*	11.2
Attachments and fittings	6.8	*Wires*	7.5
Ribs	17.6	*Fuselage fairing*	74.6
Leading-edge-sheeting	26.2	*Drive system*	79.5
Trailing edge	5.9	*Landing gear*	0
Covering	4.7	*Furnishing*	0
Bat tip	8.1		
Motor	**253**	**Rotor**	**265**
Stator core	110.7	*Main spar*	120.5
Rotor core	69.0	*Leading-edge-sheeting*	72.3
Permanent magnet	22.1	*Trailng edge*	67.5
Shaft	12.1	*Others*	4.8
Windlings	39.0		
Empennage	**11.3**	**Refrigeration system**	**100**
Horizontal tail	0	*Compressor*	54
Vertical tail	11.3	*Structural frame*	32
		Insulating materials	14
Battery	**1173**	**Motor Controller**	**65.1**
BMS (cruise)	119.3	**Flight controller**	**11.1**
Battery Cell (cruise)	477.1	**Anti-icing**	**24**
Battery Pack (cruise)	596.4	**Avionics**	**80.4**
BMS (lift)	126.3	**Payload**	**500**
Battery Cell (lift)	505.2	**Gross weight**	**2984**
Battery Pack (lift)	631.5		

Table 1 Weight breakdown list

Sizing Results

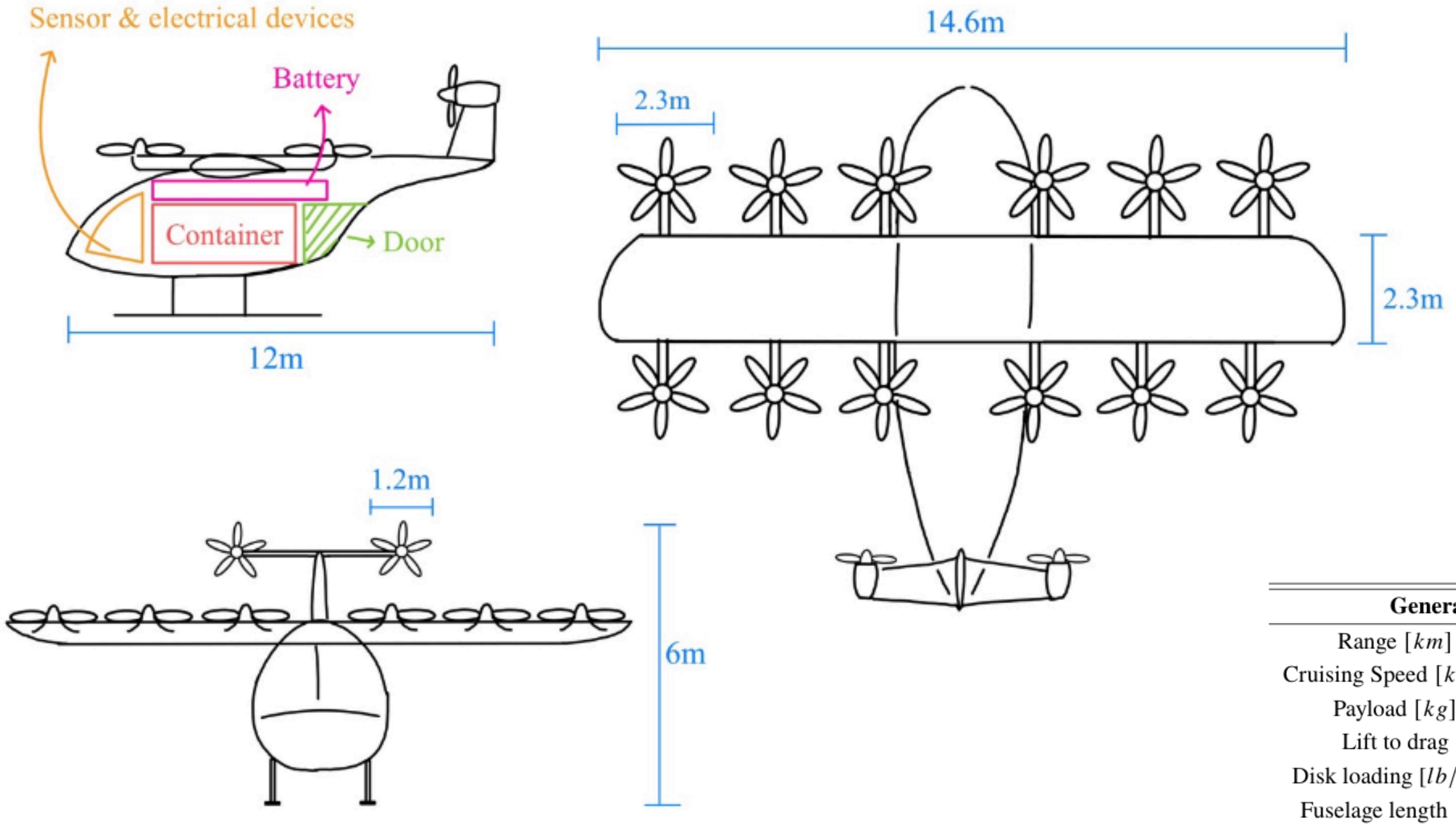


Fig. 8 Three-view drawing of designed eVTOL

General		Wing		Rotor	(lift)	(cruise)
Range $[km]$	80	Span $[m]$	14.6	# of rotor	12	2
Cruising Speed $[km/h]$	190	Aspect ratio	6.4	Diameter [m]	2.3	1.2
Payload $[kg]$	500	Area $[m^2]$	33.5	RPM	1380	3100
Lift to drag	19.1	Loading $[lb/ft^2]$	18.3	$V_{tip}[Mach]$	0.49	0.60
Disk loading $[lb/ft^2]$	12			$\theta_{tip}[°]$	10.7	18.0
Fuselage length $[m]$	12					

Table 1 Sizing Results of Cargo eVTOL

Cost Analysis

Cost Analysis

Total cost

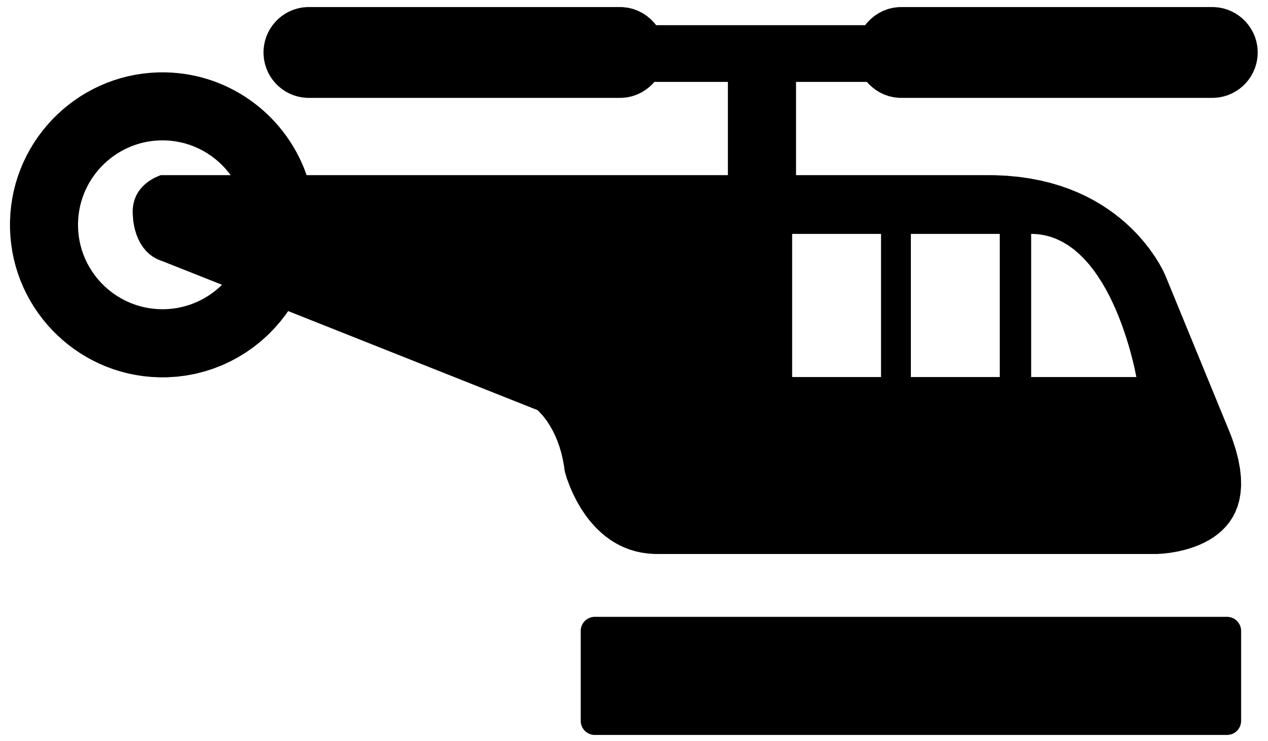
Book Depreciation Cost + Variable Cost + Fixed Cost = Operation Cost	Infrastructure Cost(15~50%)

Book Depreiciation Cost

R44

https://www.pngegg.com/en/png-zfuyk

Life cycle : 10 years
4 one-way trip per day



- **Gross Weight : 1,134kg**
- **Cost : $473,000**

- **Gross Weight : 3,000kg**
- **Cost : $1,251,000**

-> $86 per one-way trip

Variable Cost

https://www.pngegg.com/en/png-ppzyg

- Battery Weight : 1,200kg
- Charging cost : $0.12/kWh
- Charging efficiency : 0.9
- Battery pack cost : $400/kWh
- Battery Life : 2000 cycles

$$\approx 0.25(Variable\ Cost)$$

-> $240 per one-way trip

Fixed Cost / Infrastructure Cost

$$Fixed\ Cost \approx 0.5(Variable\ Cost)$$

-> $120 per one-way trip

$$Infrastructure\ Cost(50\%)$$

https://www.rolandberger.com/en/Insights/Publications/Urban-Air-Mobility-Designing-vertiports-following-a-non-exclusive-ecosystem.html

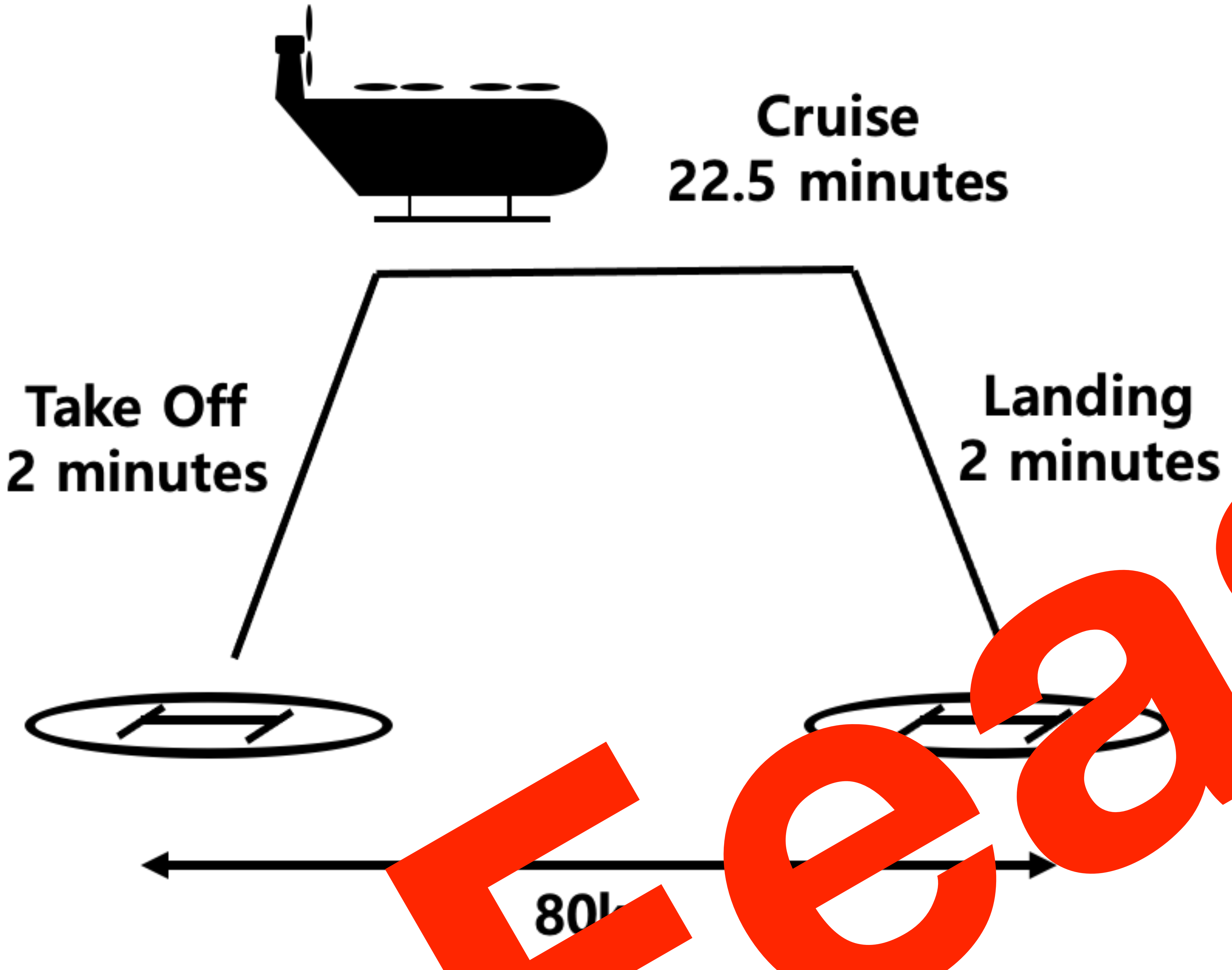
$$Operation\ Cost \approx \$450$$

+

$900 per one-way trip << $4500(=$9/kg * 500kg)

Conclusion

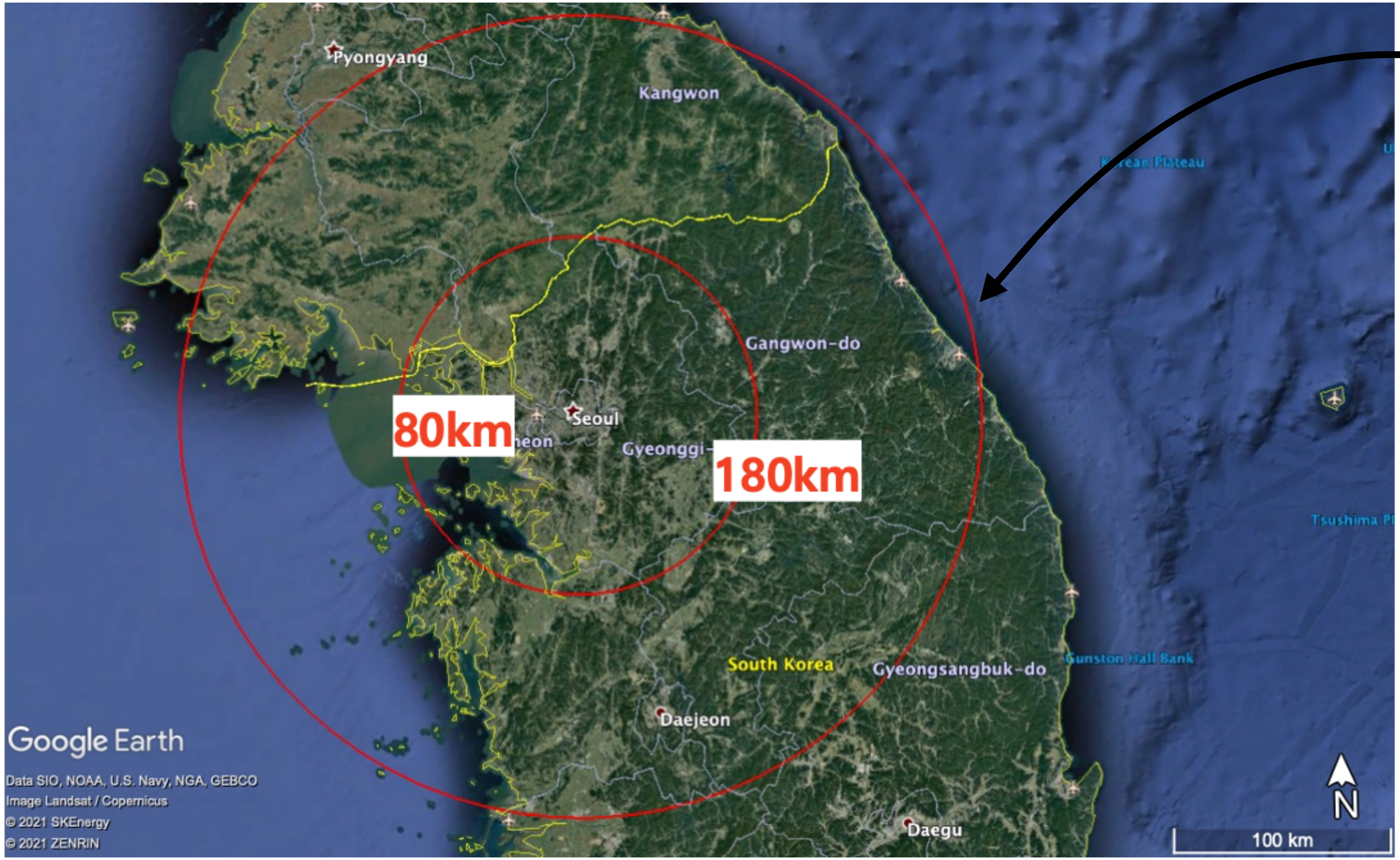
Conclusion



Feasible!

- Total Gross Weight < 3000kg
- Tip Speed < 0.40M
- Battery : 5C, 200Wh/kg
- Payload : 500kg
- Range > 80km
- Price < $9/kg

Conclusion



Near future

http://www.ainet.link/4004

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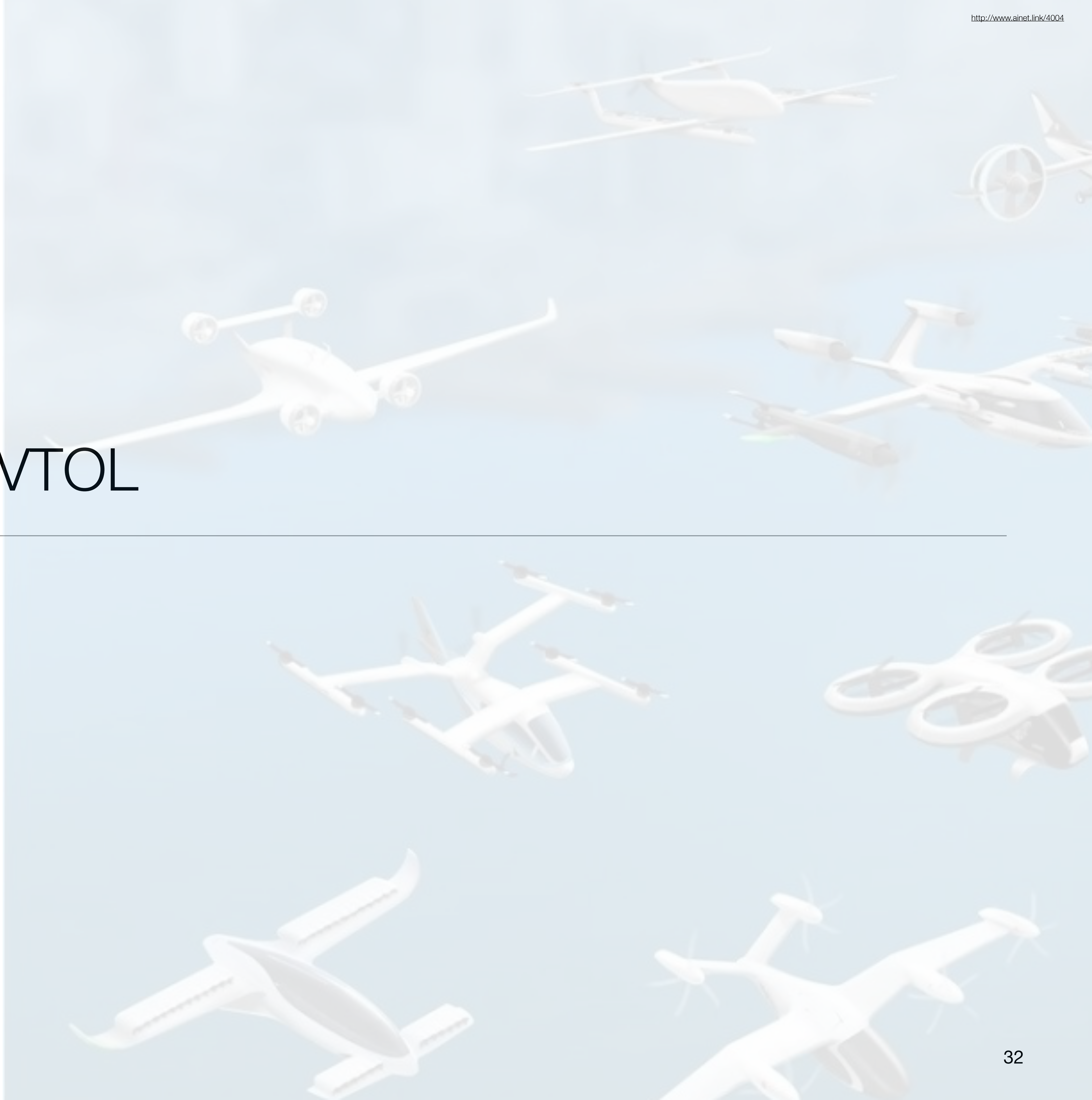

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