4. Weight and Performance Estimation for eVTOL aircraft

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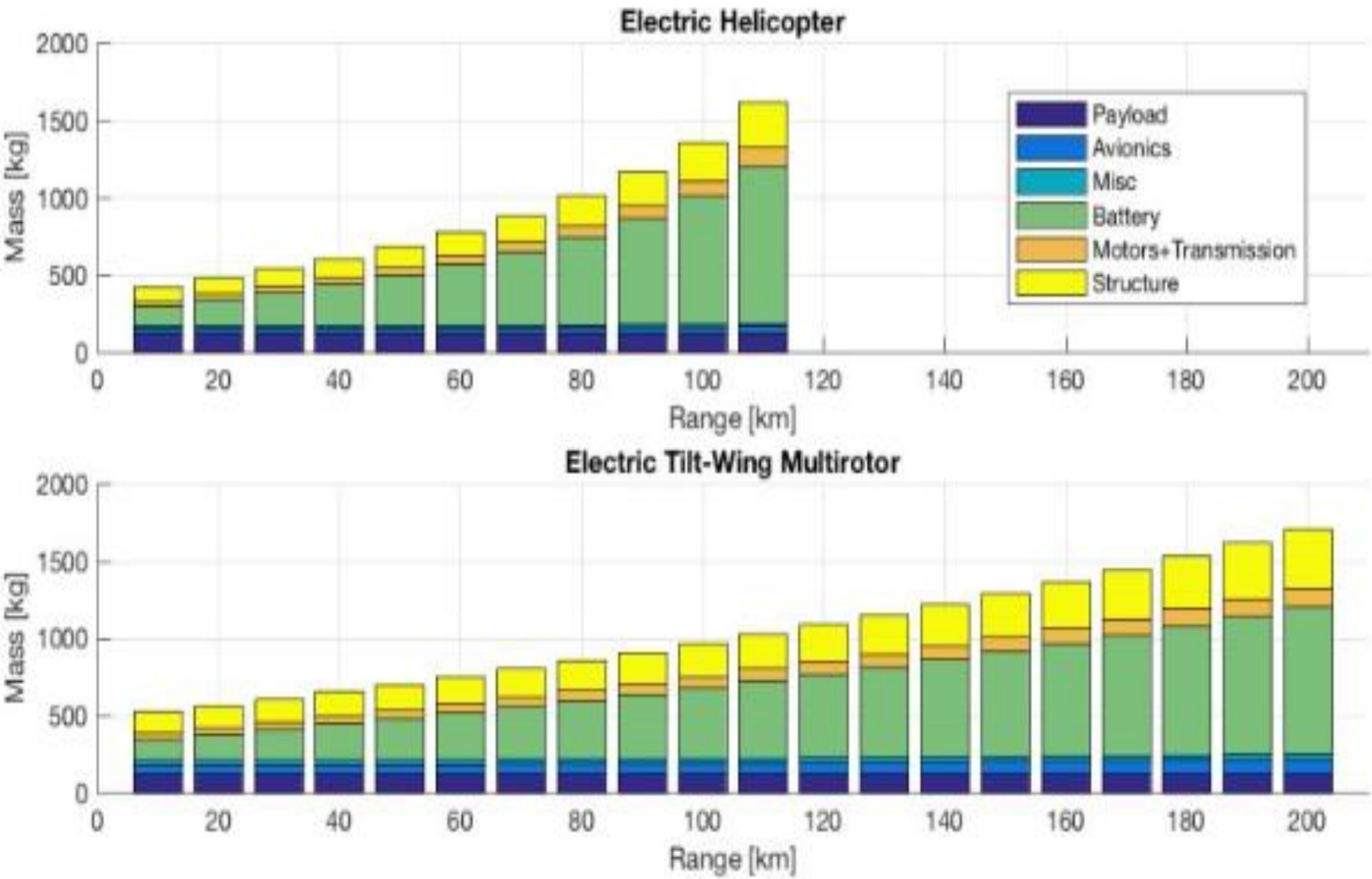
eVTOL Weight Breakdown

Weight Breakdown for a UAM eVTOL Aircraft

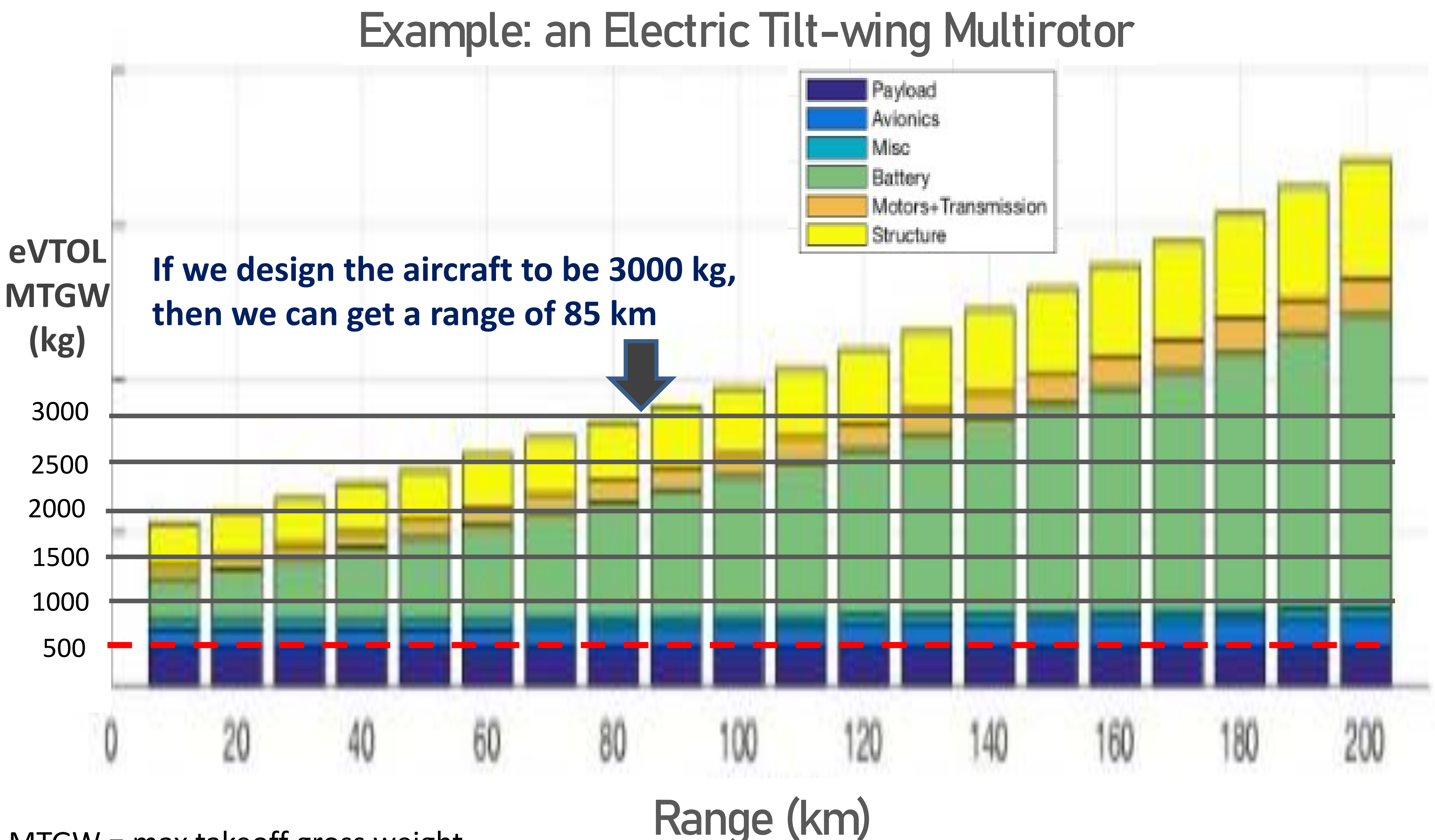
- **Payload (? kg = ? pax, or pax + cargo)**
  - Passengers, pilot
- **Avionics must be light**
  - Electrical wiring
  - Navigation instruments, communication, weather radar, etc…
- **Battery = around 25 - 35% of takeoff weight**
  - Cell & pack
  - Management system
  - Cooling?
- **Structure must be light**
  - Fuselage, wing, tail, landing gear, motor pylon, tilting mechanism…
- **Propulsion, use best technology**
  - Electric motor, inverter, electrical wiring, rotors….
- **Miscellaneous must be light**
  - Furnishing: seats, cabin interior, headsets, etc….
  - Parachute?
  - Environmental control system
  - Contingency (5 or more %?)

Electric Helicopter vs eVTOL Weight Breakdown



Source: https://acubed.airbus.com/blog/vahana/vahana-configuration-trade-study-part-ii/

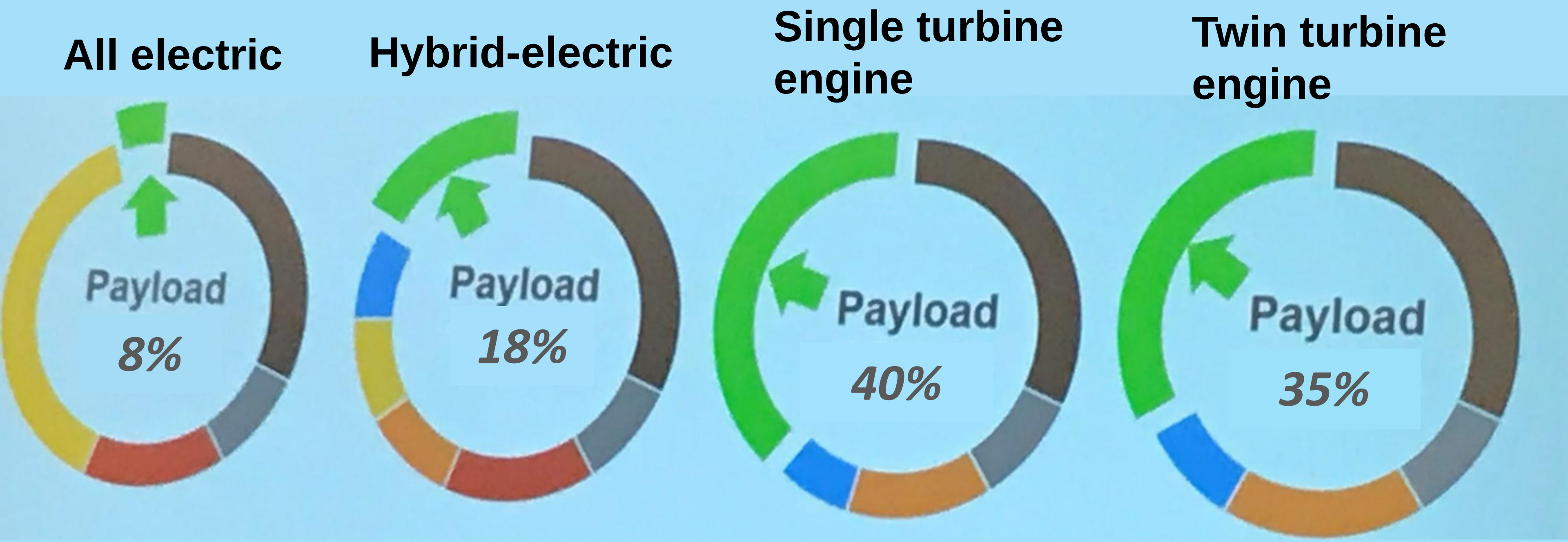
Use this chart to see if we fix the payload at 500kg, then what range can we obtain at different eVTOL aircraft weight?



MTGW = max takeoff gross weight

Source: https://acubed.airbus.com/blog/vahana/vahana-configuration-trade-study-part-ii/

Assume the MTGW are Identical, Below Results from Honeywell Shows All-Electric VTOL Has the lowest Percentage Useful Payload

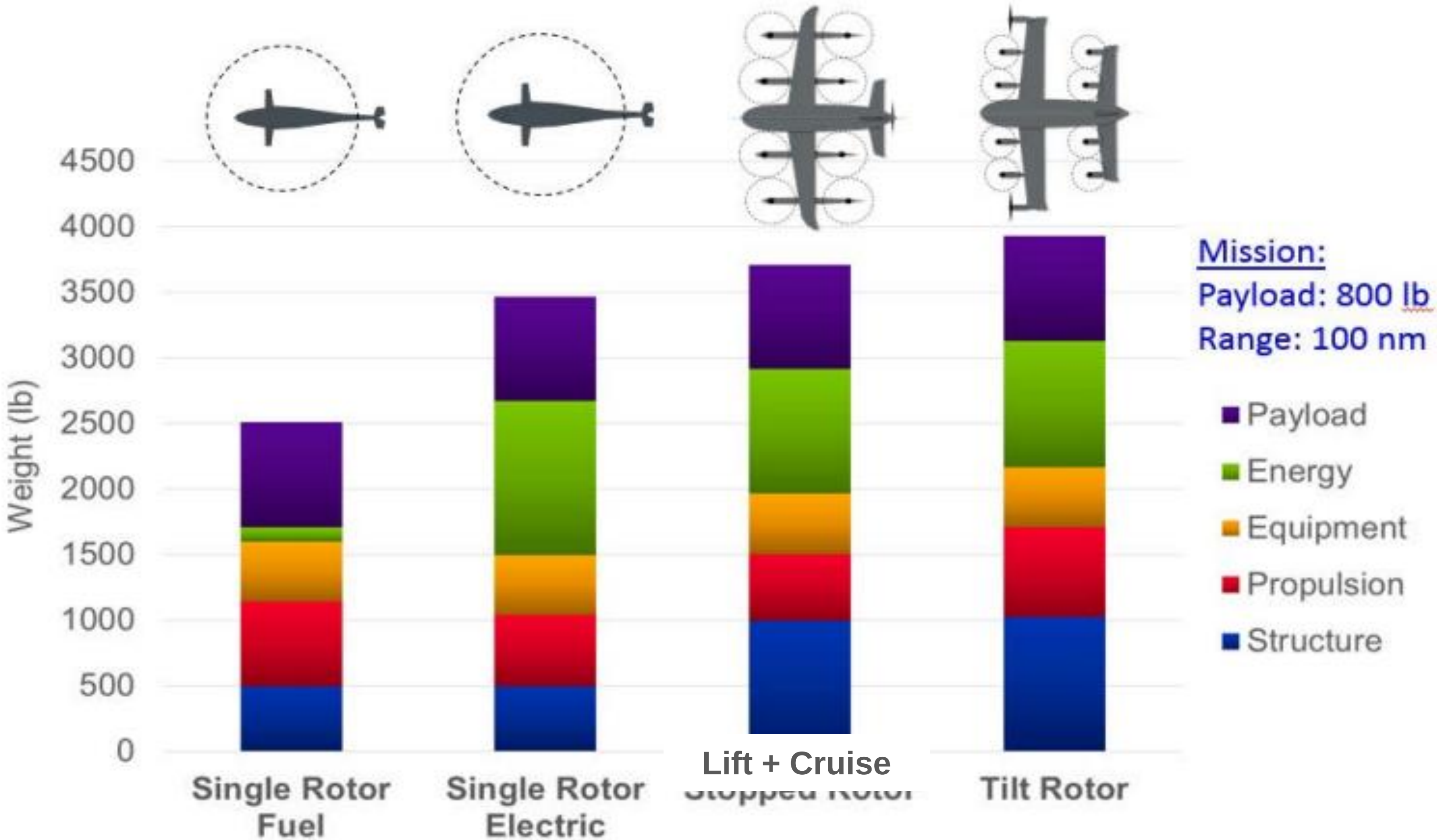


- Payload
- Structure
- Equipment
- Electric propulsion
- Mechanical propulsion
- Battery
- Fuel

From data presented by Honeywell at 2019 VFS Arizona eVTOL Conference

Weight Breakdown of Conceptual Designs

This shows to carry the same payload and do the same range, a helicopter has the lowest MTGW



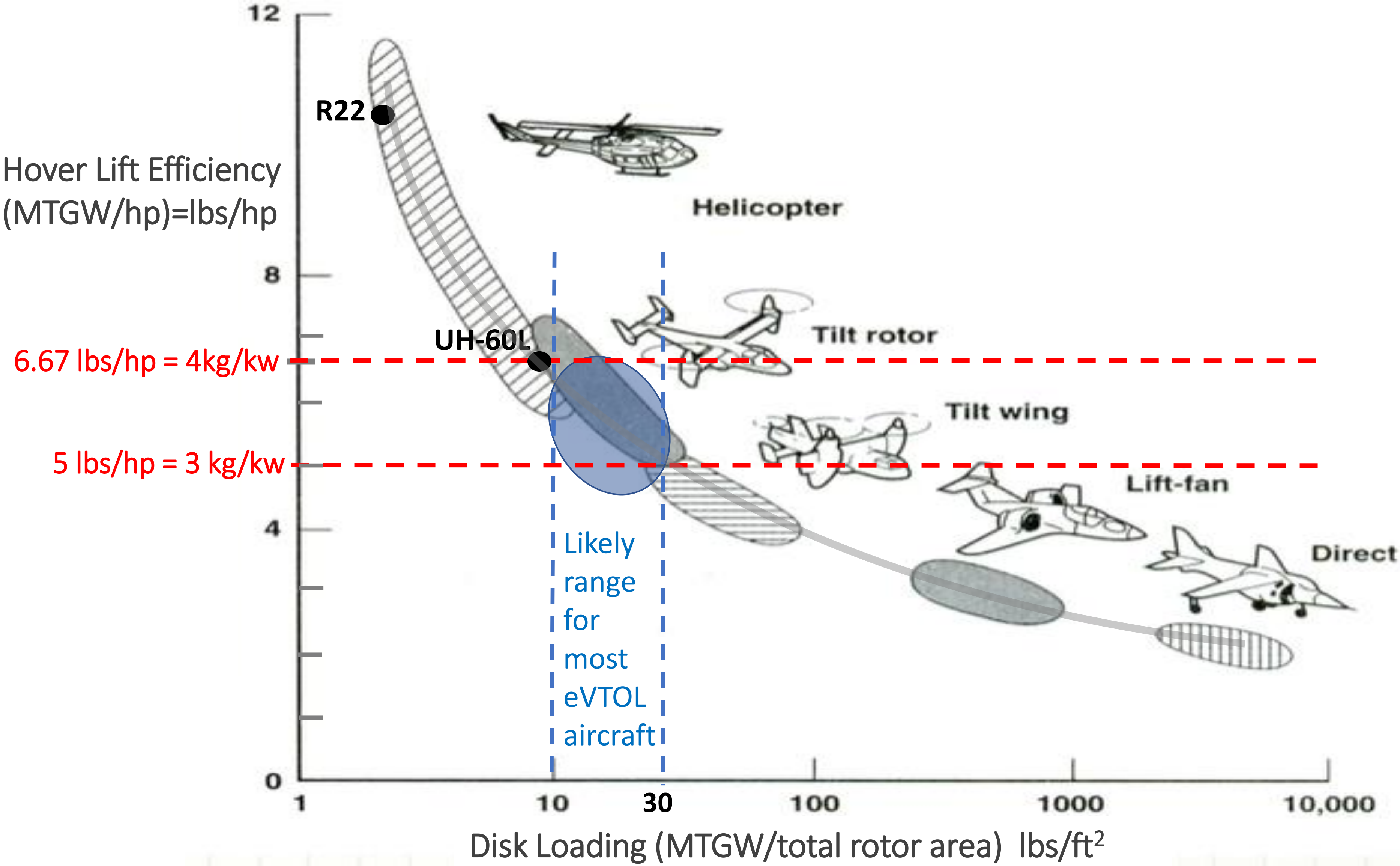
Source: Boeing's paper on reducing electric VTOL aircraft cost
https://www.researchgate.net/publication/318235979_A_Study_in_Reducing_the_Cost_of_Vertical_Flight_with_Electric_Propulsion?enrichId=rgreq-be42bcbb976fca34e696d338bcafd754-XXX&enrichSource=Y292ZXJQYWdlOzMxODIzNTk3OTtBUzo1NzAwNDI4OTEwOTYwNjRAMTUxMjkyMDIyNDQ0OQ%3D%3D&el=1_x_3&_esc=publicationCoverPdf

However, this does not mean all-electric VTOL aircraft is not practical as compared to engine powered helicopters or airplane.

In this decade, eVTOL aircraft will be suited for intra-city UAM (Urban Air Mobility) with range around 200 km. Next decade, we can go well beyond 200 km, which is required for inter-city.

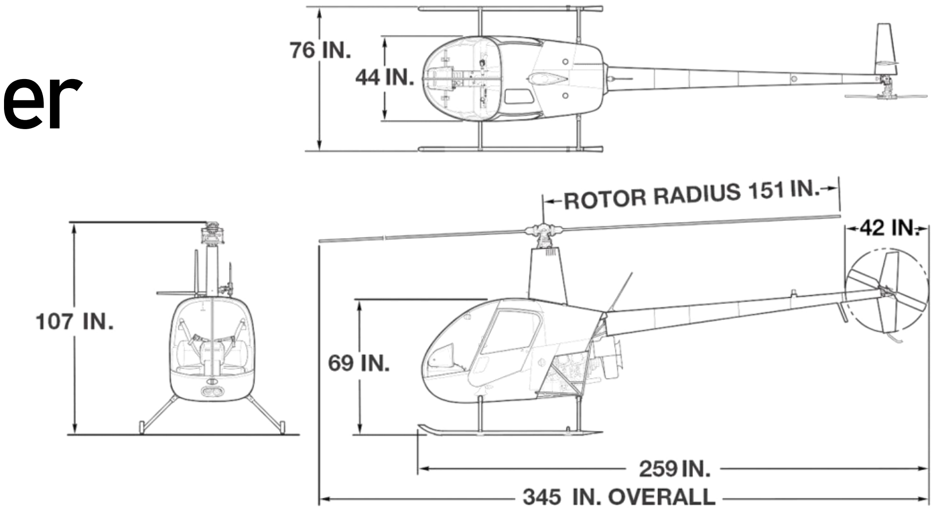
Let's design an eVTOL together, and do a quick performance and weight estimate

High Disk Loading Reduces Hover Efficiency



Source: https://history.nasa.gov/monograph17.pdf

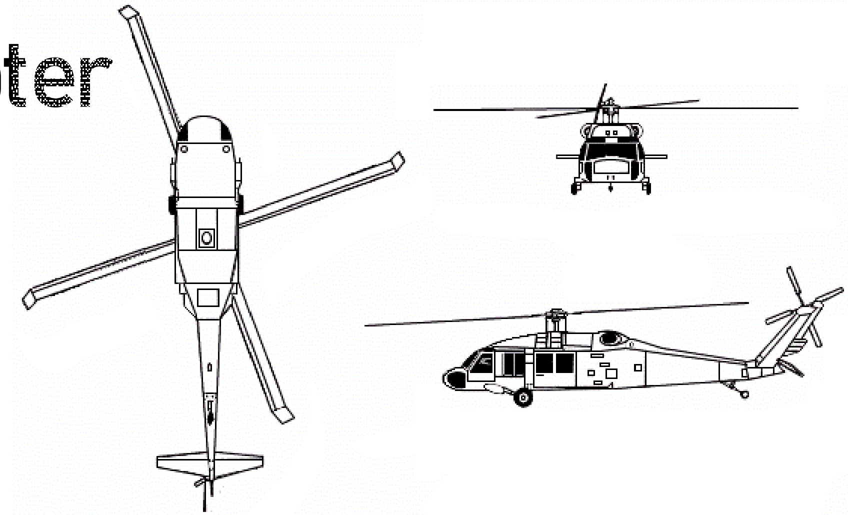
Robinson R22 Helicopter



Power loading in hover = 1370 lbs / 131 hp = **10.5 lbs/hp**
= 95.6 hp/1000 lbs
Power loading in hover = 622 kg / (131 hp x .746 kw/hp)
= **6.36 kg/kw**
Disk loading = 1370 lbs / 497.4 ft^2 = **2.75 lbs/ft^2**

Helicopter	R22 Beta II
Engine	Lycoming O-360, four cylinder
Horsepower	Derated to 131 hp for takeoff and 124 continuous
Maximum Gross Weight	1370 lb (622 kg)
Approximate Empty Weight (including oil & standard avionics)	880 lb (399 kg)
Standard Fuel (16.9 gal)	101 lb (46 kg)
Auxiliary Fuel (9.4 gal)	56 lb (25 kg)
Pilot, Passenger, and Baggage (with standard fuel)	389 lb (176 kg)
Max Airspeed (Vne)	102 kts (189 km/h)
Cruise Speed	up to 96 kts (178 km/h)
Maximum Range (no reserve)	approx 250 nm (460 km)
Hover Ceiling IGE at 1370 lb, ISA	9400 ft
Hover Ceiling OGE at 1300 lb, ISA	8000 ft
Maximum Operating Altitude, ISA	14,000 ft
Electrical System	14 volt

Sikorsky UH-60L Helicopter



Max power loading in hover = 22,000 lbs / 3300 hp = **6.7 lbs/hp**

= 149 hp / 1000 lbs

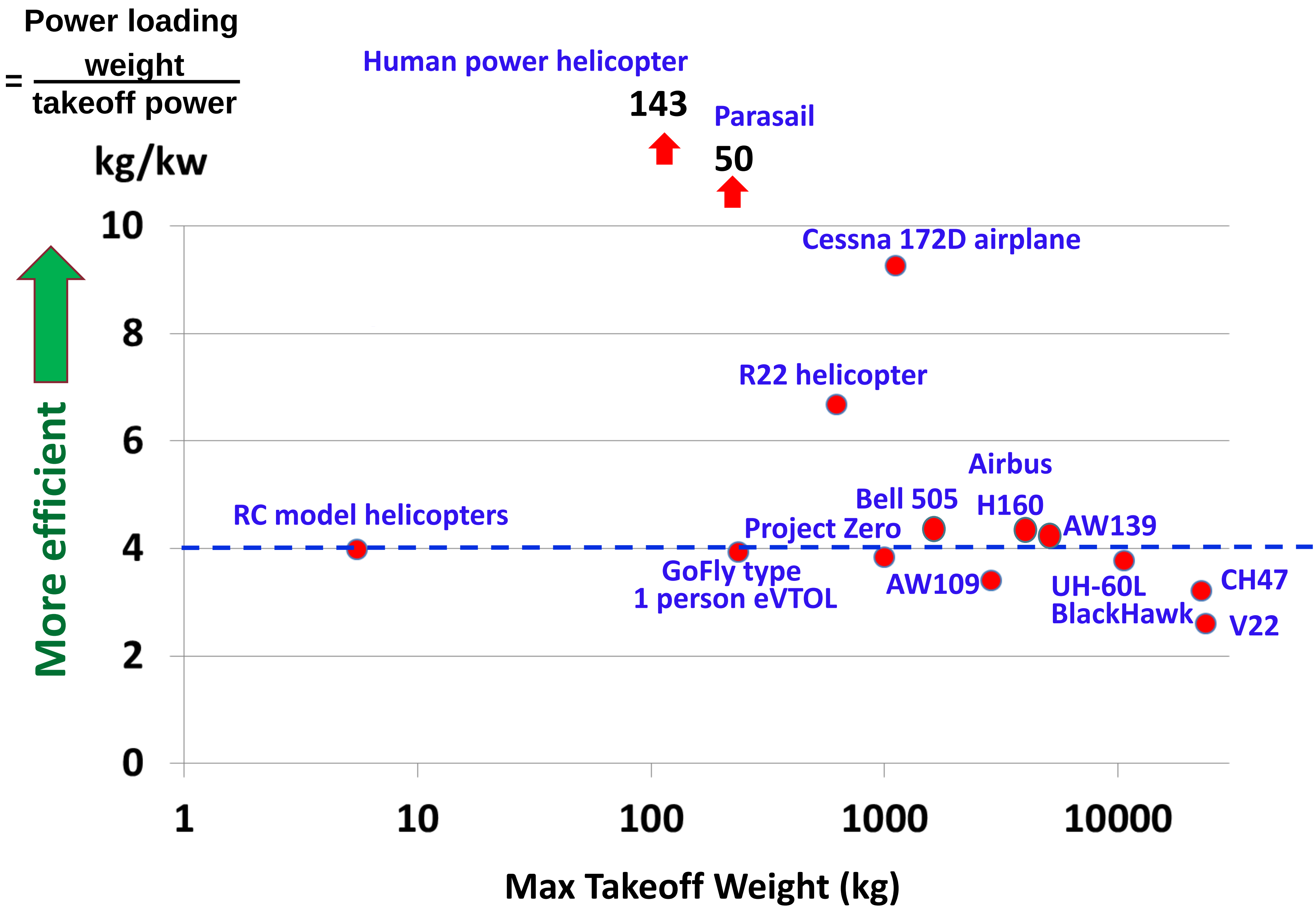
Max Power loading in hover = 9979 kg / (3300 hp x .746 kw/hp)

= **4 kg/kw**

Disk loading = 22,000 lbs / 2262 ft^2 = **9.73 lbs/ft²**

Helicopter	Sikorsky UH-60L Black Hawk
Engine	Two T700-GE-701Cs
Horsepower	1,880 hp each
Maximum Gross Weight	22,000 lb (9,979 kg)
Approximate Empty Weight (including oil & standard avionics)	11,516 lb (5,224 kg)
Main rotor radius	26.83 ft
Hovering torque	90%
Main rotor rpm	258
Max Airspeed (Vne)	193 knots
Cruise Speed	4,000 ft; 95°F 152 knots
Maximum Range (internal fuel)	approx 315 nm (583 km)
Hover Ceiling OGE at 70 deg F	9,375 ft
Hover Ceiling OGE at 95 deg F	7,650 ft
Maximum Operating Altitude ISA	19,151 ft
Length	64 ft 10 in

Trend Shows Most Rotorcraft Have 4 kg/kw for Power Loading

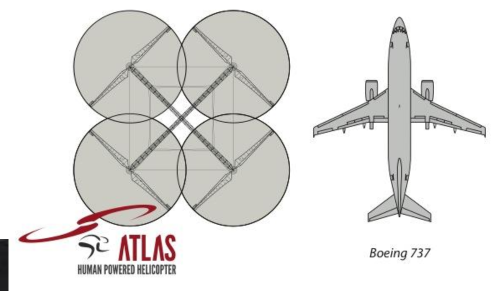


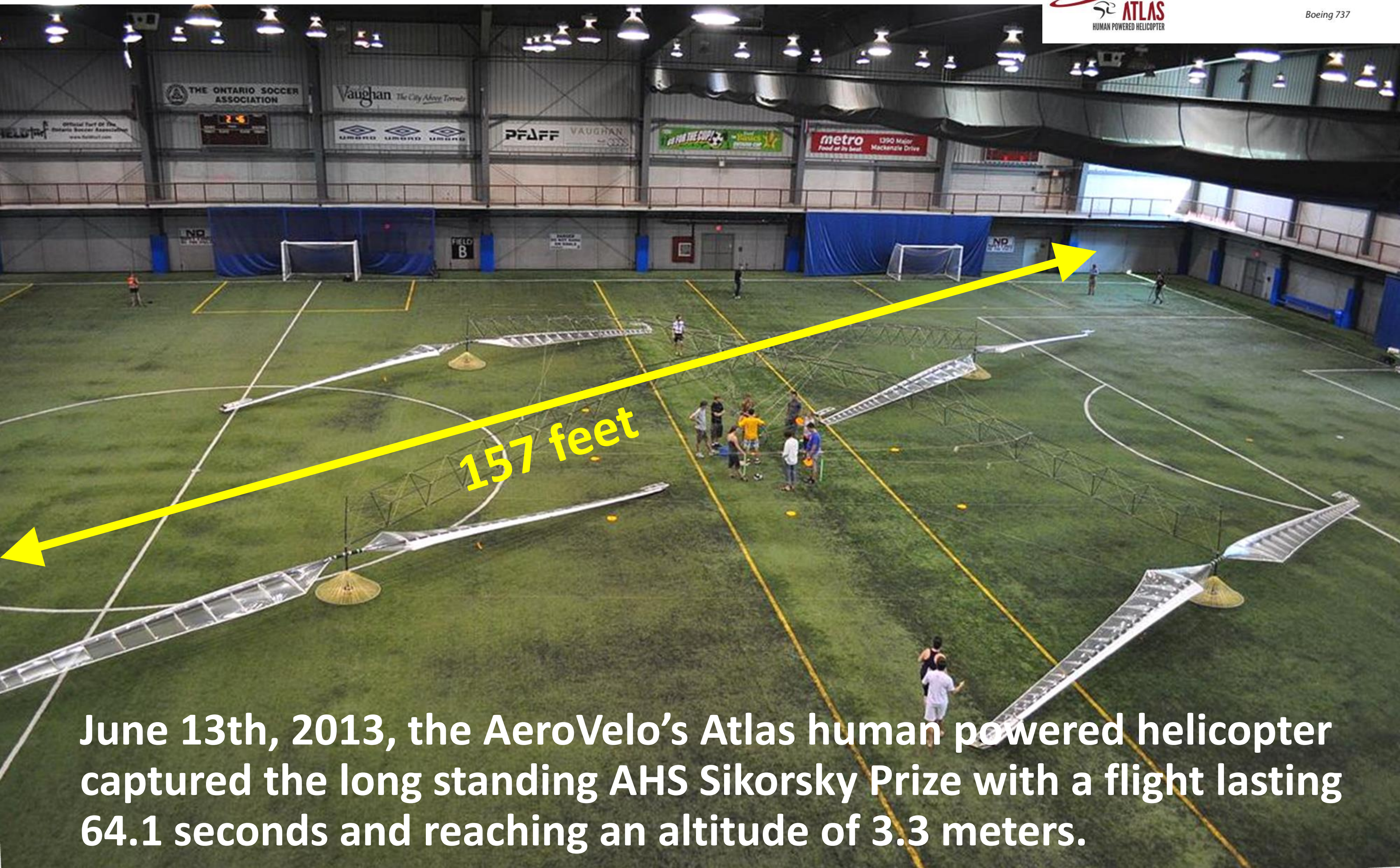
Atlas Human Powered Helicopter

Professional track cyclist produced burst of 770 watts (roughly 1 hp) for one minute. Atlas' empty weight 55 kg, with cyclist 110 kg. Power loading = 110 kg/.77kw = 143 kg/kw

Source: https://verticalmag.com/news/22771-canadian-aerovelo-atlas-human-powered-helicopter-expands-fli-html/

Atlas Human Powered Helicopter





June 13th, 2013, the AeroVelo's Atlas human powered helicopter captured the long standing AHS Sikorsky Prize with a flight lasting 64.1 seconds and reaching an altitude of 3.3 meters.

Question

If our eVTOL MTGW = 7,000 lbs = 3,175 kg, how much power is required to takeoff?

(I choose 7000 lbs because FAA and EASA certification rules for eVTOL are written around Part 23 + Part 27 where MTGW < 7000 lbs)

Answer

Based on previous chart, we see most helicopters (they usually have disk loading < 12 lbs/ft^2) have a power loading of 4 kg/kw for taking off and hovering.

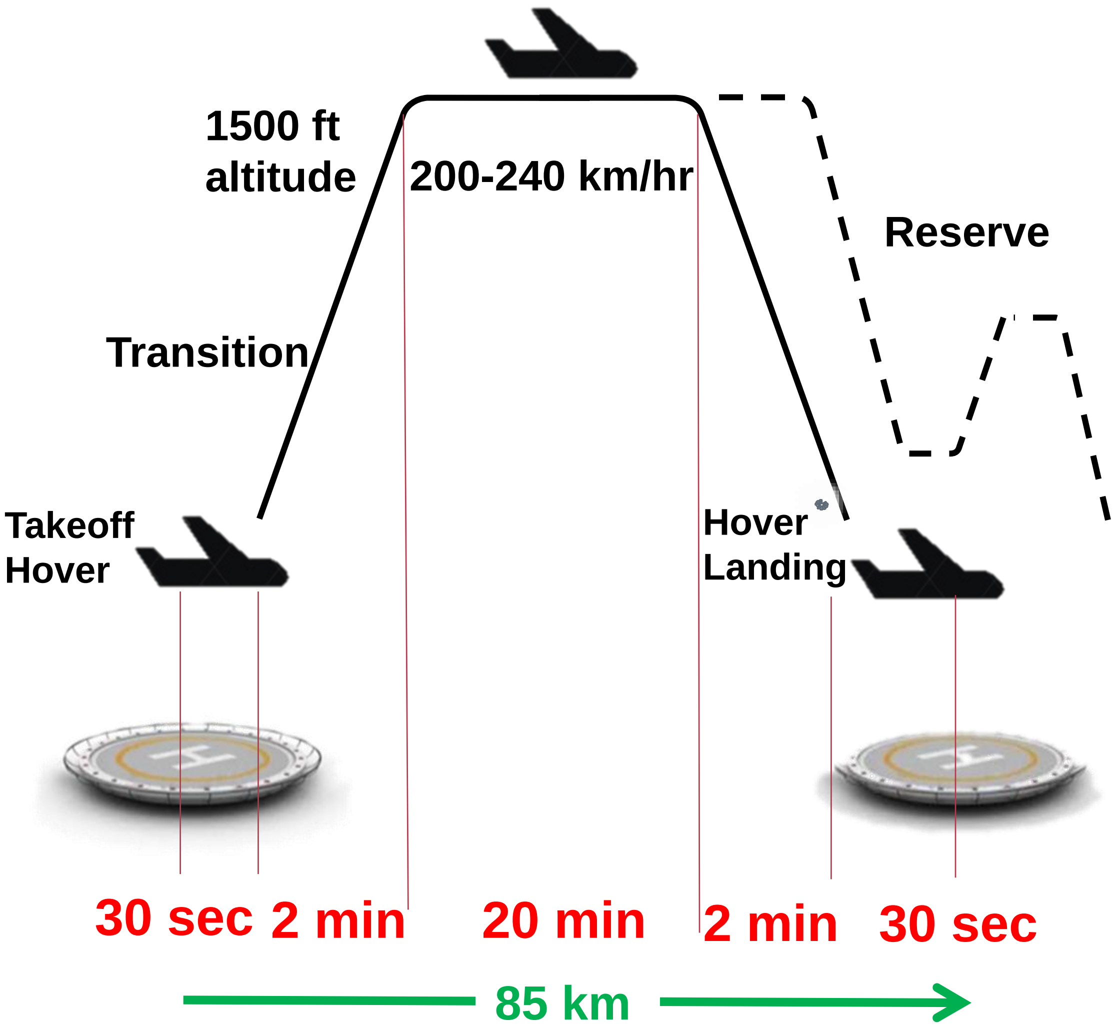
Assume a light disk loading, then 3,175 kg / 4 kg/kw = 794 kw power required to takeoff.

Notice that higher disk loading VTOL aircraft, like V22 (close to 20 lbs/ft^2), have a power loading of only 3 kg/kw. Then 3175 kg / 3 kg/kw = 1.058 kw power required.

Question

How heavy is the battery if we want to fly for 85 km + 10 min reserve?

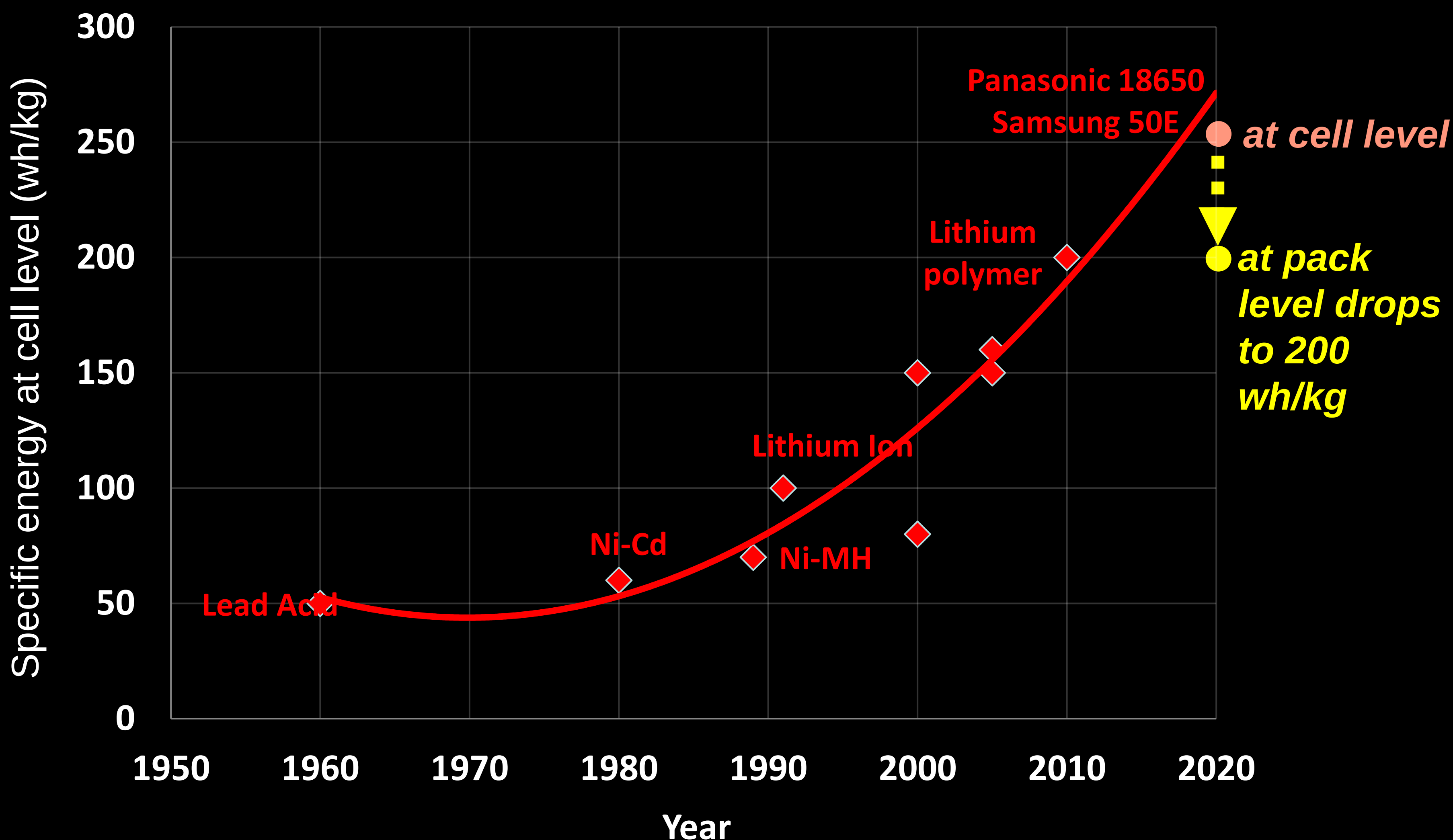
We should be able to easily execute this intra-city mission by 2025, and improve range to >200 km by 2030



Mission

Range = 85 km
Flight time = 25 min
Reserve = 10 min
MTGW = 7,000 lbs
Battery = ? lbs

Base on this chart below, let's assume and use 250 wh/kg at the cell level and 200 wh/kg at pack level



How heavy is the battery if we hover for 20 min + 10 min reserve, and use 200 Wh/kg at pack level?

Power required to hover

794 kw x 0.5 hr = 397 kWh of battery required.

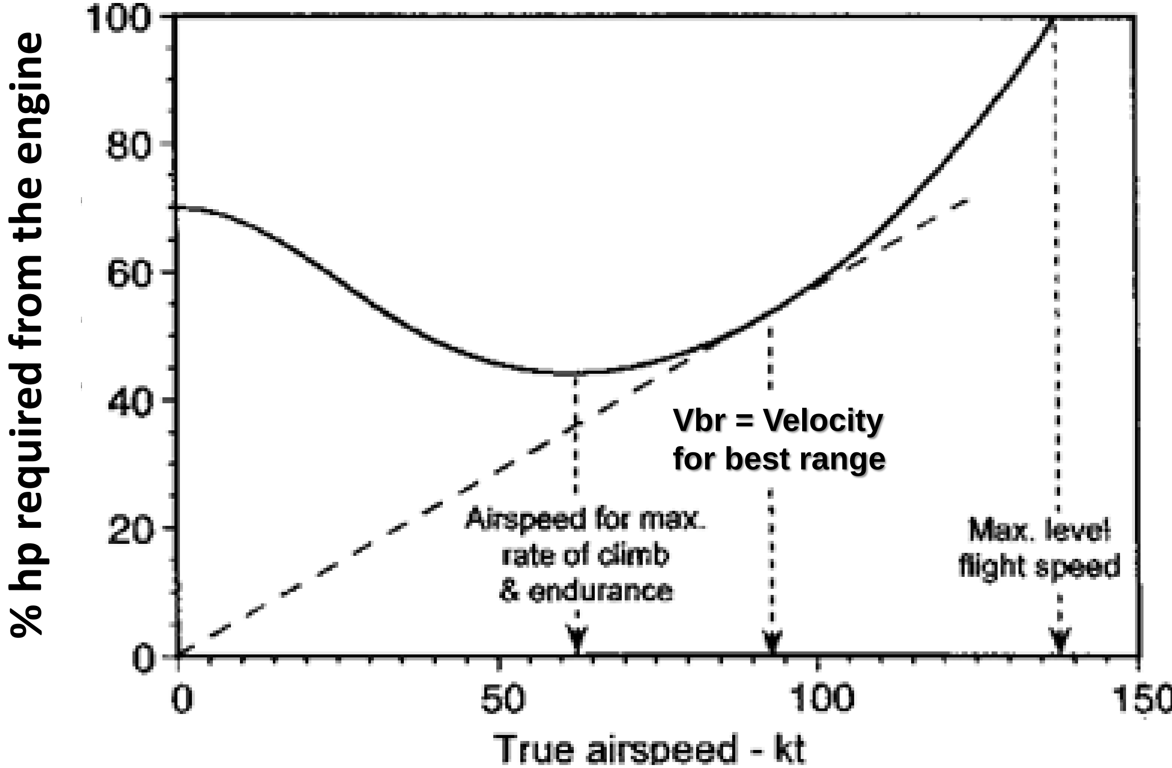
397 kWh / 200 Wh/kg = 1,985 kg = 4,367 lbs

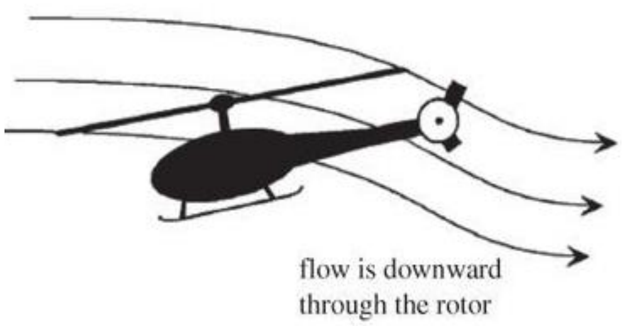
too heavy, that's 63% of our entire aircraft weight !

This is why eVTOLs are not designed to hover all day

Translational Lift Reduces Power at Cruise

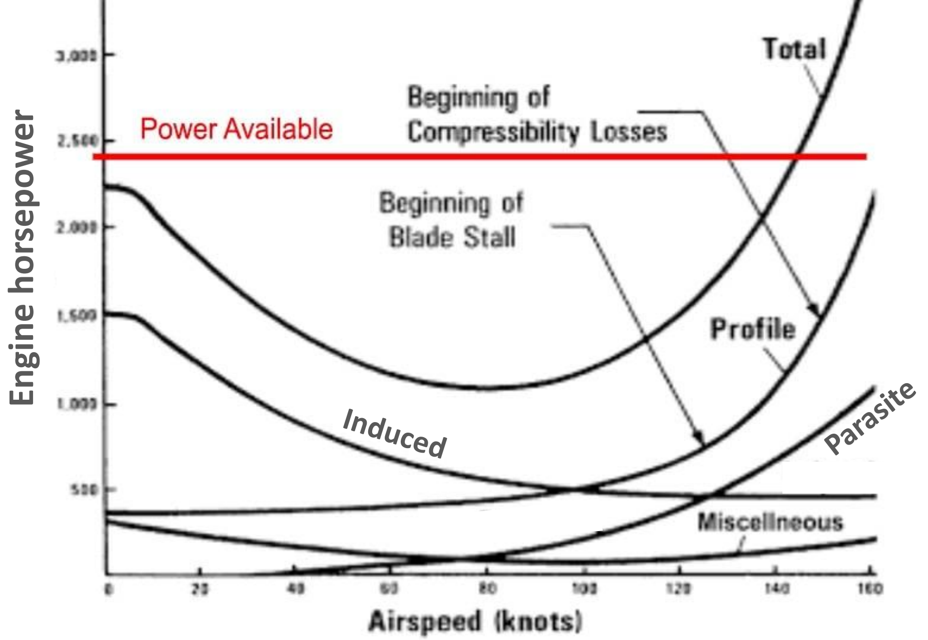
Typical power required curve shape for helicopters





Once the rotor gets into forward flight, the rotor disk starts to behave like a wing, plus the freestream air also flow through the rotor, together that helps reduce the power required to fly at the bucket speed, this region is ideal for cruising.

Power Required vs. True Airspeed for Helicopter



Total Power for a rotorcraft is the sum of these:

Profile power is the *rotor power* required to overcome the friction drag on the blades and push the rotor's shape through the viscous air. It does not change significantly with a change in angle of attack and accounts for 15% to 40% of the main rotor power required in a hover. It stays relatively constant with airspeed until at high speeds compressibility and/or blade stall drive it up.

Induced power is the *rotor power* required to overcome the induced drag C_{Di} developed during the creation of rotor thrust. With an increase in angle of attack, the airflow that moves down through the rotor causes the total reaction lift vector of the blade to tilt rearwards, creating induced drag. It takes around 60% to 85% of the total main rotor power in a hover to overcome it.

Parasitic power is the *additional power* required to move everything else attached to the rotor through the air — the fuselage and everything attached to it. (To overcome C_{D0}) It rises with the cube of airspeed.

Miscellaneous power is to power the tail rotor, hydraulic pumps, gearbox losses, generators, etc.

Source: https://www.rotorandwing.com/2017/10/10/understanding-helicopter-power-requirements-power-struggle/

Power Required is Proportional to Velocity Cubed

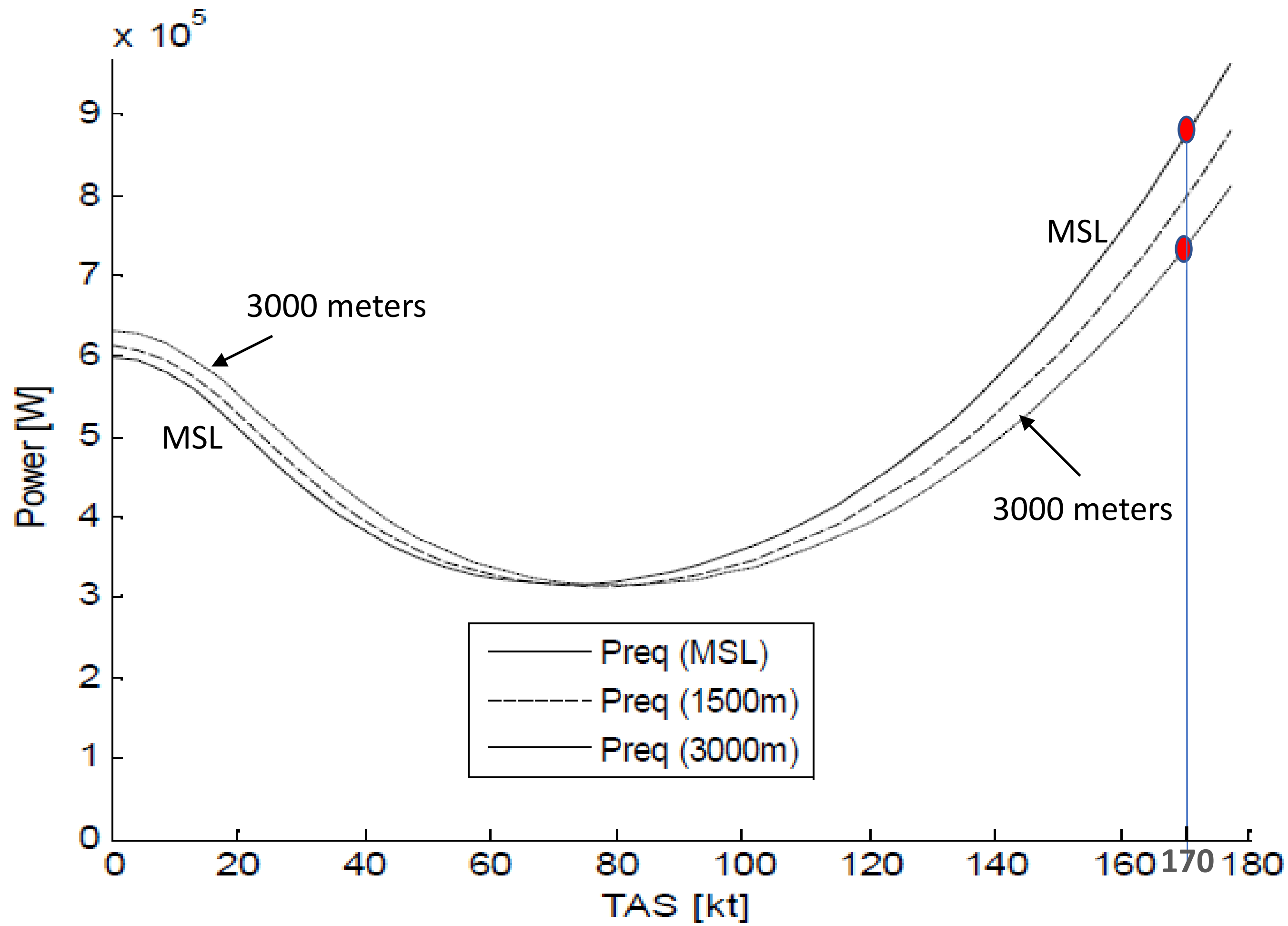
Power = Force x velocity
= Drag x velocity

Drag $D = \frac{1}{2} C_D \rho v^2 S$ where $C_D = C_{D0} + C_{Di}$

Power proportional to v^3

Source: https://aviation.stackexchange.com/questions/58622/how-does-the-power-requirement-change-when-weight-and-speed-change

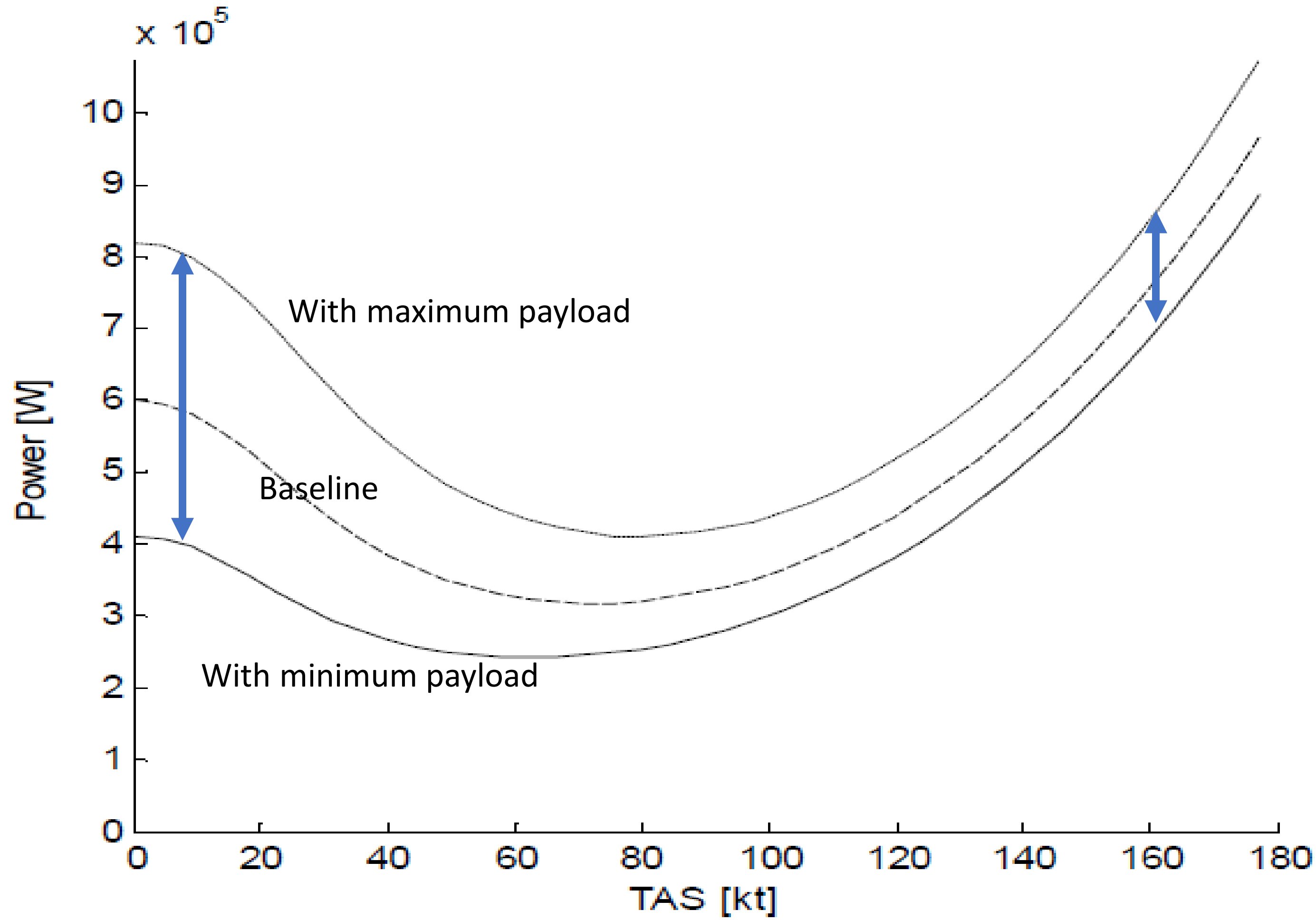
Effect of Airspeed and Altitude on Power Required



Conclusion: at higher altitude, even though there is less engine power available, but its requires a lot less power to fly at similar airspeed.

Source: www.eurocontrol.int/sites/default/files/2019-03/bada-family-h.pdf

Effect of Airspeed and Weight on Power Required

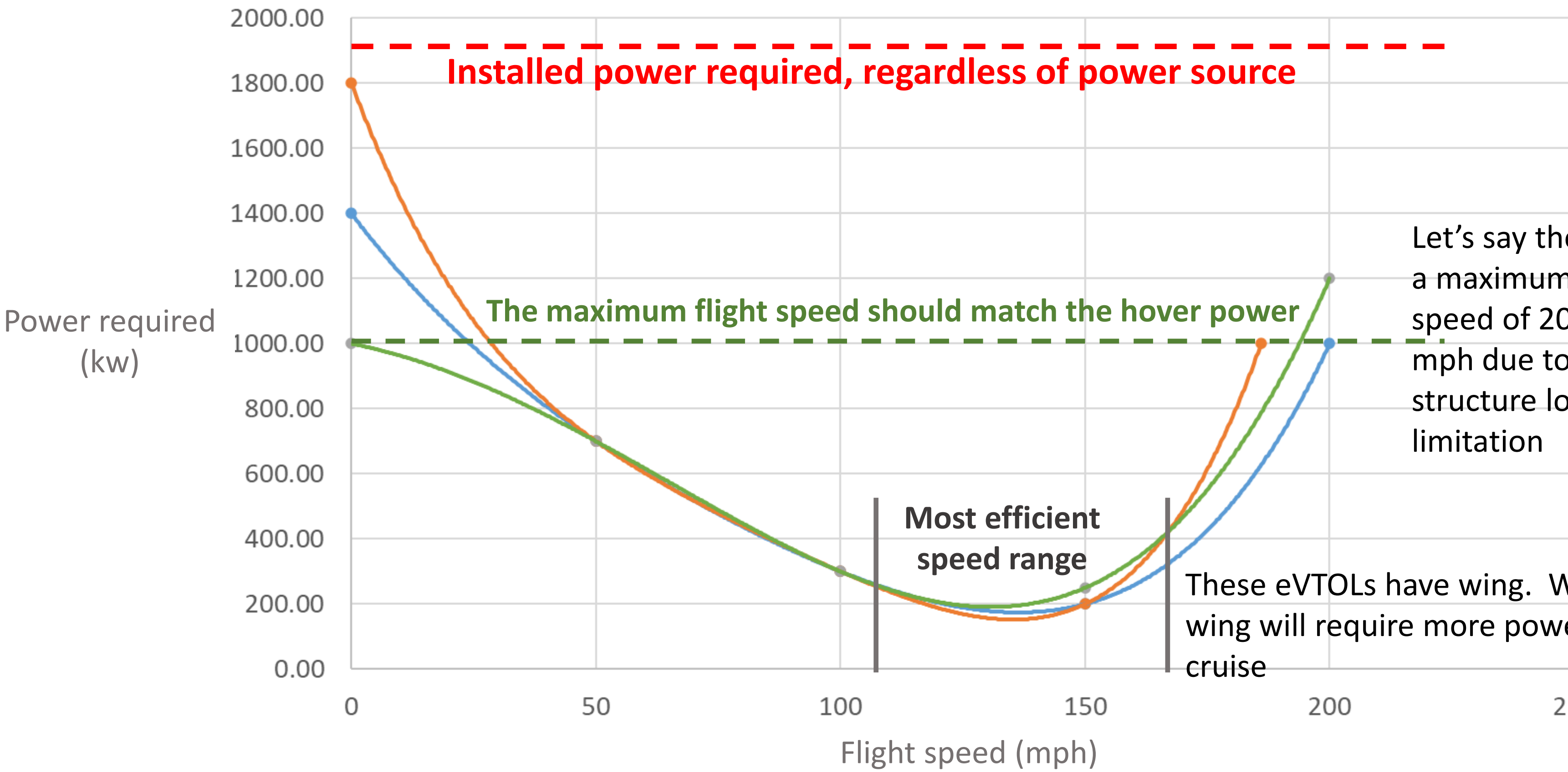


Question for class: Why at higher airspeed, the difference in power required becomes less between the heavy and the light helicopter?

Source: www.eurocontrol.int/sites/default/files/2019-03/bada-family-h.pdf

Predicted Power Required for Three eVTOLs

U-shape power curve is very typical for VTOL aircraft, it does not matter it is electric or not electric power.

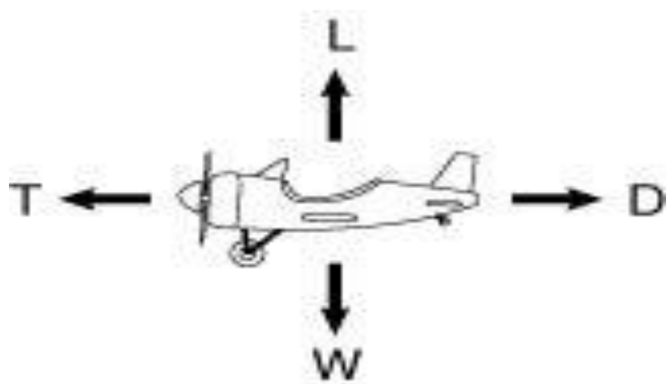


Let's say there is a maximum speed of 200 mph due to structure load limitation

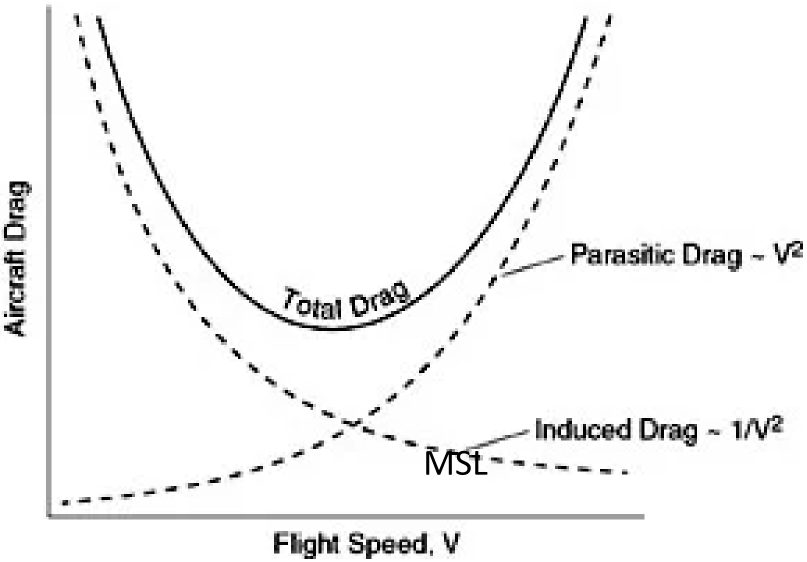
These eVTOLs have wing. Without a wing will require more power during cruise

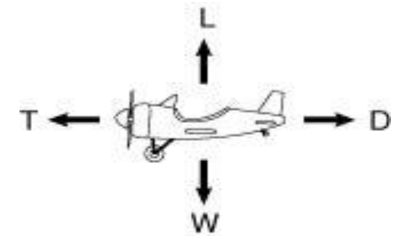
Source: own calculations

Now Let's Look at an Airplane



Airplane Drag in Forward Flight (No Rotor)





$$T = D, \quad L = W \qquad W = L = D\frac{L}{D} = T\left(\frac{L}{D}\right)$$

$$C_D = C_{D_0} + \frac{C_L^2}{\pi e AR}$$ where $L = \frac{1}{2}\rho V^2 S C_L$ and $D = \frac{1}{2}\rho V^2 S C_D$

$$D = \frac{1}{2}\rho V^2 S C_{D_0} + \frac{L^2}{\frac{1}{2}\rho V^2 S}\left(\frac{1}{\pi e AR}\right)$$

$$D = \frac{1}{2}\rho V^2 S C_{D_0} + \frac{W^2}{\frac{1}{2}\rho V^2 S}\left(\frac{1}{\pi e AR}\right)$$

The **minimum drag** is a condition of interest. We can see that for a given weight, it occurs at the condition of maximum lift-to-drag ratio

$$D = L\frac{D}{L} = W\left(\frac{D}{L}\right) = W\left(\frac{C_D}{C_L}\right)$$

We can find a relationship for the maximum lift-to-drag ratio by setting

$$\frac{d}{dC_L}\left(\frac{C_{D_0} + \frac{C_L^2}{\pi e AR}}{C_L}\right) = 0$$

Source: https://ocw.mit.edu/ans7870/16/16.unified/propulsionS04/UnifiedPropulsion4/UnifiedPropulsion4.htm

Minimum Drag Occurs at Maximum L/D

$$\frac{d}{dC_L}\left(\frac{C_{D_o} + \frac{C_L^2}{\pi e AR}}{C_L}\right) = 0$$

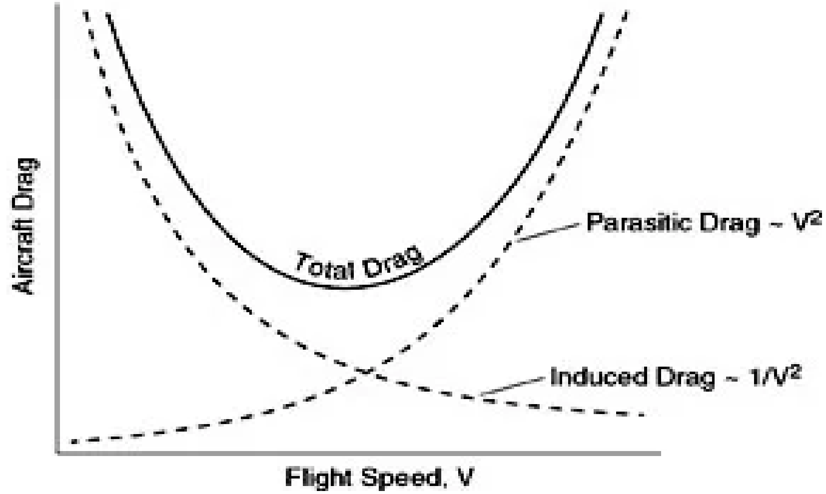
from which we find that $C_{L_{mindrag}} = \sqrt{\pi e AR C_{D_o}}$ $\quad C_{D_{mindrag}} = 2C_{D_o}$

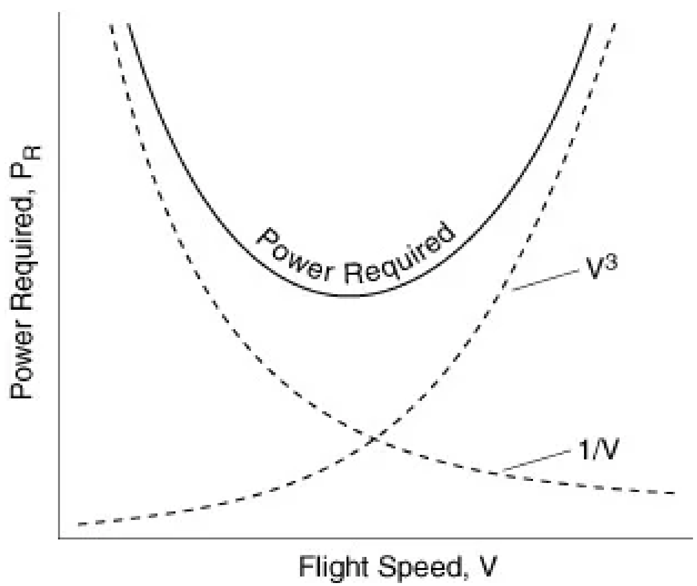
$$\left(\frac{C_L}{C_D}\right)_{max} = \frac{1}{2}\sqrt{\frac{\pi e AR}{C_{D_o}}}$$

$$V_{mindrag} = \sqrt{\frac{W}{\frac{1}{2}\rho S C_{L_{mindrag}}}} = \left[4\left(\frac{W}{S}\right)^2 \frac{1}{\rho^2}\frac{1}{C_{D_o}}\left(\frac{1}{\pi e AR}\right)\right]^{1/4}$$

Source: https://ocw.mit.edu/ans7870/16/16.unified/propulsionS04/UnifiedPropulsion4/UnifiedPropulsion4.htm

Derive Power Required Equation





Now we can look at the propulsion system requirements to maintain steady level flight since

$$T_{req} = D \quad \text{and} \quad P_{req} = T_{req} V = DV$$

Thus the power required (for steady level flight) takes the form

$$D = \frac{1}{2}\rho V^2 S C_{D_o} + \frac{W^2}{\frac{1}{2}\rho V^2 S}\left(\frac{1}{\pi e AR}\right)$$

$$P_{req} = \frac{1}{2}\rho V^3 S C_{D_o} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi e AR}\right)$$

Source: https://ocw.mit.edu/ans7870/16/16.unified/propulsionS04/UnifiedPropulsion4/UnifiedPropulsion4.htm

Maximum Endurance Occurs at Minimum Power

The velocity for minimum power is obtained by taking the derivative of the equation for P_{req} with respect to V and setting it equal to zero.

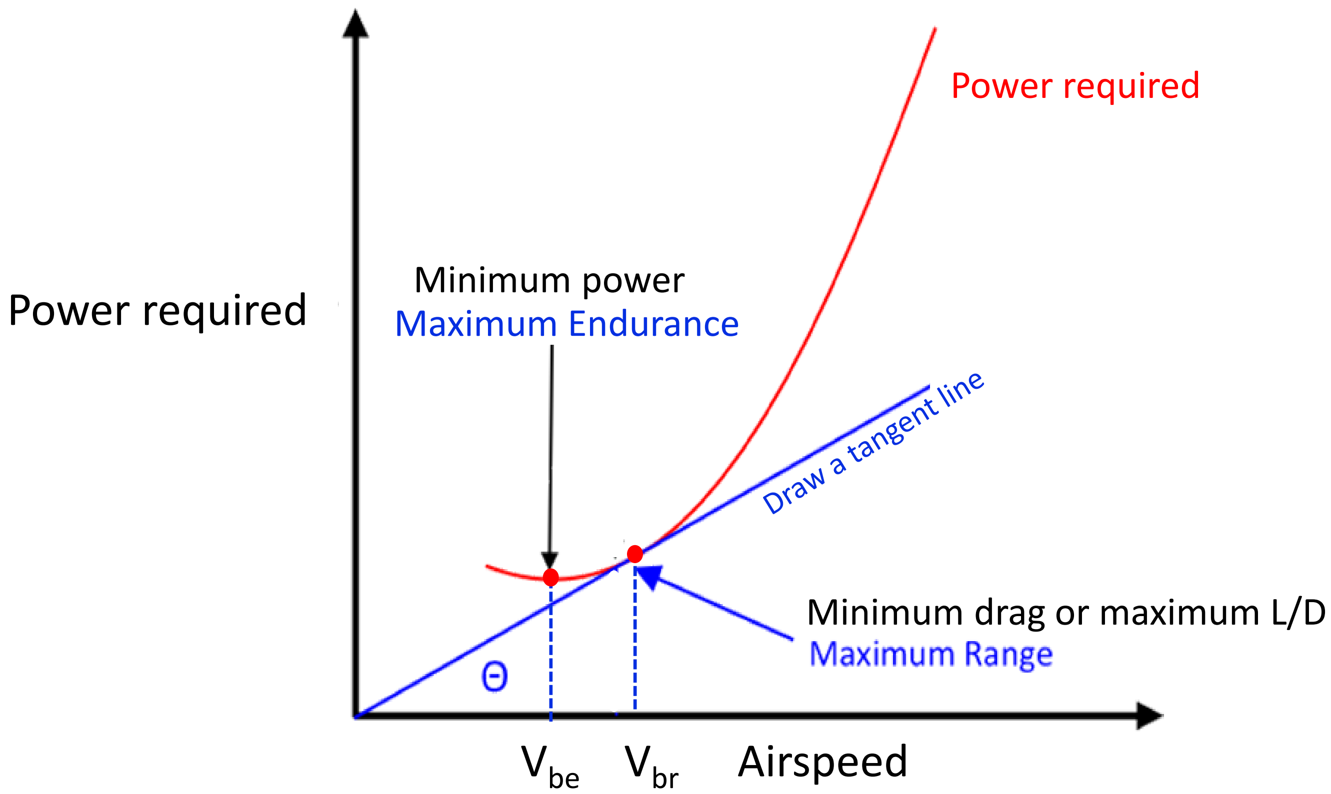
$$P_{req} = \frac{1}{2}\rho V^3 S C_{D_o} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi e AR}\right)$$

As we will see shortly, **maximum endurance** (time aloft) occurs when the minimum power is used to maintain steady level flight. **Maximum range** (distance traveled) is obtained when the aircraft is flown at the most aerodynamically efficient condition (maximum C_L/C_D).

$$V_{minimum\ power} = \left[\frac{4}{3}\left(\frac{W}{S}\right)^2 \frac{1}{\rho^2} \frac{1}{C_{D_o}} \left(\frac{1}{\pi e AR}\right)\right]^{1/4}$$

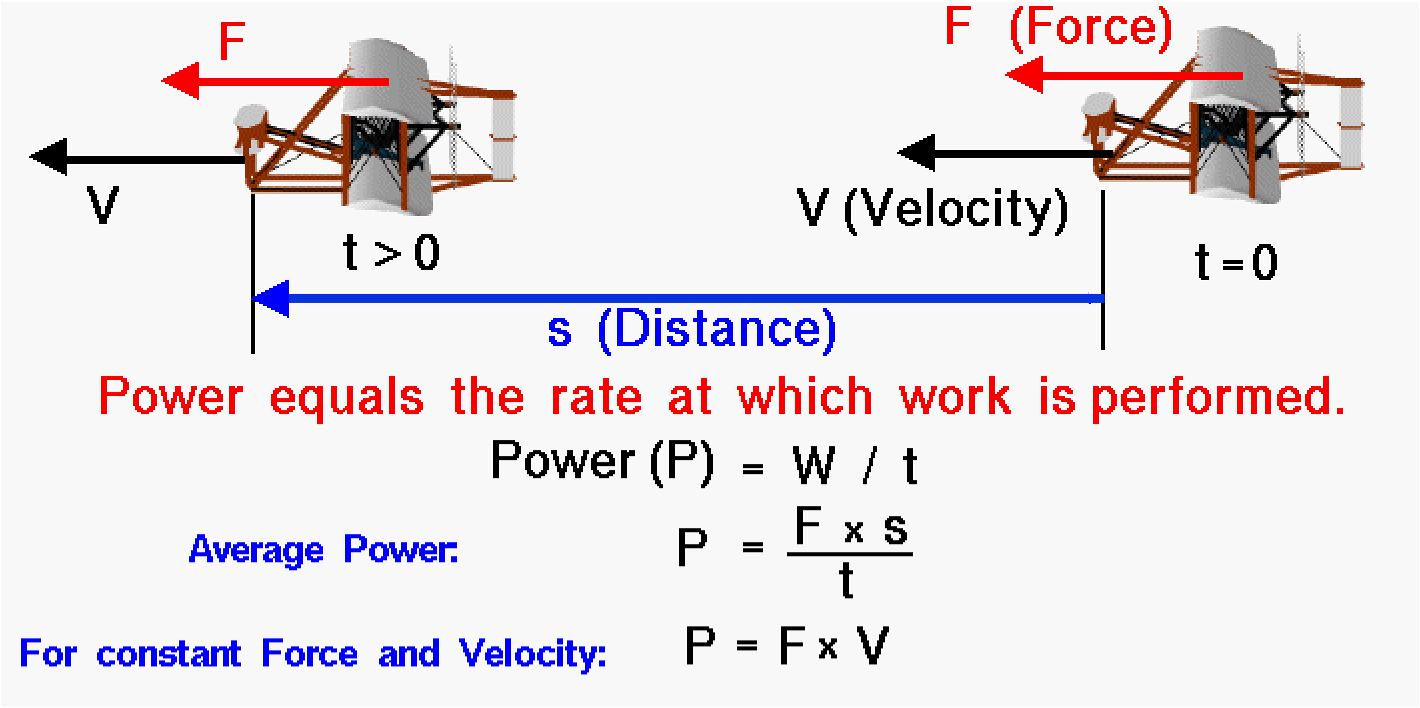
Source: https://ocw.mit.edu/ans7870/16/16.unified/propulsionS04/UnifiedPropulsion4/UnifiedPropulsion4.htm

Maximum Endurance and Maximum Range



Remember: Minimum power = maximum endurance
Minimum drag, or max L/D = maximum range

Example: Calculate the Power of Wright Bro Plane



The Wright aircraft developed 130 pounds of thrust and required 32 miles per hour airspeed to fly. The motor was then developing about 11 horsepower.

130 pounds times 32 mph (converted to feet per second 88 fps = 60 mph) divided by 550 foot-pounds per second per horsepower = 11 hp

Source: https://www.grc.nasa.gov/www/k-12/airplane/powr.html

How to get Maximum Range for eVTOL?

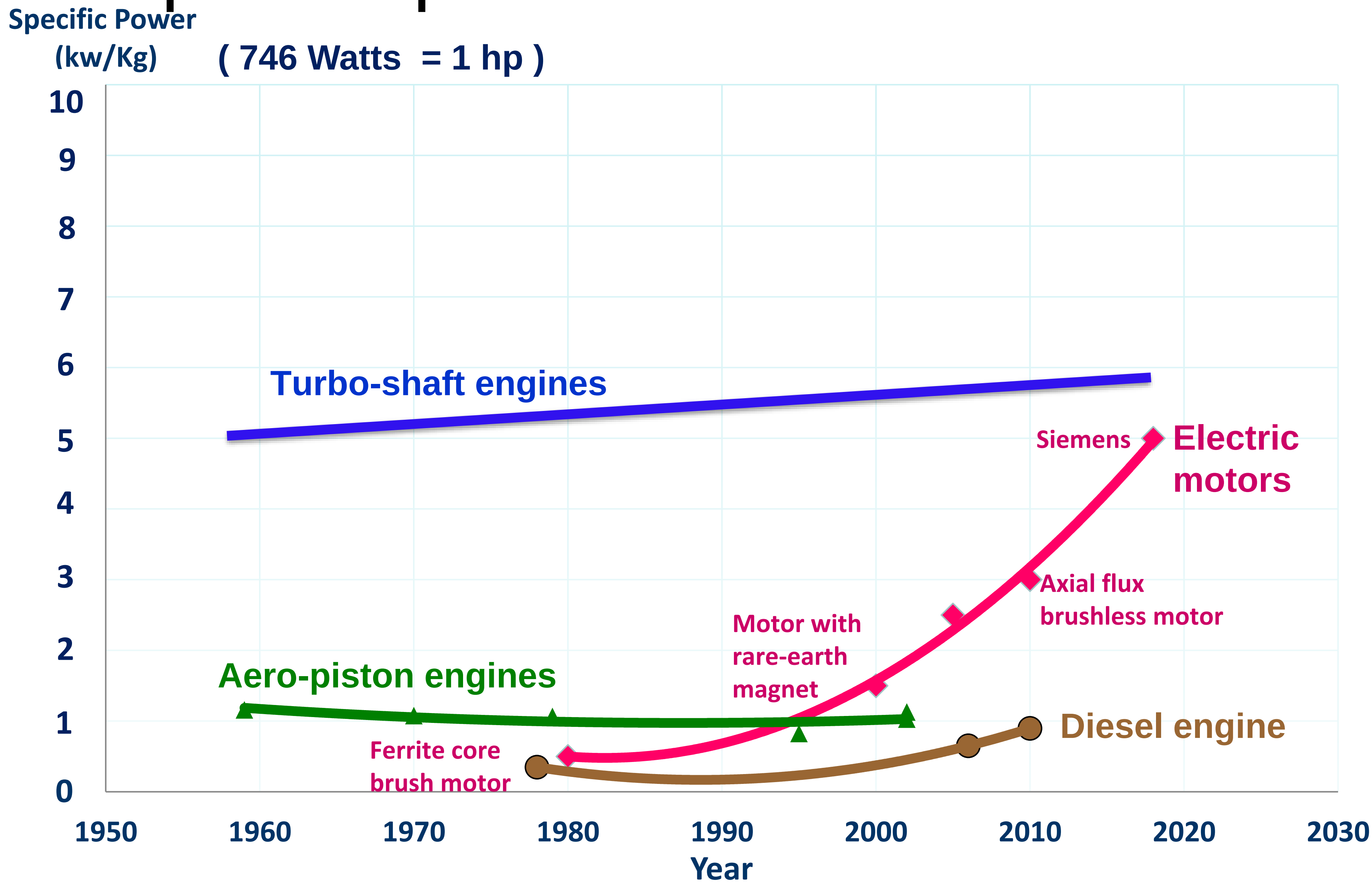
The Trick is to Minimize Hovering Time

From last few slides, if a VTOL aircraft cruises at around 125 mph (200 kmh) for majority of its flight, then it will achieve the best endurance and range.

Our calculated 4367 lbs of battery assumed operating at maximum power loading continuously (4kg/kw). If we spend most of the time cruising, then can reduce to 2000 to 3000 lbs of battery.

If the battery at the pack level is 200 Wh/kg, then 2000 lbs (907 kg) of battery is roughly 181 kwh, 3000 lbs (1360 kg) of battery is roughly 272 kwh.

Propulsion Specific Power Trend

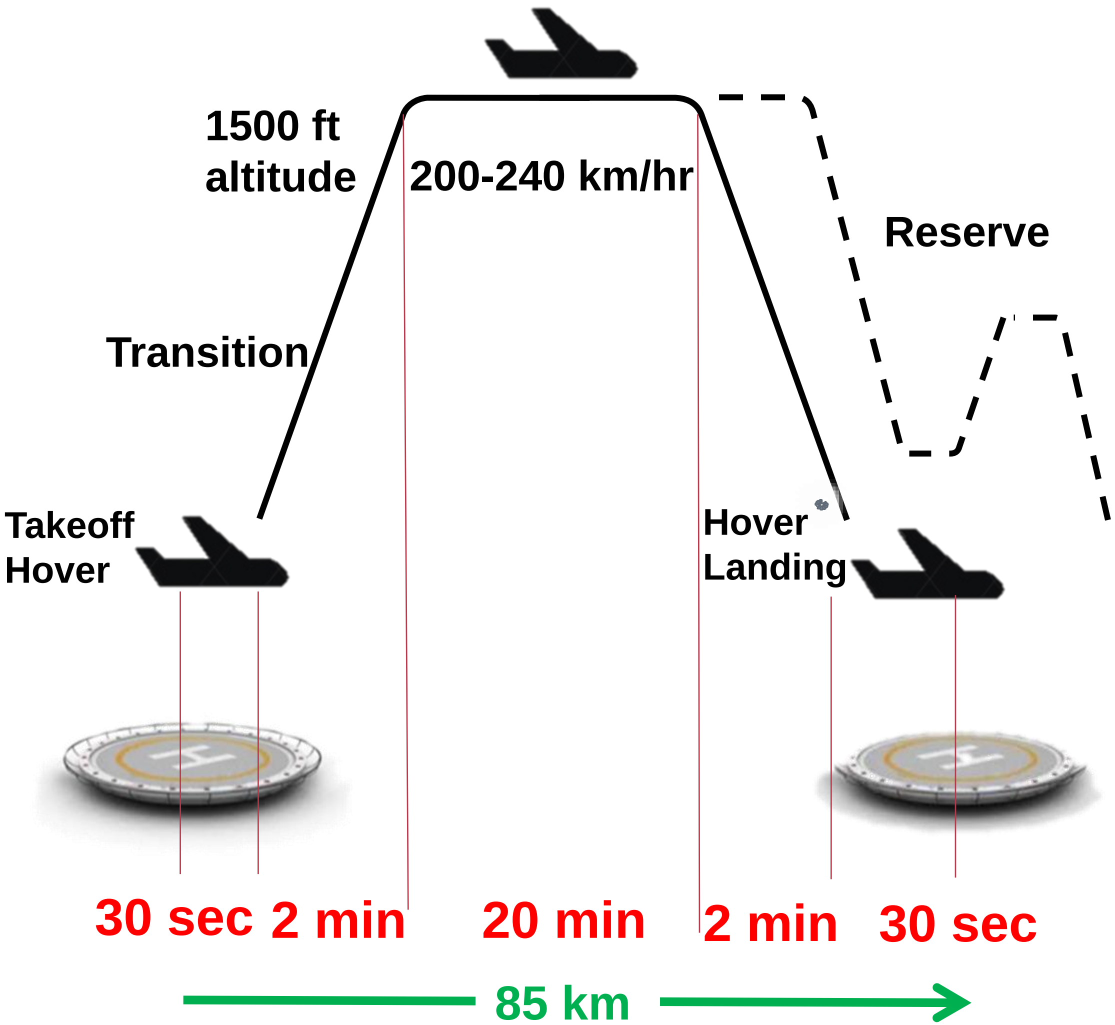


Motor and Inverter weight?

Assume motor's Specific Power is 5 kw/kg,
then 1 Mw / 5 kw/kg = 200 kg = 440 lbs

Inverter technology is about 7 kw/kg
then 1 Mw / 7 kw/kg = 143 kg = 315 lbs

We should be able to easily execute this intra-city mission by 2025, and improve range to >200 km by 2030

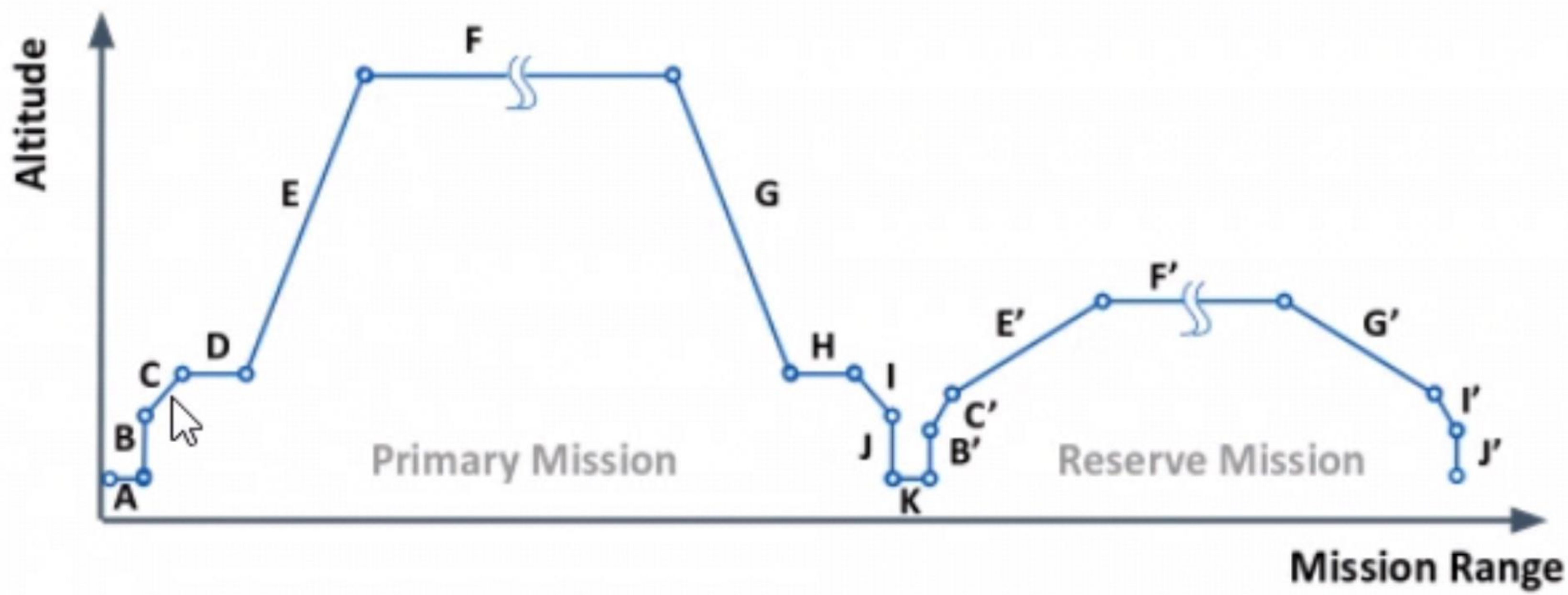


<u>Mission</u>

Range = 85 km
Flight time = 25 min
Reserve = 10 min
MTGW = 7,000 lbs
Battery = ? lbs

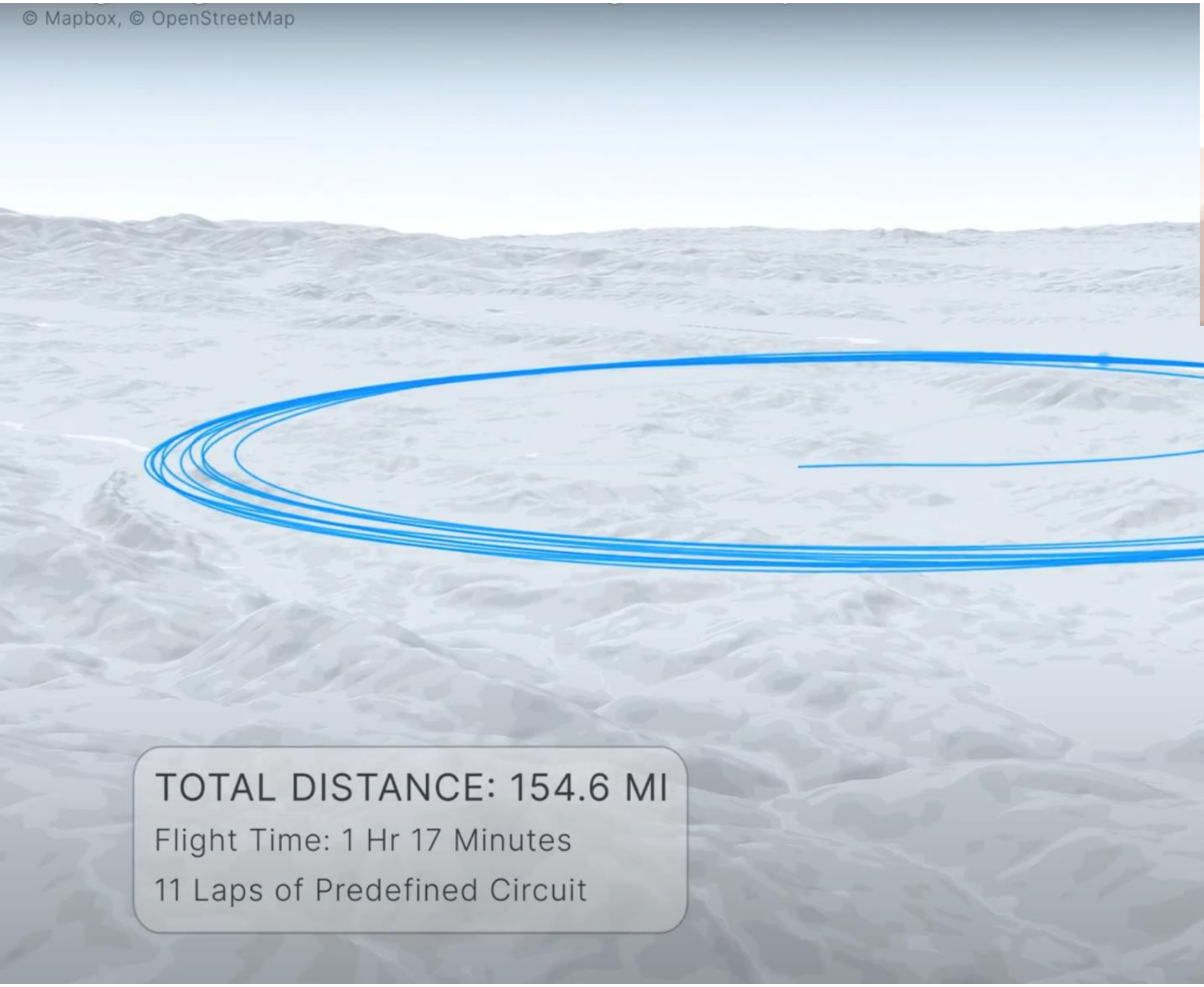
10 minutes reserve maybe is not enough

Energy Required (kWh) for One eVTOL Mission

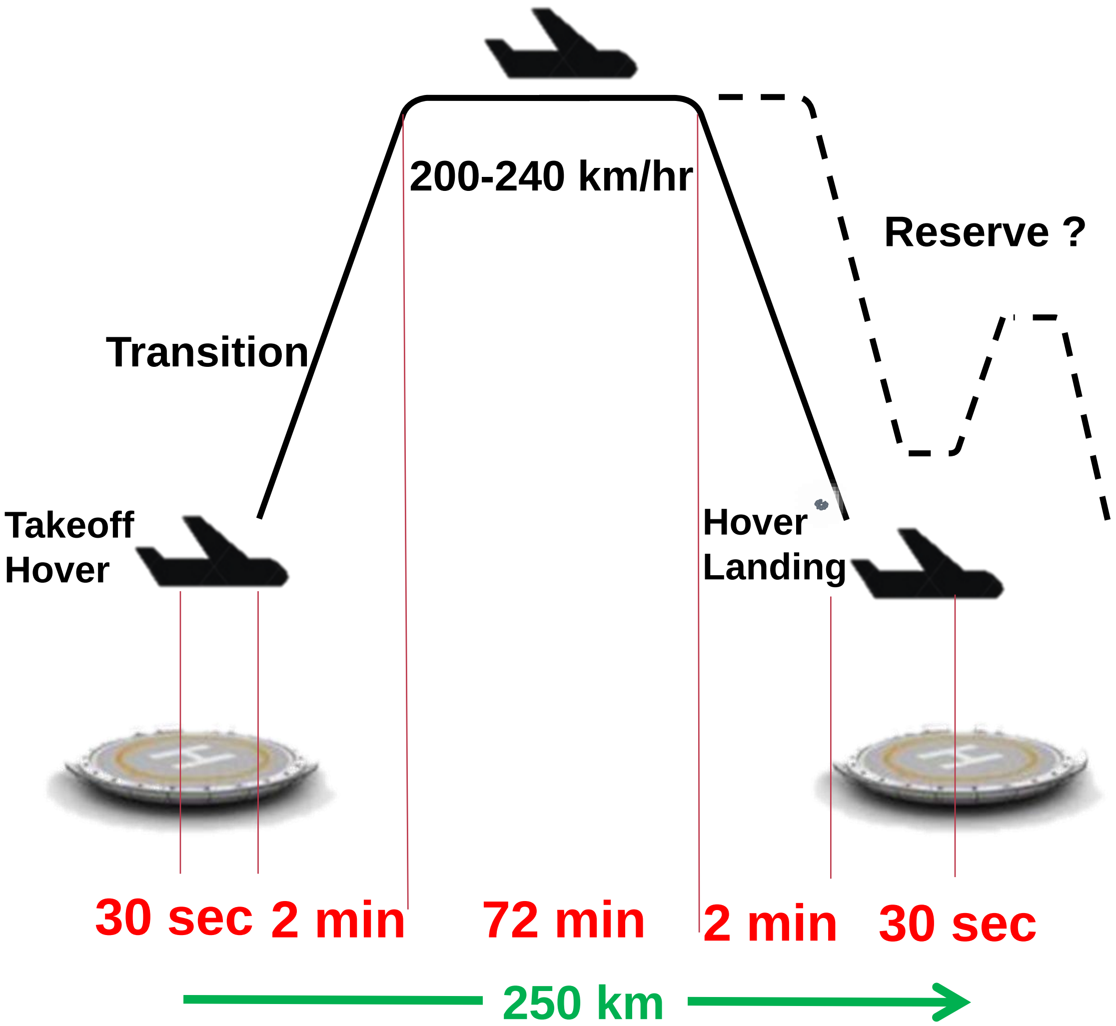


Estimate Joby S4 Performance

Joby Sets a New eVTOL Record in July 2021



As an Exercise, Let's Assume this Mission Profile

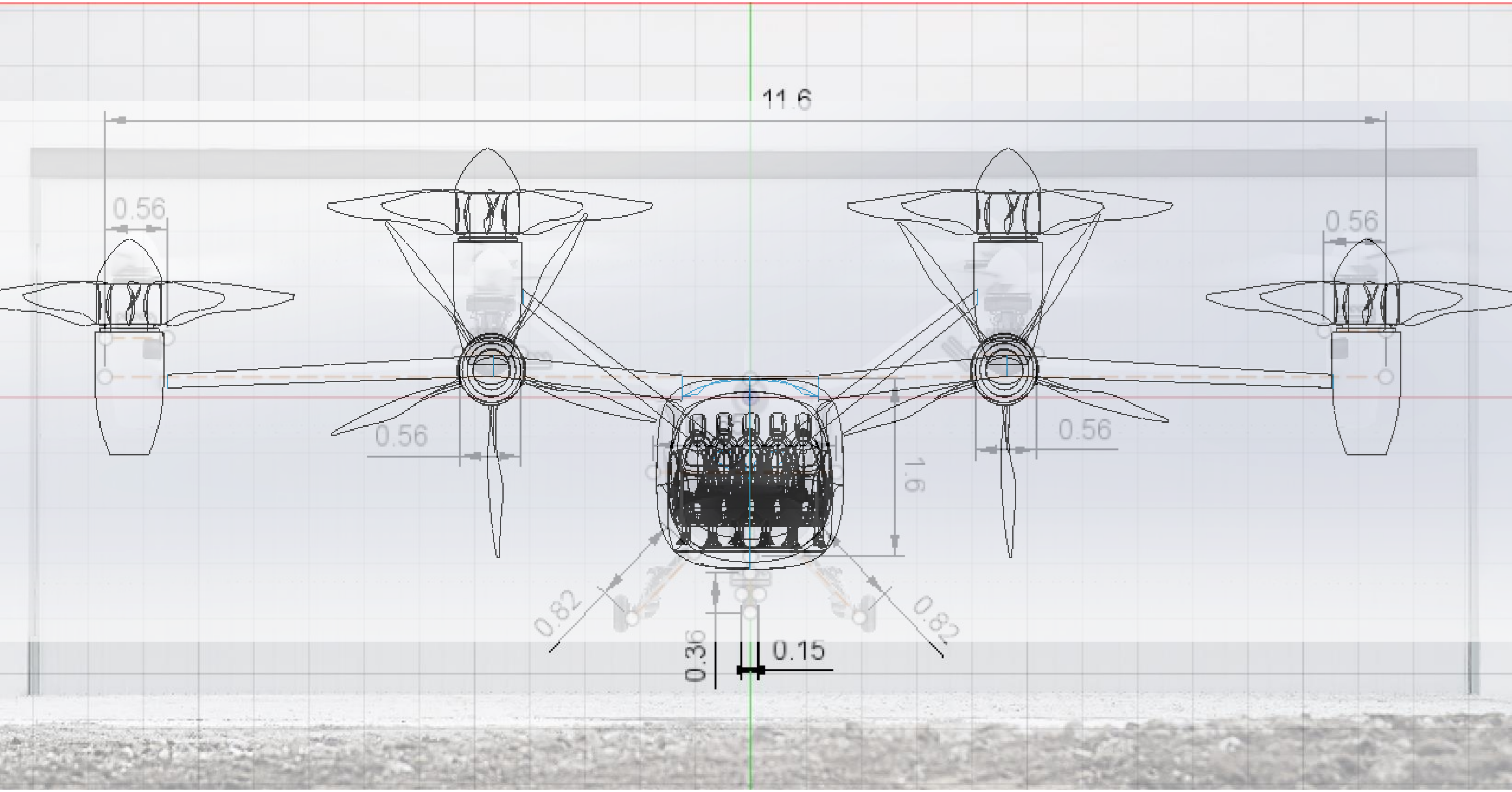


Mission

Range = 250 km
Flight time = 77 min
MTGW = 4200 lbs
Battery = 160 kWh
Reserve = ? min

Now Do a More Rigorous Performance Calculation Using Our Computer Code

Any Analysis is Only as Good as the Input !



Important: For any computer analysis, the discrepancy between calculation and reality could be due to the mathematical model and/or the input.

Estimate the Energy Using Our Computer Code For the Joby Flight

<table>
<tr><th>Mission Profile</th><th>Range (km)</th><th>Time / s</th><th>Power Req / kW</th><th>Energy Req / kJ</th><th>Energy Req / kWh</th><th>Climb rate (ft/min)</th><th>Altitude (ft)</th></tr>
<tr><td>Takeoff Hover</td><td>0</td><td>15</td><td>528.94</td><td>7934.1</td><td>2.2039</td><td>500</td><td>0 to 125</td></tr>
<tr><td>Hover Transition</td><td>0</td><td>15</td><td>528.94</td><td>7934.1</td><td>2.2039</td><td>0</td><td>125</td></tr>
<tr><td>Cruise Climb*</td><td>6.5</td><td>120</td><td>400</td><td>48000</td><td>13.3333</td><td>687.5</td><td>125 to 1500</td></tr>
<tr><td>Cruise**</td><td rowspan="2">241.4</td><td rowspan="2">4440</td><td>111.9</td><td>496900.0</td><td>138.0281</td><td>0</td><td>1500</td></tr>
<tr><td>Cruise Descend***</td><td>0</td><td>0</td><td>0</td><td>-625</td><td>1500 to 75</td></tr>
<tr><td>Descent Transition</td><td>0</td><td>15</td><td>528.94</td><td>7934.1</td><td>2.2039</td><td>0</td><td>75</td></tr>
<tr><td>Hover Landing</td><td>0</td><td>15</td><td>486.42</td><td>7296.4</td><td>2.0268</td><td>-300</td><td>75 to 0</td></tr>
<tr><td>Takeoff Hover (R)</td><td colspan="7" rowspan="7">160 kWh total

No reserve mission for this analysis.</td></tr>
<tr><td>Transition (R)</td></tr>
<tr><td>Cruise Climb (R)</td></tr>
<tr><td>Cruise (R)</td></tr>
<tr><td>Cruise Descend (R)</td></tr>
<tr><td>Transition</td></tr>
<tr><td>Hover Descend (R)</td></tr>
</table>

Notes

R stands for reserve mission

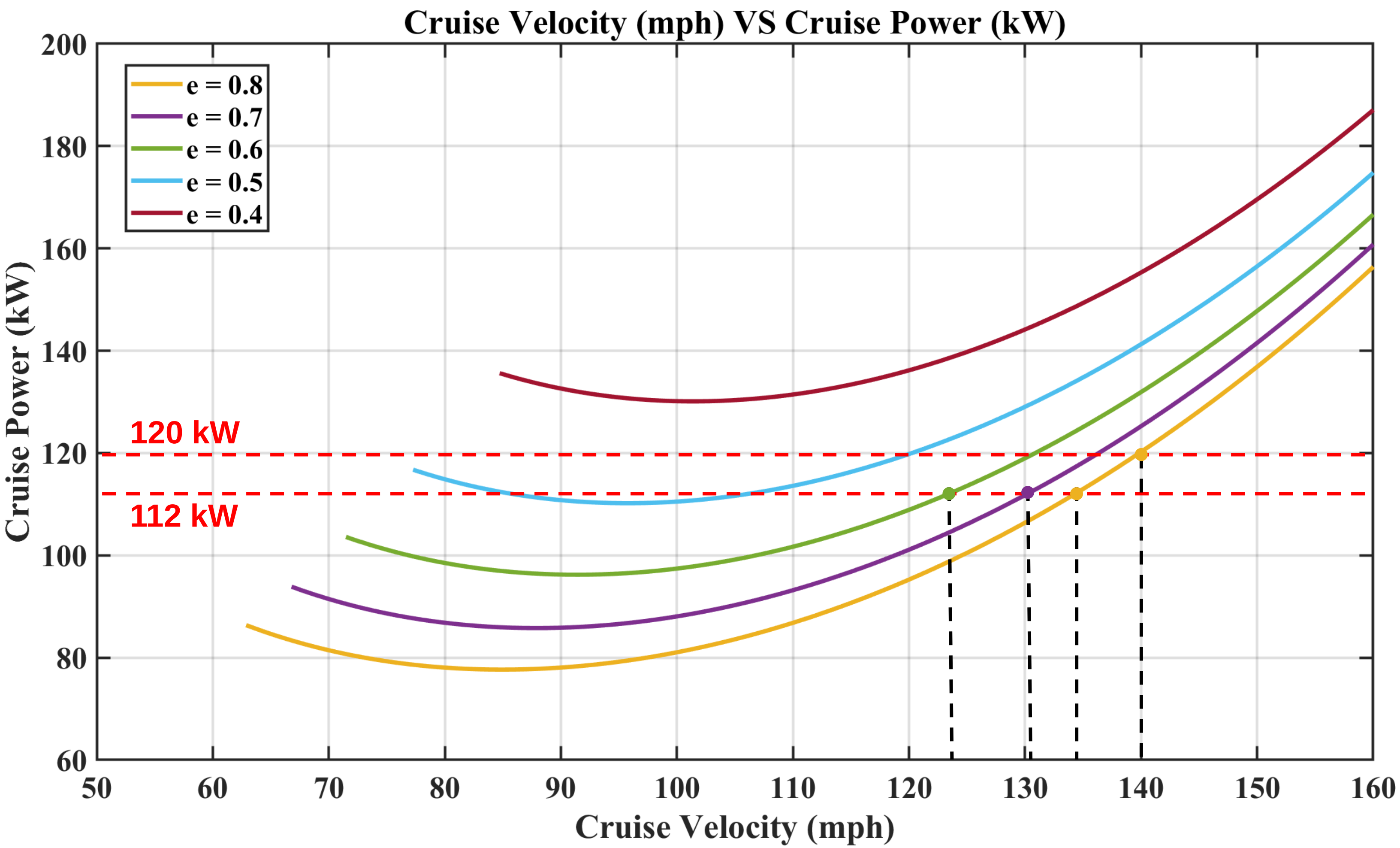
* Now accounts for both vertical and horizontal portions of cruise climb

** Cruise accounts for horizontal portion of cruise descent. Range calculated using Desired Cruise Velocity ≈ 121.6 mph.

*** Only accounts for vertical portion of cruise descent. Assume cruise descent consumes little power and can be neglected.

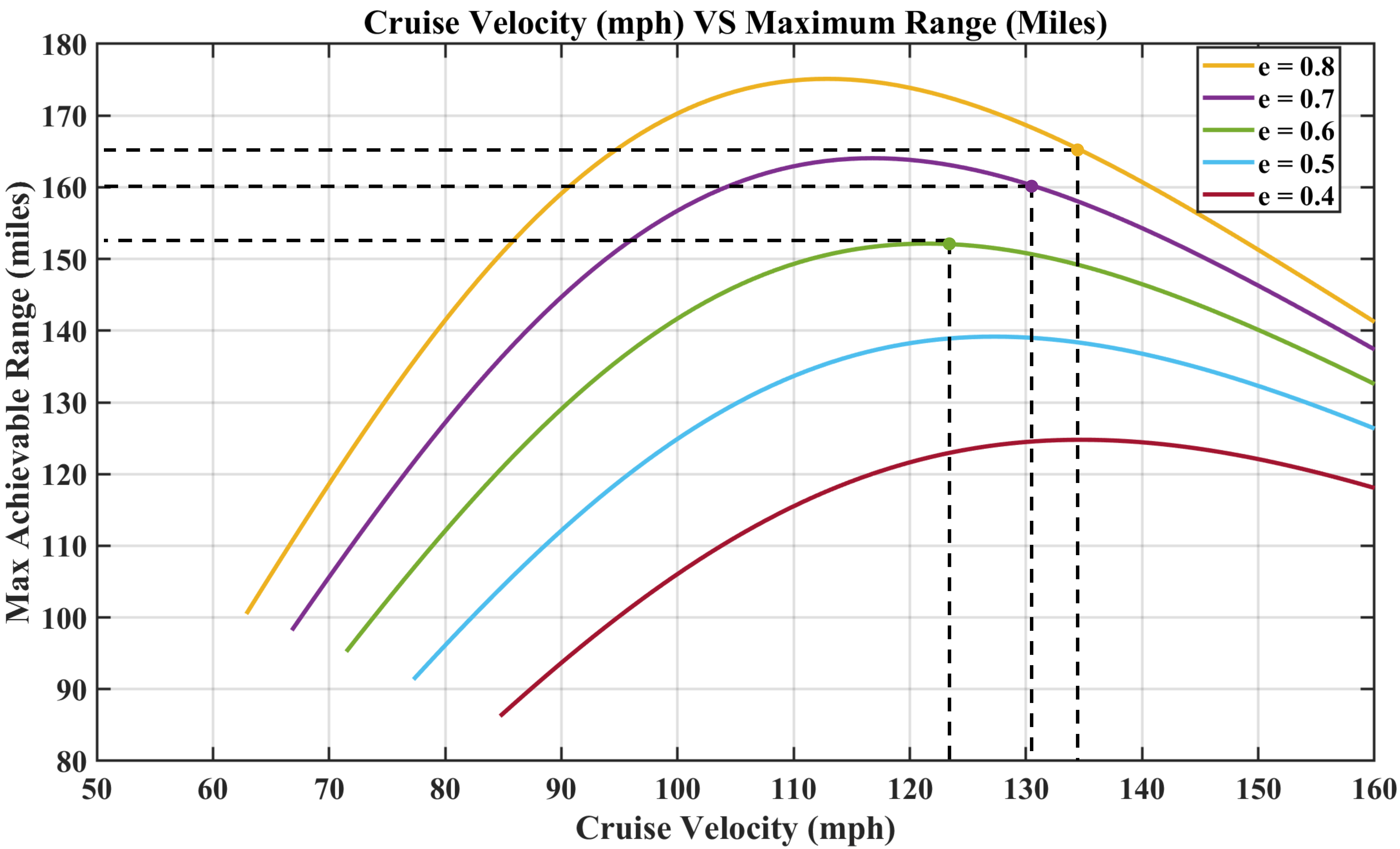
Cruise Power to Cruise Velocity for different Oswald Efficiency Factors e

Mass = 1905kg   Propulsive Efficiency = 0.85



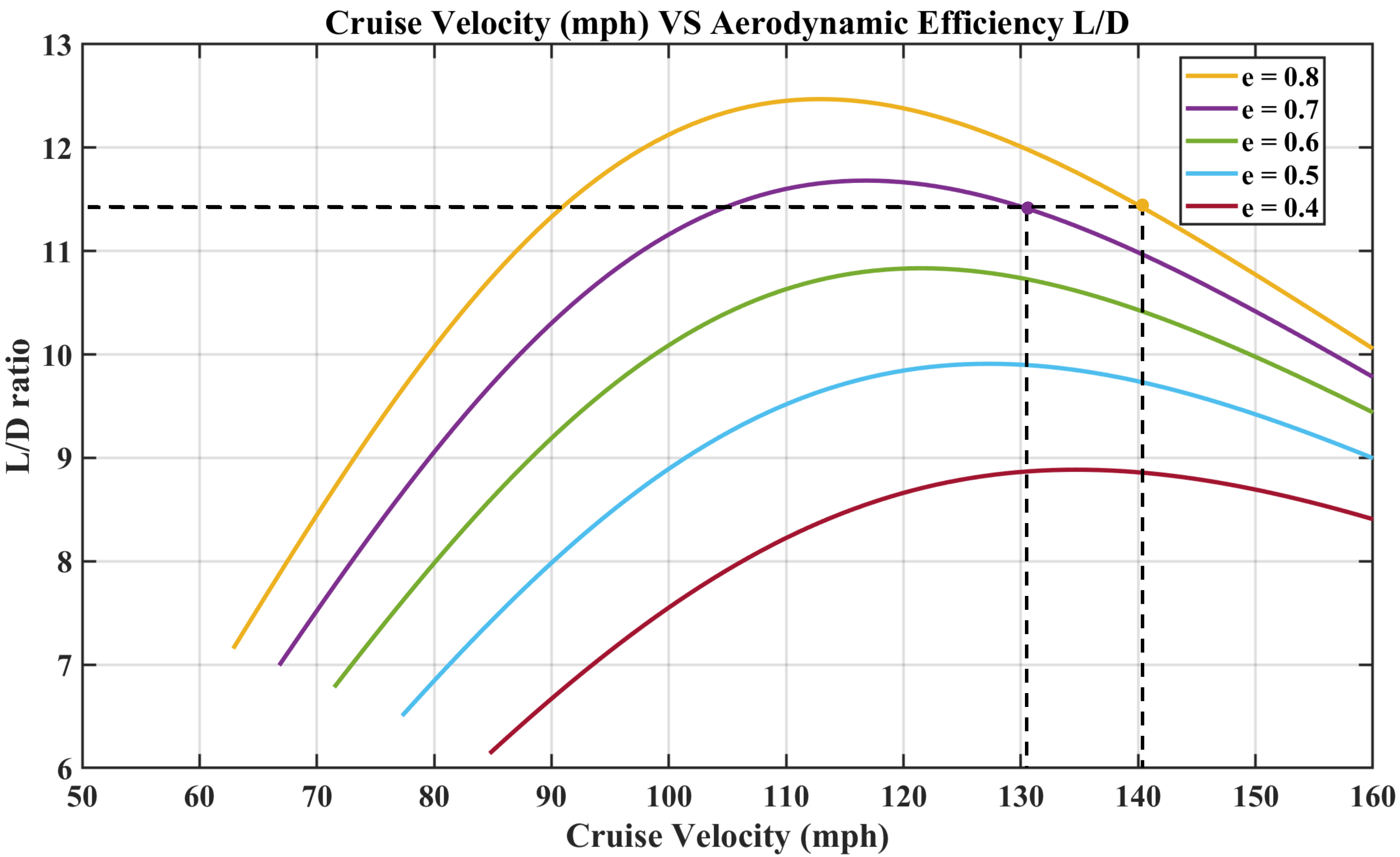
Matching Cruise Velocity to Maximum Achievable Range for different Oswald Efficiency Factors e

Note: Max achievable range include both mission and reserve ranges.
Mass = 1905kg   Propulsive Efficiency = 0.85
*Desired Range = 150 miles * 1.1 = 165 miles*

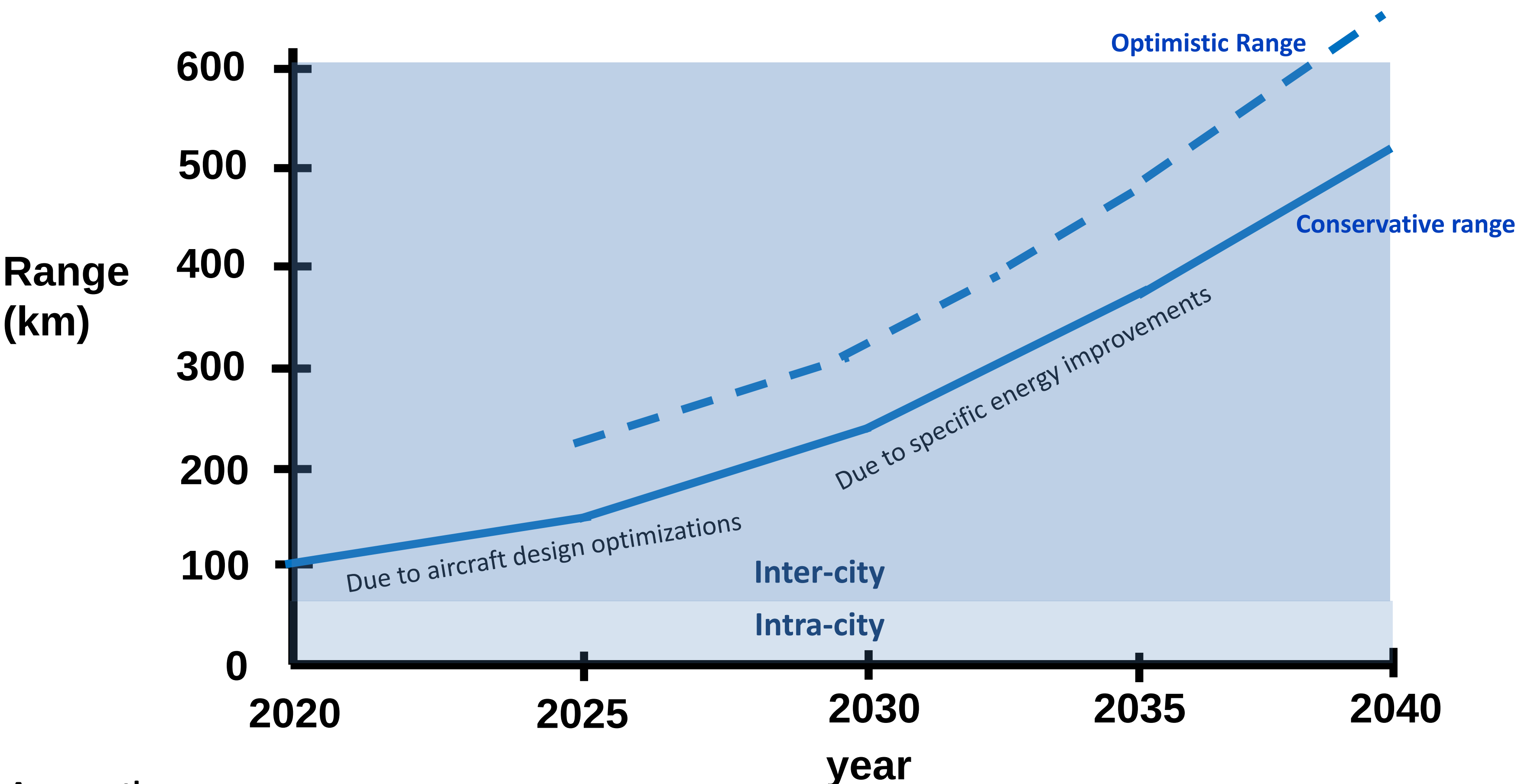


Same L/D but different Oswald efficiency factors e can yield different answer for airspeed

Mass = 1905kg   Propulsive Efficiency = 0.85



Predicted Range versus Year for Generic eVTOL

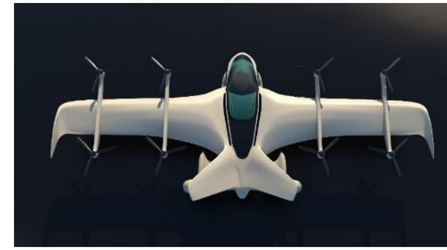


Assume these specific energies at Pack Level for energy source* **160 Wh/kg** **200 Wh/kg** **330 Wh/kg** **500 Wh/kg** **750 Wh/kg**

*If using cells, assumed a lost of about 35% in specific energy from cell level to pack level

Predicted by James Wang

Compare a Cessna to a Hypothetical eVTOL



Parameter	Cessna 172D Skyhawk	Example 5-seat eVTOL
Lift Coefficient (no flap)	1.60	1.2
Wingspan (m)	10.9	12.3
Wing chord (m)	1.63 (at root)	1.7
Wing Area (m^2)	16.2	21
Aspect Ratio	7.46	7.3
MTOW	1000kg (2200 lb)	3175kg (7000 lb)
Payload (kg)	400	500
Wing Loading (kg/m^2)	61.5	143
Best cruise speed (km/hr)	200	200
Power (kw)	120 kw (160hp) installed	1,000 kw for hover 200kw at Vbr cruise

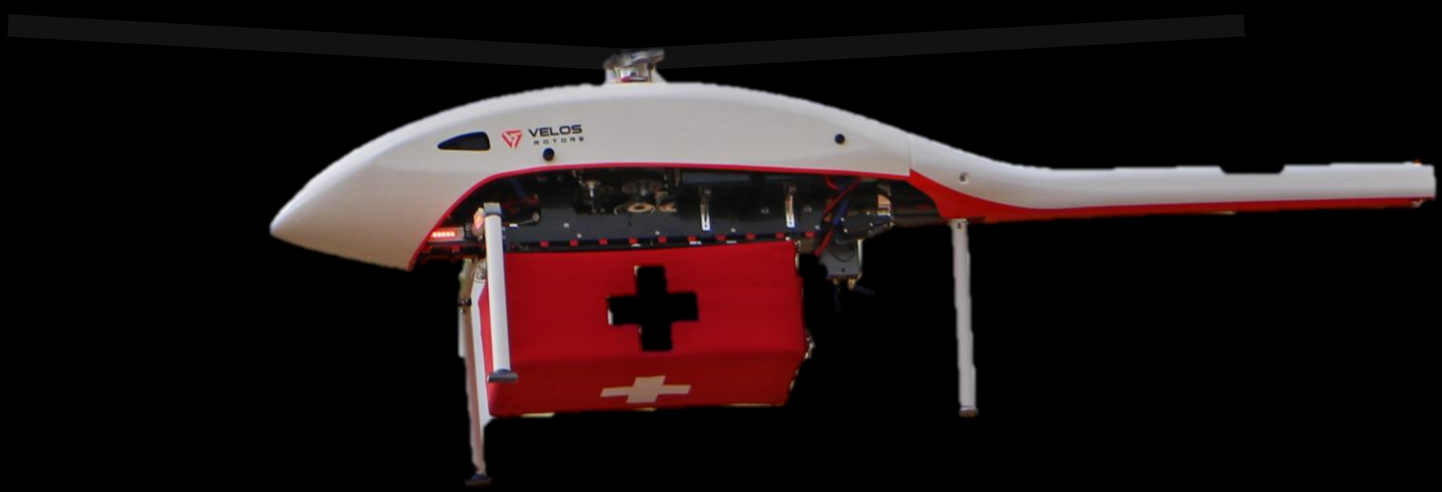
Porsche Taycan Turbo vs. eVTOL Aircraft

Max weight	3100 kg	3175 kg
Curb weight	2300 kg	2675 kg
Payload	5 pax	5pax or 500 kg
Range	450 km	100 km
Max speed	250 kmh	300 kmh
Installed power	761 hp (567 kw)	1340 hp (1 Mw)
Inverter	800 volts	800 volts
Battery	93 kWh, 650 kg (143 Wh/kg at pack level)	180 kWh, 900 kg (200 Wh/kg at pack level)
Development	4 years, 6 million miles	7 years, 2500 flying hours
Development cost	US$ few billions	US$ 1 billion
Unit price	US$ 200,000	US$ 2.5 million

Tesla SP1000 vs. Joby S4

A Design Exercise:

a delivery drone



Review Electrical Engineering Definitions

Wh = Ah x Voltage

Wh = A x V x time = power x time

Question:

If a delivery drone draws 200 amps at 300 volt and can hover for 15 minutes with no reserve left, then its battery must store how much energy?

Answer: 200A x 300V x 0.25hr = 15,000 Wh or 15 kwh

A Simple Design Exercise

If this drone weighs 240 kg eVTOL, and it has a disk loading of 10 lbs/ft^2

How big is the battery if we want to hover for 15 minutes with no reserve?

Answer:

If its disk loading is 10 lbs/ft^2 then from an earlier chart, it has a thrust-to-power ratio around 4kg / kw

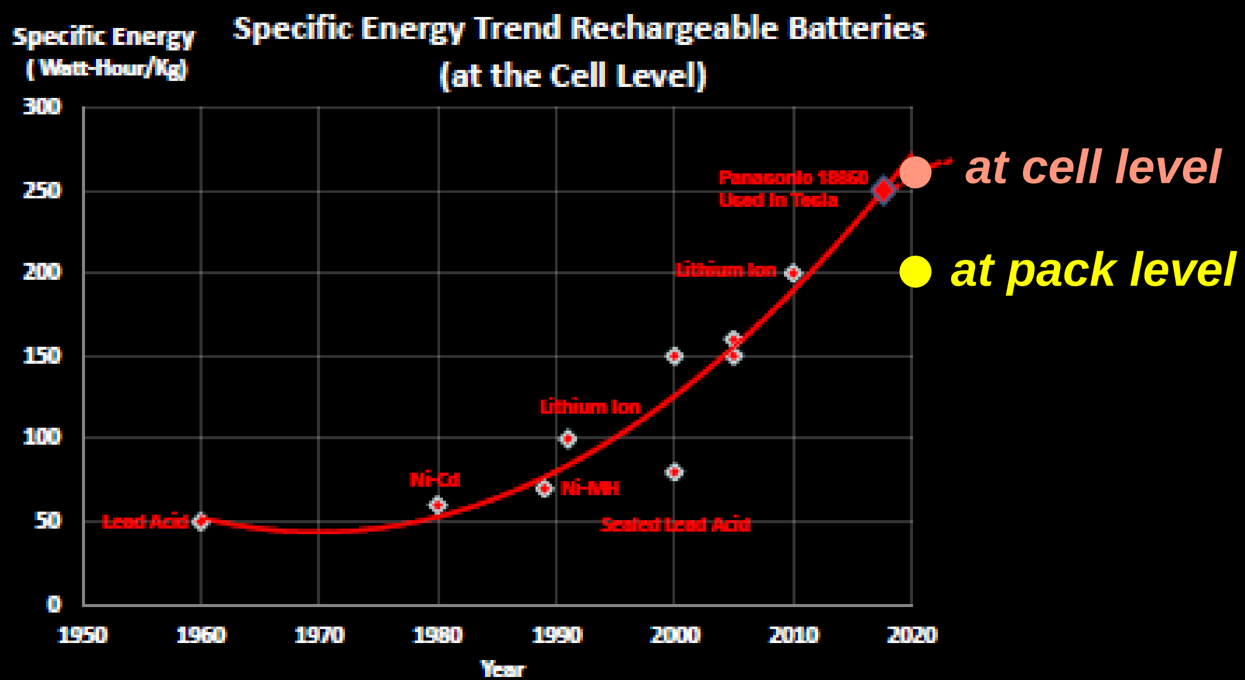
Then 240 kg / (4 kg/kw) = 60 kw power required. To fly 15 minutes, then 60 kw x 0.25 hr = 15 kWh battery is required.

Answer Continued

Last page says we need a 15 kWh battery.

If we use a 200 Wh/kg lithium rechargeable battery (at the pack level, not at cell level), then

15 kWh / 200 Wh/kg = 15,000 / 200 = 75 kg



Can this drone carry 75 kg of cargo?

We have confirmed that it’s reasonable that this drone’s MTGW = 240 kg

If the battery must weigh 75 kg for 15 min flight

and we want to carry 75 kg of cargo, then we only have 90 kg remaining for structure, rotors, motors, electronics, etc.

Let’s see if 90 kg is feasible for all these items?

Checking the Weight

It is easy to check the electric motor weight. From our chart in the motor lecture, it showed a good 2022 technology motor can do 5 kw/kg.

Since this drone requires 60 kw power to hover:

60 kw / 5 kw/kg = 12 kg total for the electric motors. Let's assume the wiring and inverter weigh 12 kg, then only 90 kg – 24 kg = 66 kg remain for the entire drone structure and miscellaneous items.

Challenging!

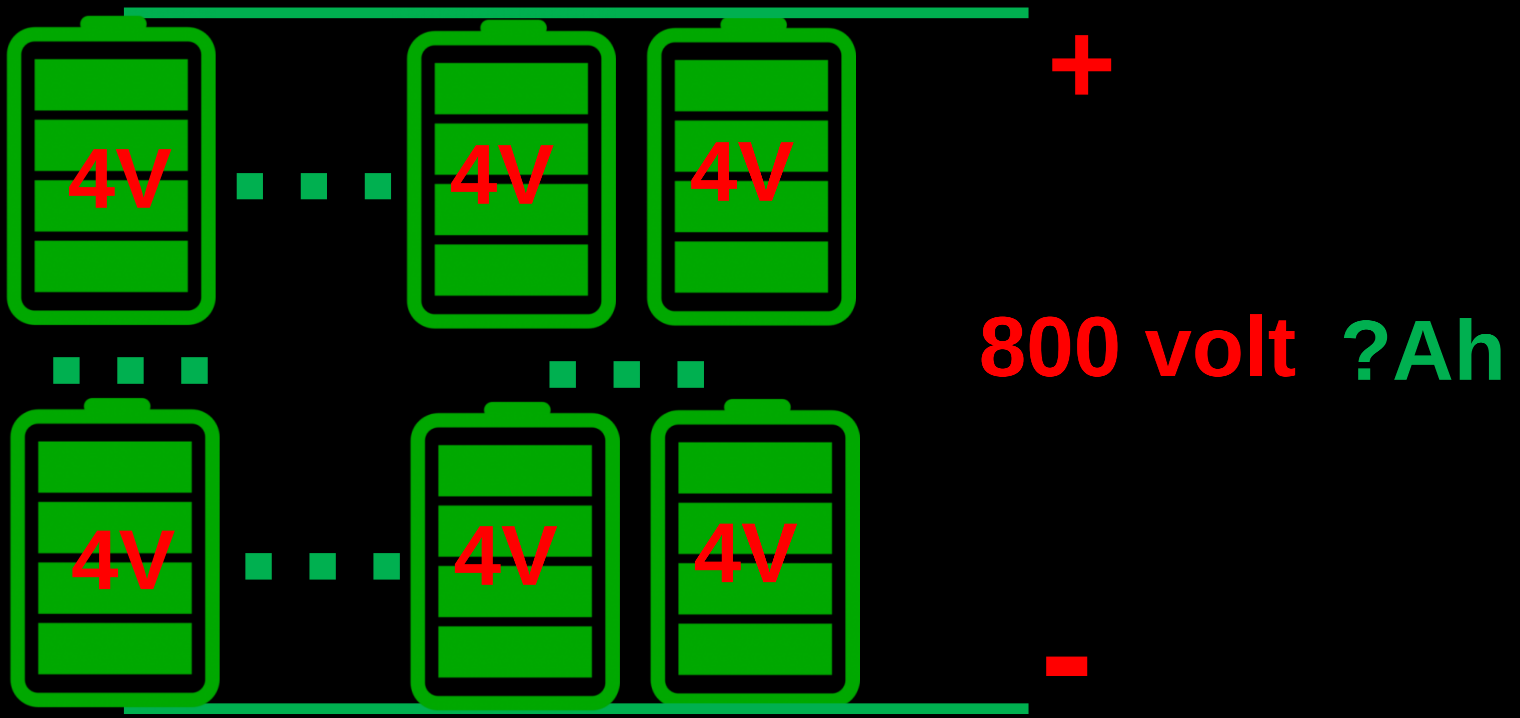
You can use this same logic and combined with aerodynamic calculation and bottoms up estimate when doing a quick estimate for conceptual design.

Design Rule

1. Use as high a voltage as possible.

2. For example, 800 volts (200 cells in series).

3. Then increase Ah by increasing number of cells in parallel so the current draw will not exceed 5C.



Questions:

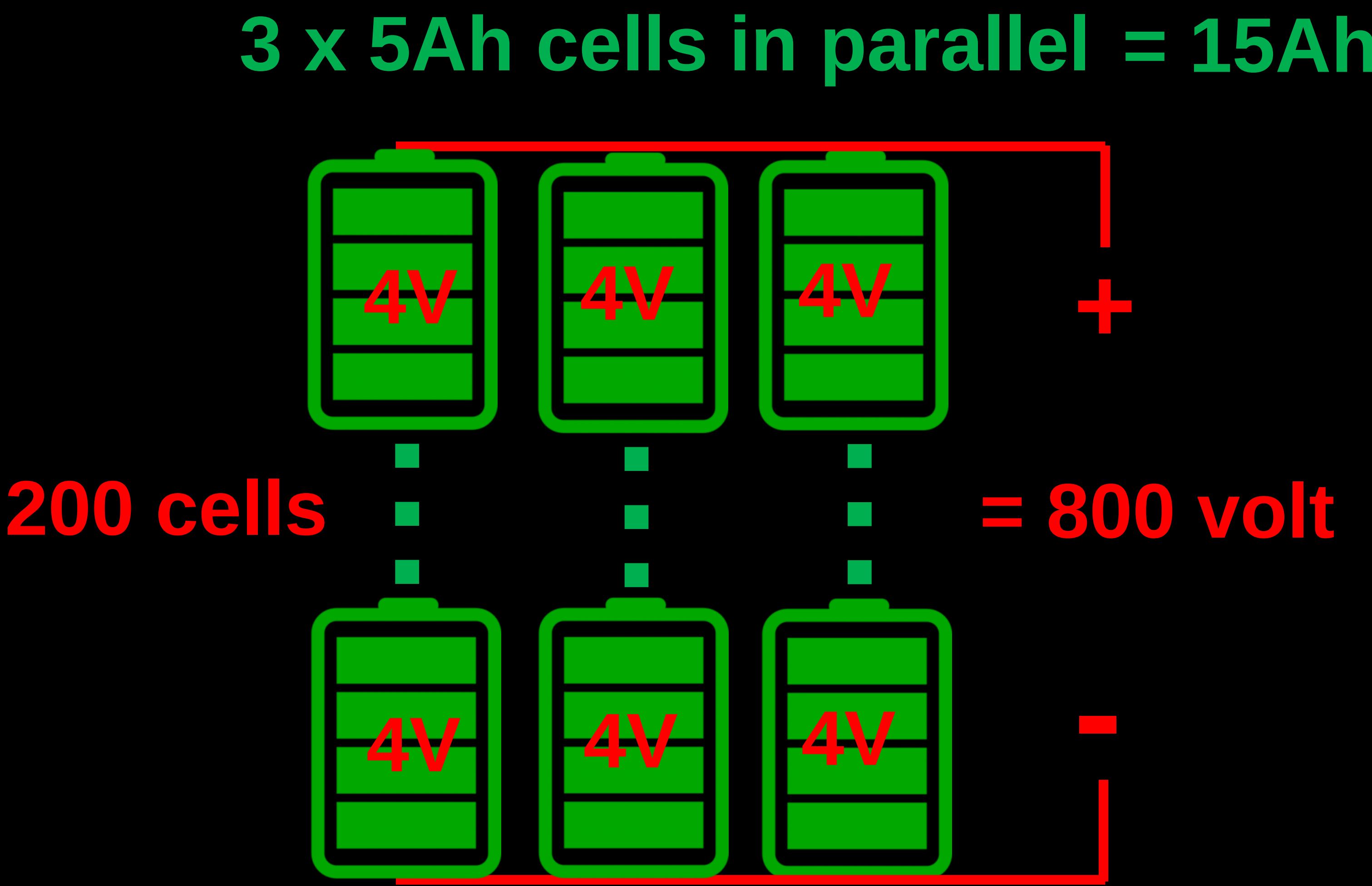
(1) If the drone battery pack is 800 volts and 60 kw power is necessary to hover, how big a battery is needed to hover 12 minutes?

Answer: 60 kw / 800V = 75A
75A x 0.2 hour = 15 Ah battery.

(2) If each cell is 4 volts and 5Ah capacity, then must use how many cells in series and parallel?

Answer: 200 in series, and 3 columns in parallel (because 15 Ah/5Ah = 3)

This 200S3P Will Provide 12 Minutes Hover



4. Weight and Performance Estimation for eVTOL aircraft

by Dr. James Wang

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