eVTOL Design Short Course

by Dr. James Wang

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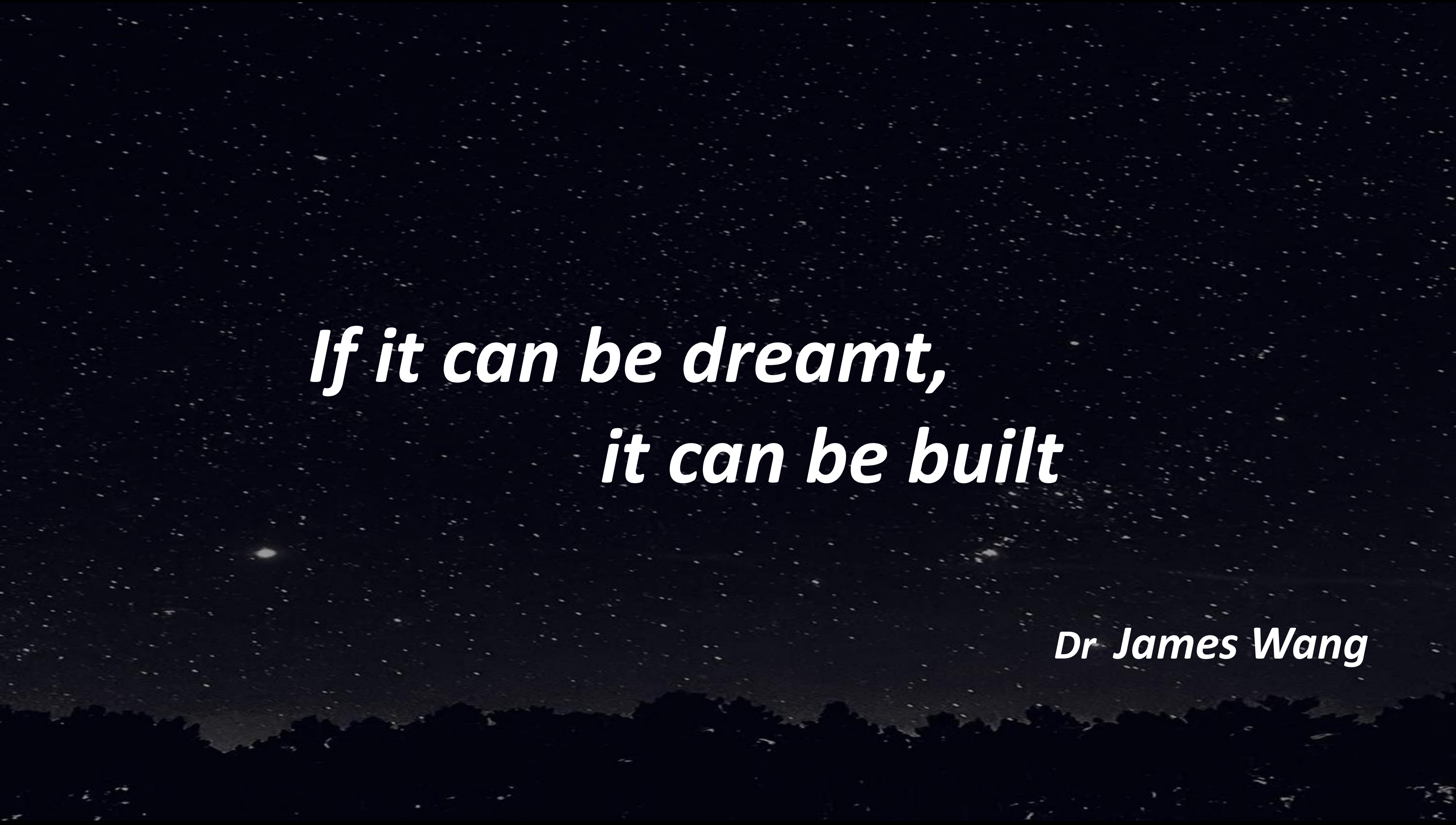
Course Topics

1. Design Phases, Different eVTOLs
2. Battery and Energy Source
3. Electric Motors and Hybrids
4. Weight and Performance Estimation
5. Rotor Design, Stability & Control, Testing
6. Rotor and Vehicle Performance Analysis
7. Benchmarking and Cost Estimation
8. Certification and Vertiport Operation


If it can be dreamt,
it can be built
Dr James Wang

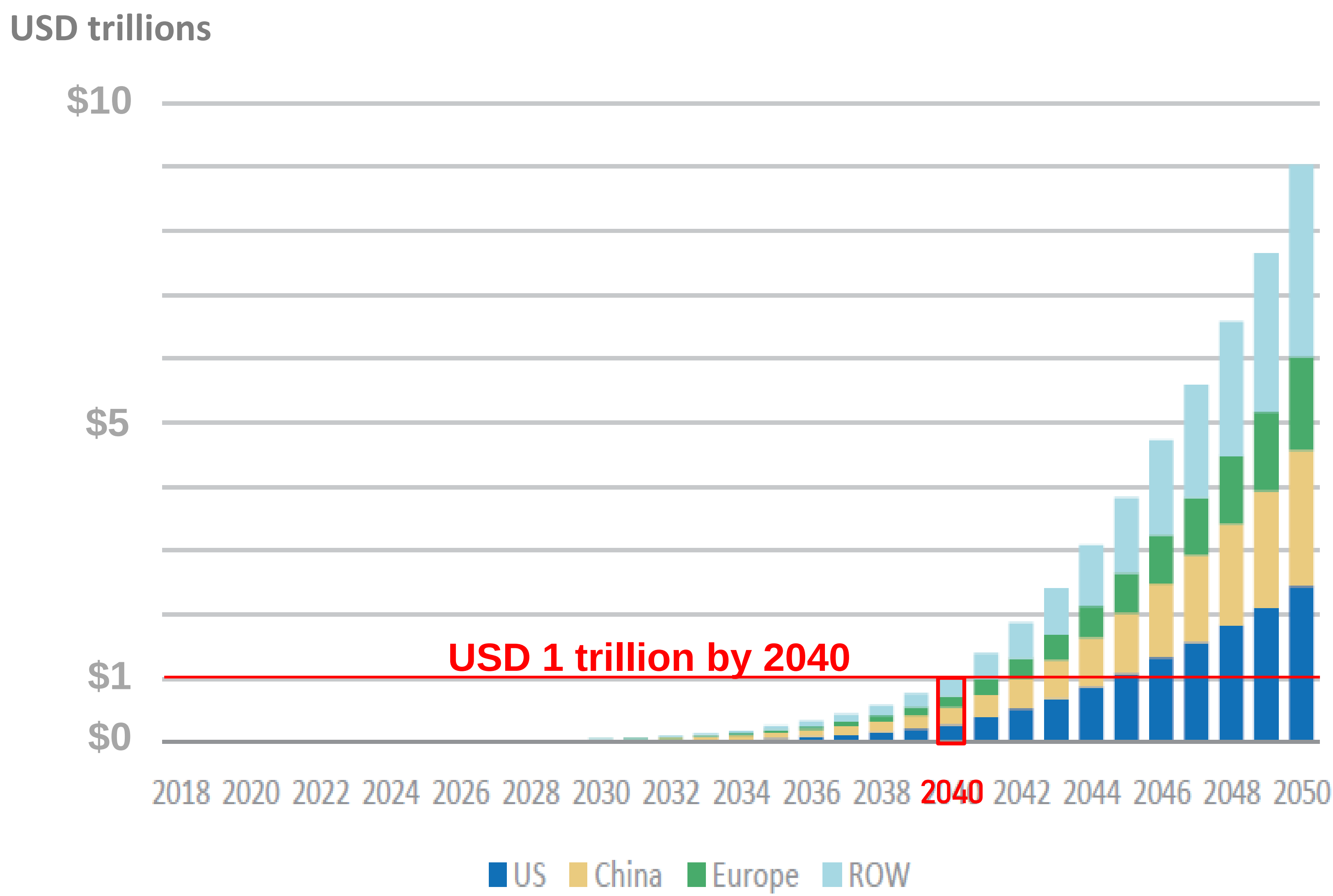
Advance Air Mobility (AAM)

NASA's Vision of AAM

- A safe, accessible, automated, and affordable air transportation system for passengers and cargo capable of serving previously hard-to-reach urban and rural locations
- by 2030 there will be as many as 500 million flights a year for package delivery services and 750 million flights a year for air metro services
- Larger air metro UAV's carry more passengers, but they fly between predetermined stops similar to how a bus or subway operates
- Urban Air Mobility (UAM) is a name given for flying in urban area

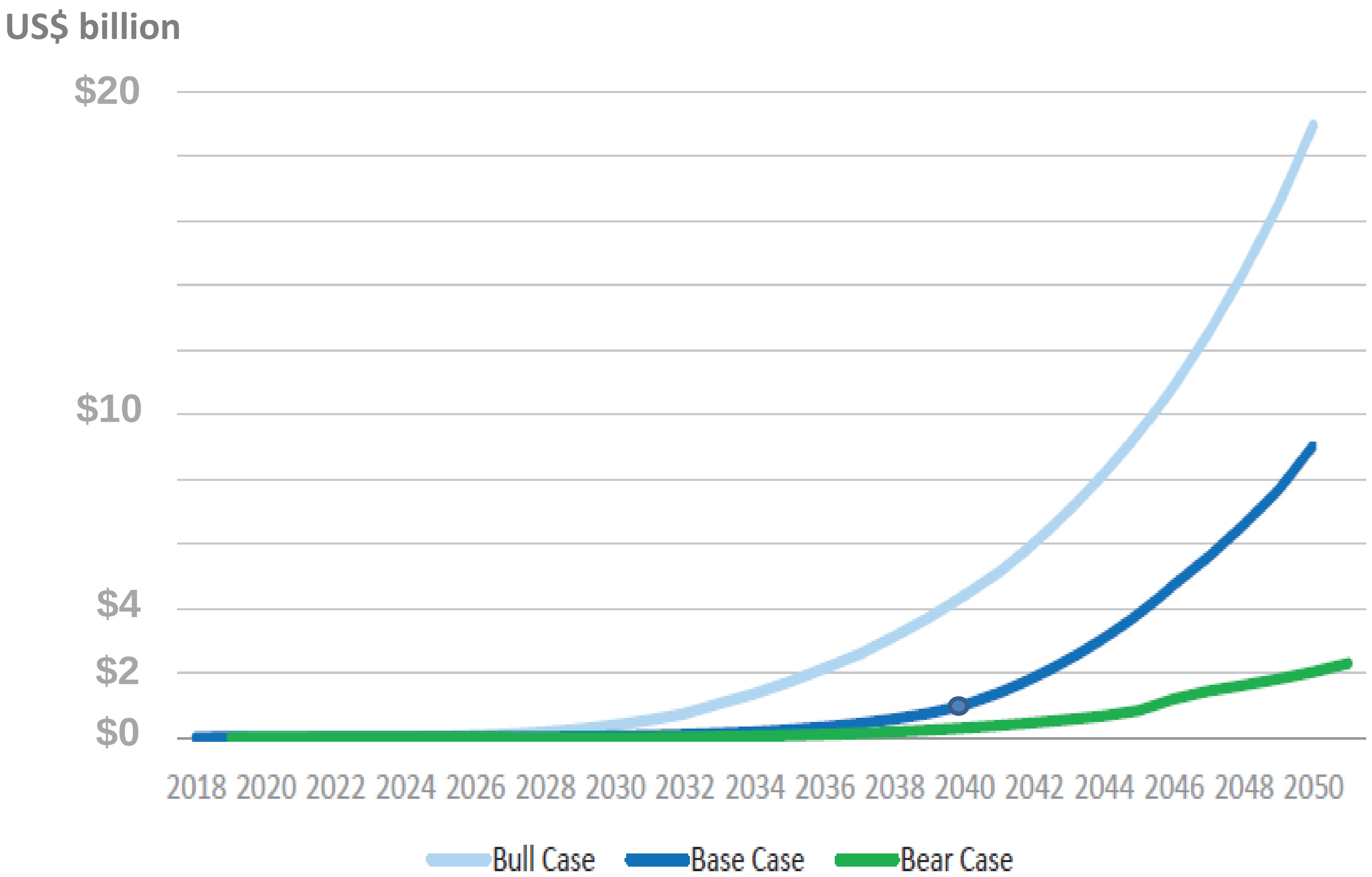
Source: https://www.nasa.gov/sites/default/files/atoms/files/what-is-aam-student-guide_0.pdf

Predicted AAM Market Size (people and cargo)



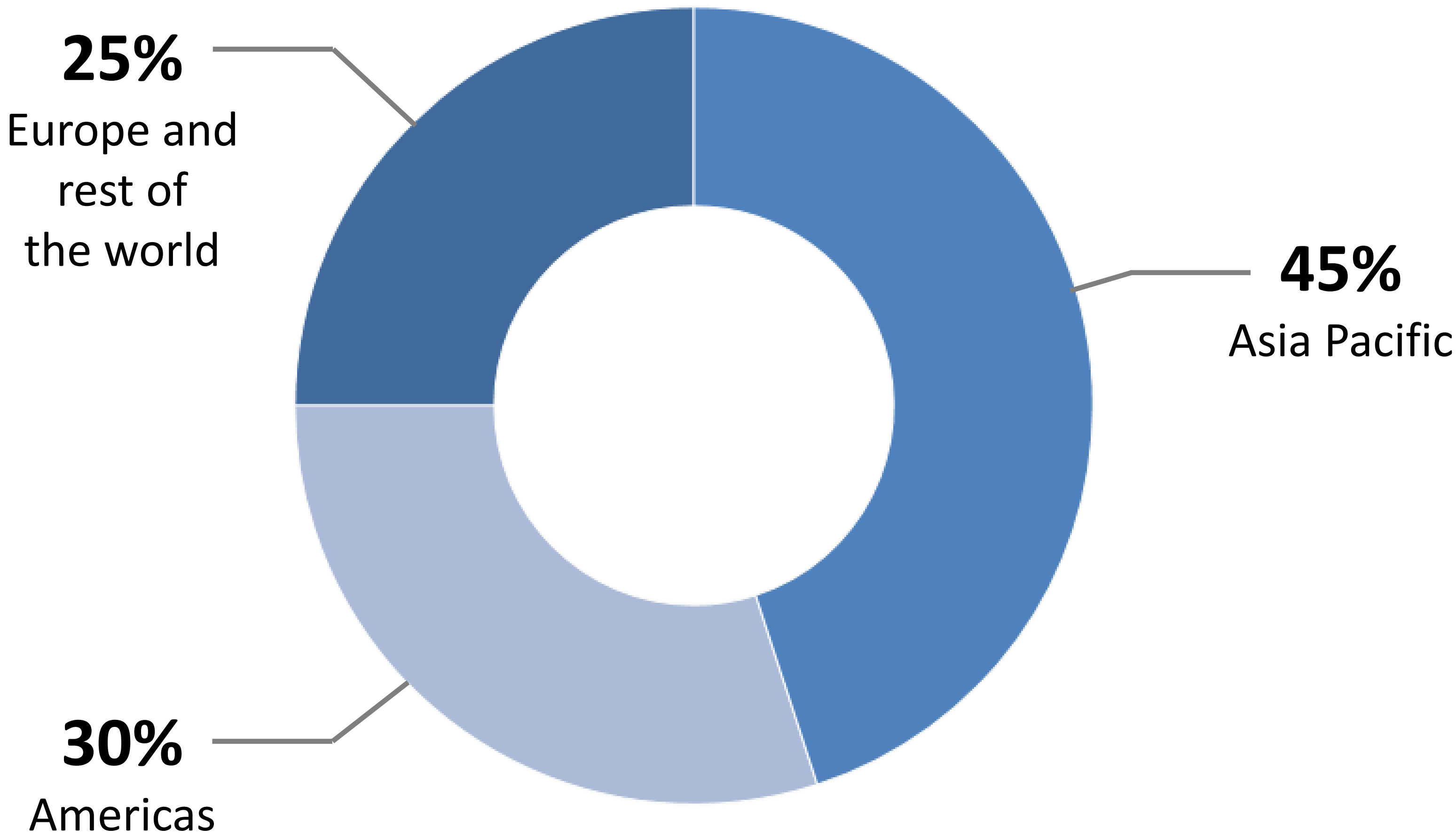
Source: Morgan Stanley Total Addressable Market Update 2021-05-06

Predicted eVTOL Market Size (people and cargo)



Source: Morgan Stanley Total Addressable Market Update 2021-05-06

Predicted eVTOL World Distribution 2035



Source: Porsche Consulting study

Optimistic Global eVTOL Market Forecast

	0 eVTOL	0 trip/year
2025		
	10,000 eVTOL	60 million trips/year
2030		
	200,000 eVTOL	1 billion trips/year
2040		
	8,000,000 eVTOL	45 billion trips/year

Source: Boston Consulting Group 2018, Morgan Stanley 2018, Porsche Consulting 2018, UBS 2019, Lufthansahub 2021

My Conservative Global eVTOL Market Forecast

	0 eVTOL	0 trip/year
2025		
	500 eVTOL	1 million trips/year
2030		
	20,000 eVTOL	100 million trips/year
2040		
	2,000,000 eVTOL	10 billion trips/year

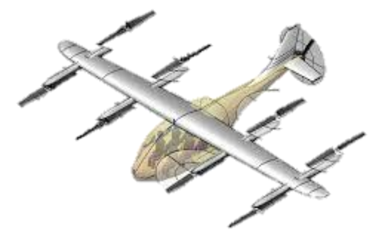
eVTOL Is not Going to Replace All Helicopters

Helicopters

Pros: proven, reliable, safe, certifiable long endurance, long range, trustworthy, large payload (as much as 50% of max gross weight

Cons: mechanically complex, more parts, expensive to maintain

eVTOL aircraft



Pros: maybe quieter, fewer parts, lower cost of ownership, cool, hip, game-changing idea

Cons: unproven, can not autorotate if lost power, short endurance and short range because of battery, low payload capability

1. Design Phases for a New Aircraft Program Different types of eVTOL

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Historically it Takes 7 to 9 years to Develop a New Aircraft

Years for each task

7-9 yrs

Years	Task	
1	**Conceptual design phase**	
1	**Preliminary design phase**	
2	**Detail design, wind tunnel test**	<- Start marketing
1	**Make protoypes, fatique test**	<- Start selling
3	**Ground vehicle test, flight test, certification, tooling prepare manual, training, etc**	
	Start delivery	
40 yrs	**Average service life per aircraft. OEM will continuously improve the product during first 20 years and support the spares another 20 yrs**	

Most eVTOL startups are trying to squeeze this into 5 to 6 years

Conceptual Design Phase

Define business needs, mission, KPP

Trade studies, competitive analysis, sketches, brainstorm

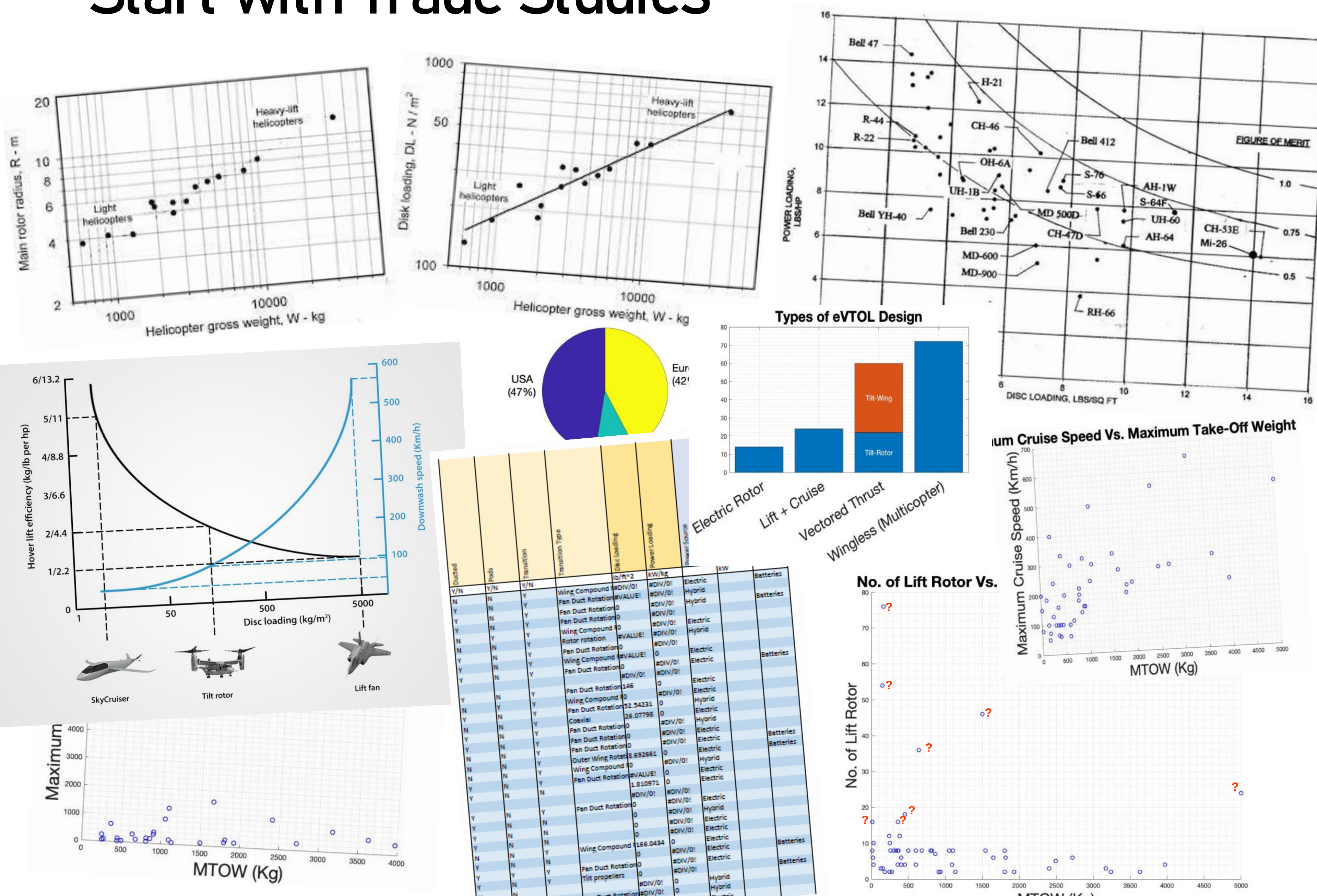
Down-select to a couple concepts

Write Down Goals & KPP for Your Aircraft

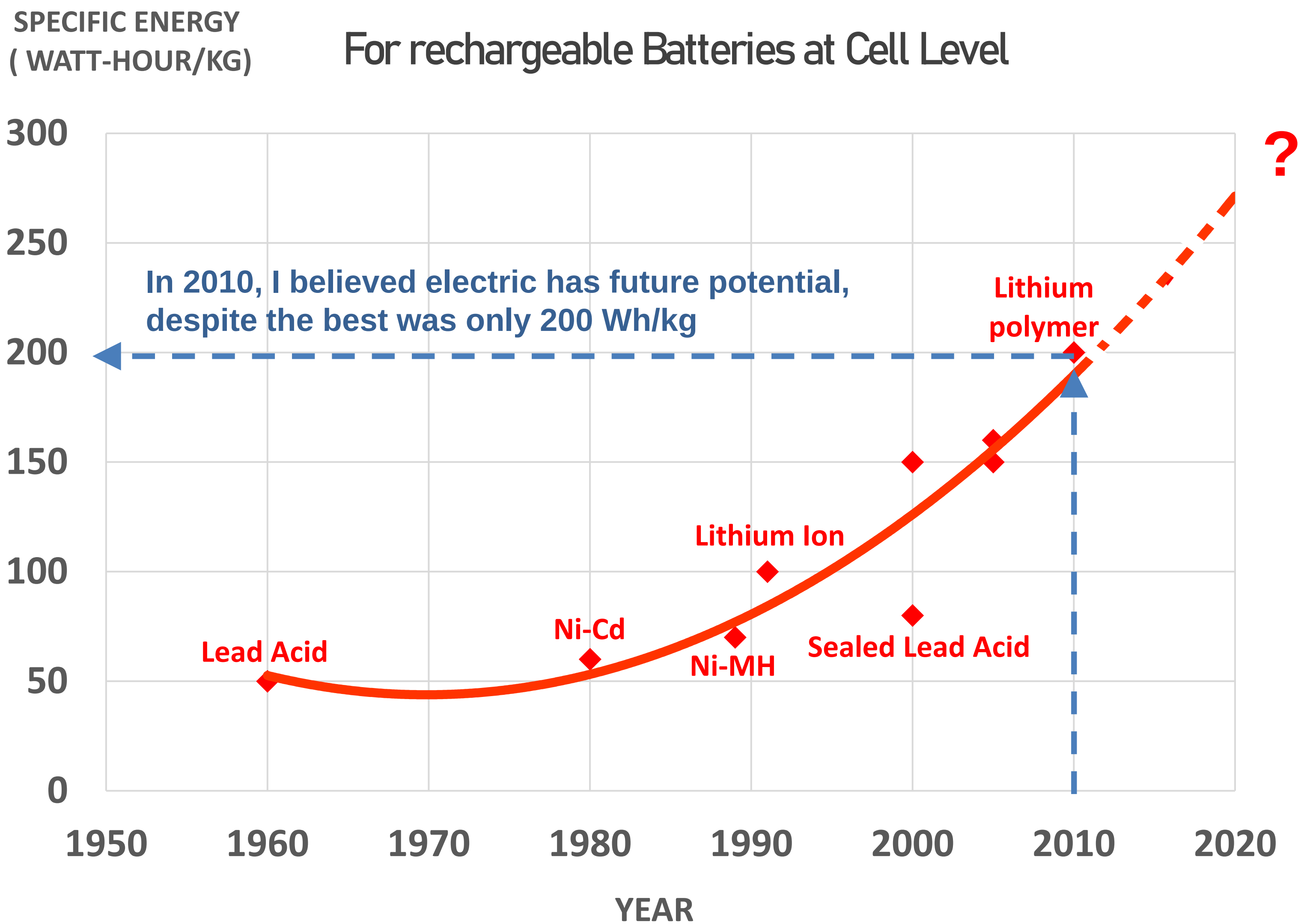
(KPP = Key Performance Requirements) Numbers for class examples only

Maximum Never Exceed Speed (VNE)	186 mph	300 km/hr
Maximum Flight Speed (VH)	149 mph	240 km/hr
Best Range Cruise Speed (VBR)	? mph	? km/hr
Max ceiling	8,840 ft	3,000 m
Hover ceiling, in ground effect	? ft	? m
Hover ceiling, out of ground effect	? ft	? m
One motor inoperative service ceiling	? ft	? m
Range – Long range cruise at VBR at 4000 ft		
With ? min reserve	? miles	? km
With no reserve	? miles	? km
Max takoff Gross weight	7,000 lbs	3,175 kg
Useful Load internal	800 lbs	363 kg

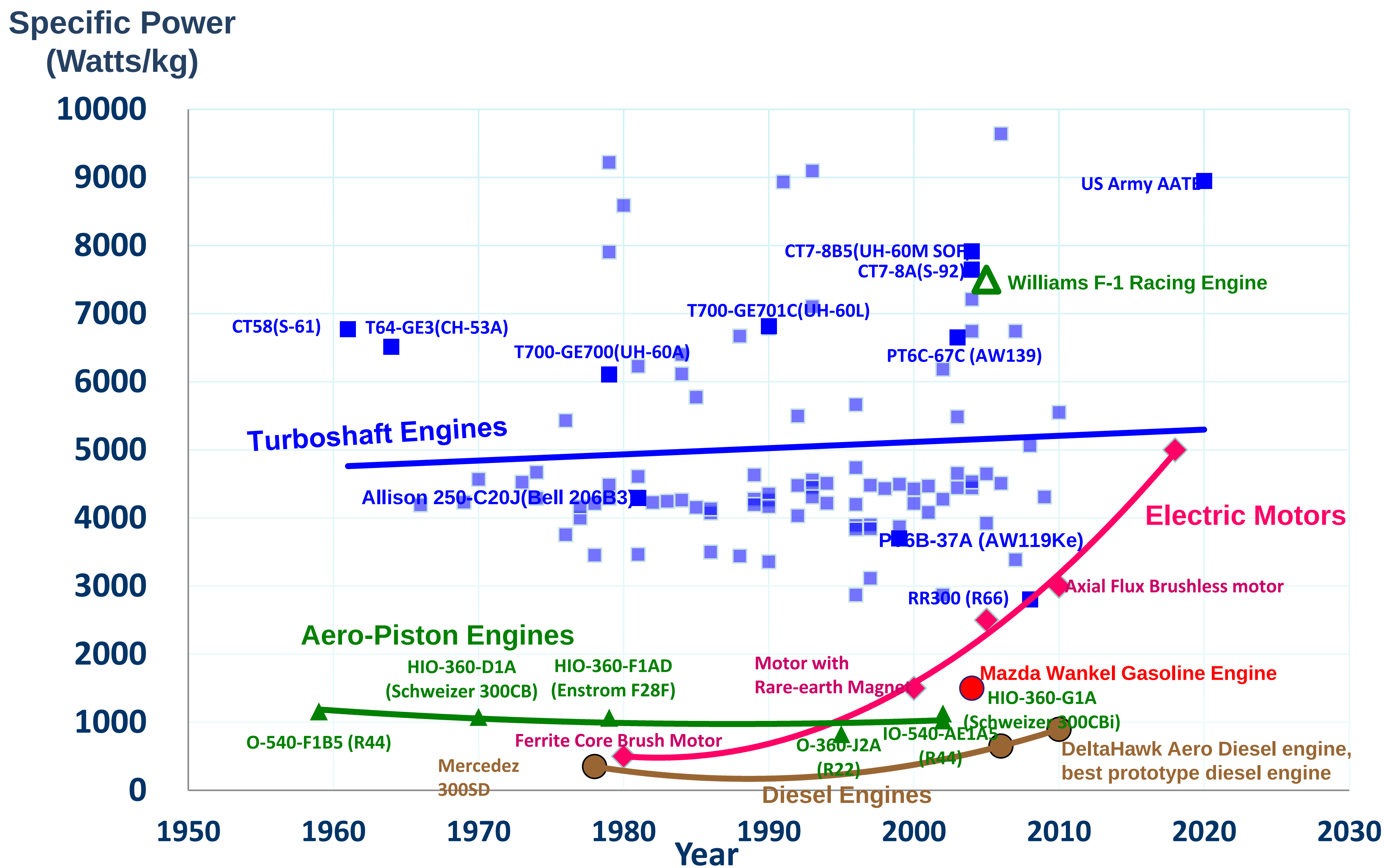
Start with Trade Studies



Specific Energy Data up to 2010, then Extrapolate

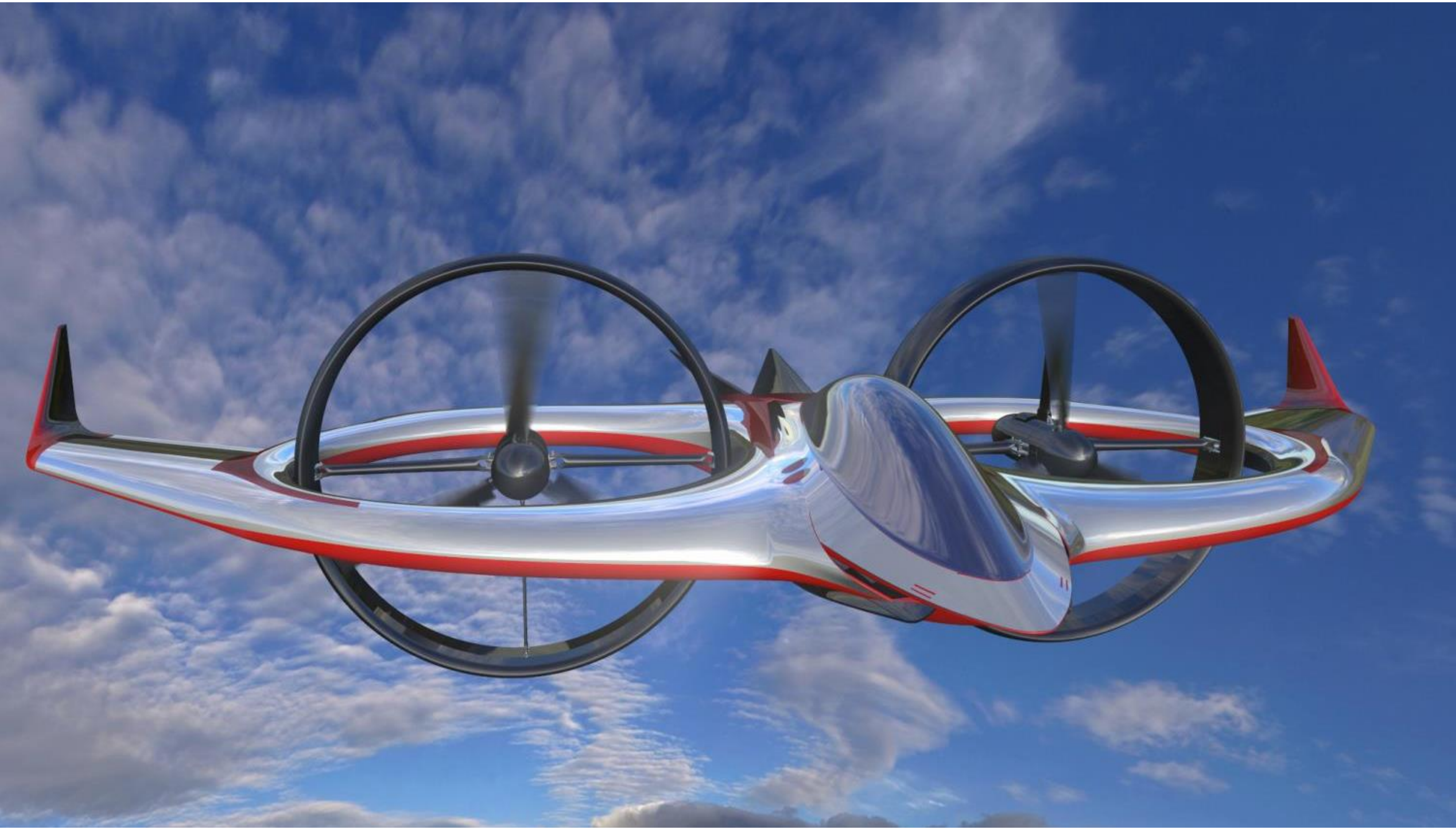


Propulsion Specific Power Trend up to 2010



Note, 746 watts = 1 horsepower

Conceptual Design Phase



Example Outcome: the AgustaWestland Project Zero Designed by Dr James Wang in 2010

Afterward, conduct a CoDR (Conceptual Design Review)

Preliminary Design Phase

More detailed calculation

Small flying models, wind tunnel, software simulations

Talk to potential suppliers/partners, find investors

Down-select to one concept

Build a large scale demonstrator

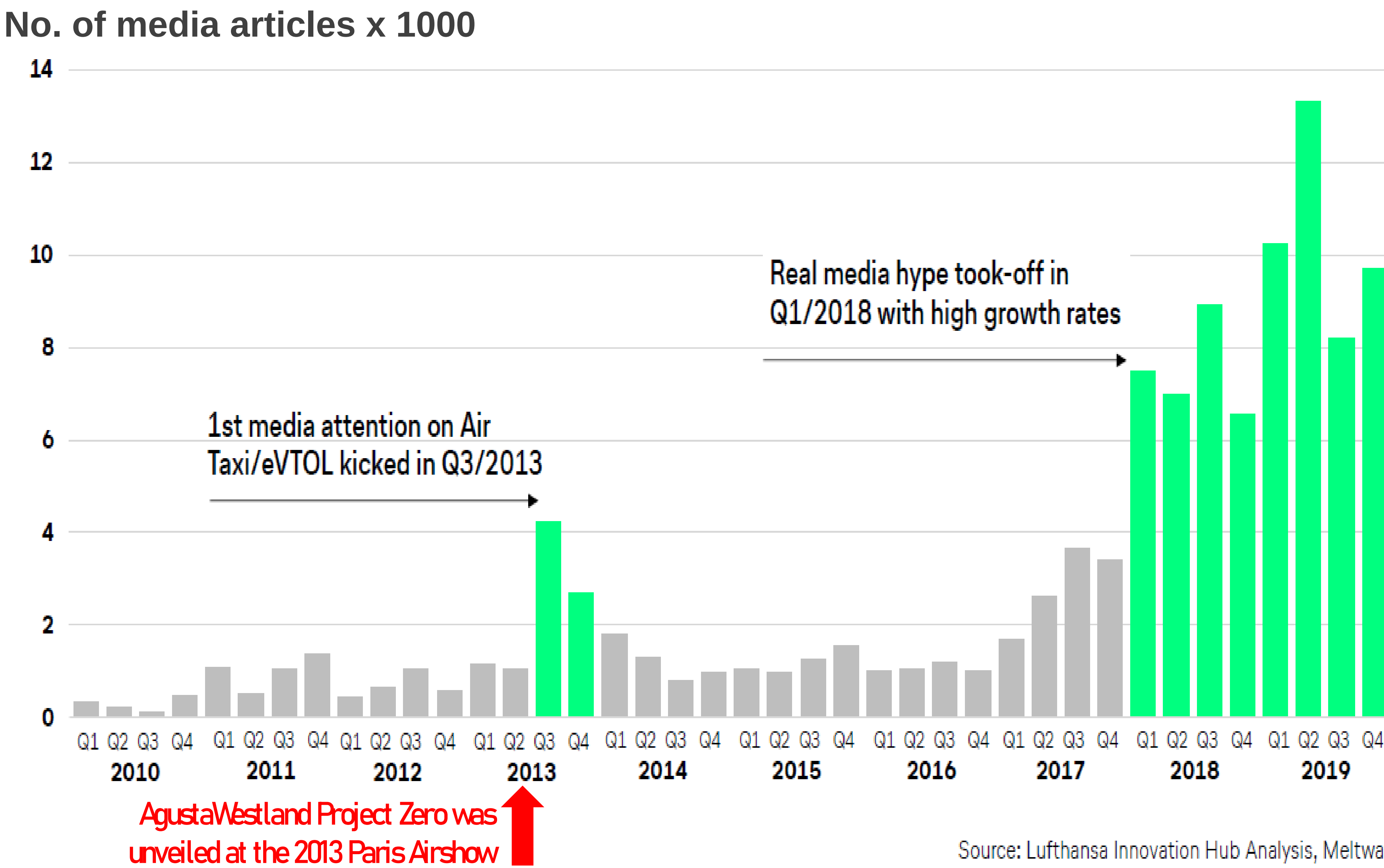
Project Zero technology demonstrator in 2011

Afterward, conduct a PDR (Preliminary Design Review)

Usually this is when come out of the stealth mode

Project Zero unveiled at the 2013 Paris Airshow

Number of Media Reports on eVTOL and UAM



Source: Lufthansa Innovation Hub Analysis, Meltwater

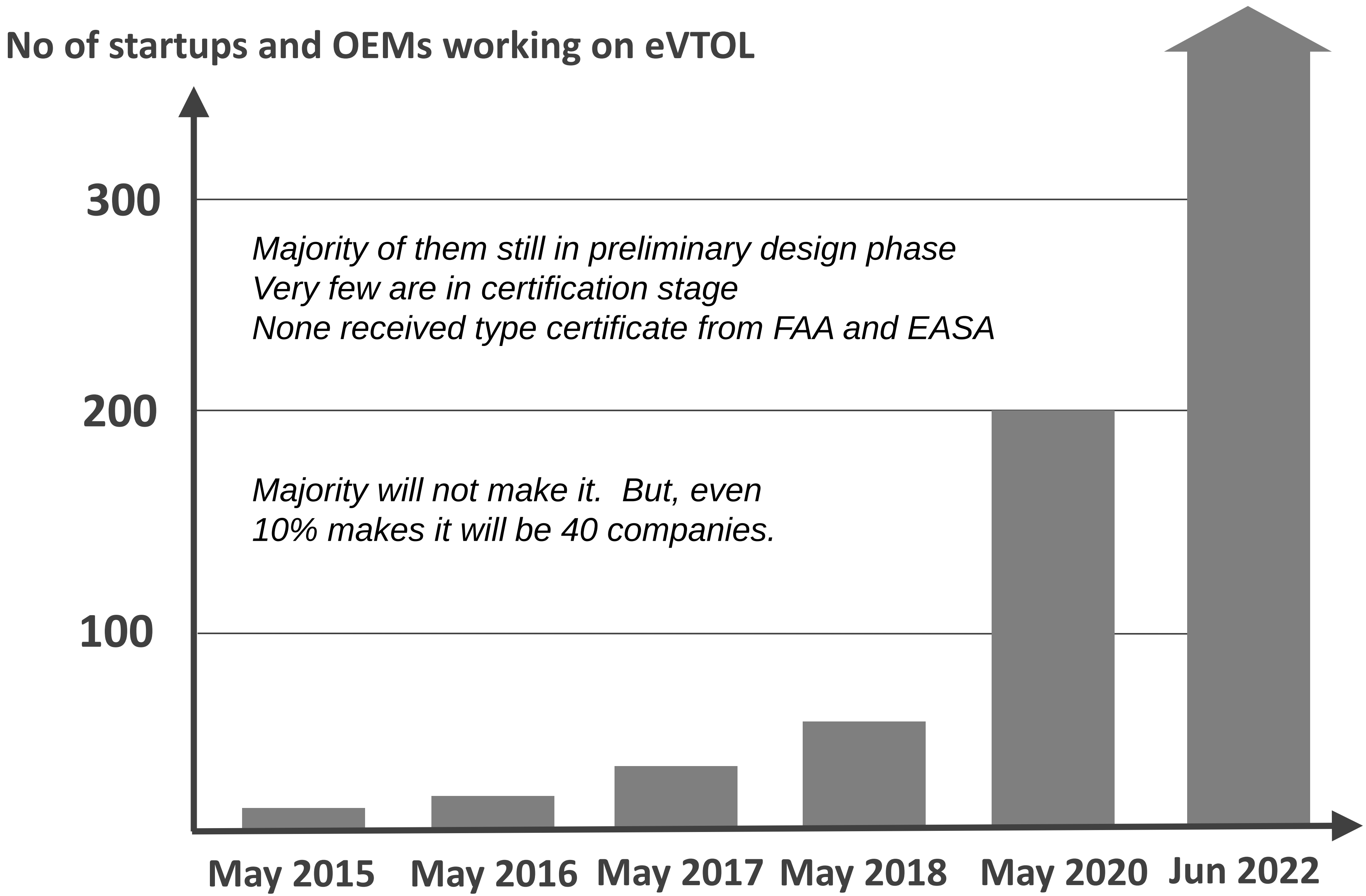
Airbus started eVTOL in 2015

Bell started Nexus in 2018

Boeing Started PAV in 2018

2018, Purchased Aurora Flight Science
2019, Start collaborate with Google, Porsche.
Boeing just invested $450 million into Wisk

Exponential Growth in eVTOL R&D



Detail Design Phase

One aircraft concept remains

Do all the detailed calculations, analysis, designing

Generate all the detailed drawings for producing

Work with suppliers, engage certification authority

Conduct laboratory tests, more flight test of demonstrator

Afterward, conduct a CDR (Critical Design Review)

Prototype

Build 3 to 4 prototypes, each at few months apart

Conduct fatigue tests, whirl test, EMI test, software test, hardware in the loop test

Fly the prototype toward type certificate

Start tooling and plant build up, work toward production certificate

FRR before flying the prototype
(Flight Readiness Review)

eVTOL Schedule and Budget (average 7+ years)

US $100m

US$ $900m

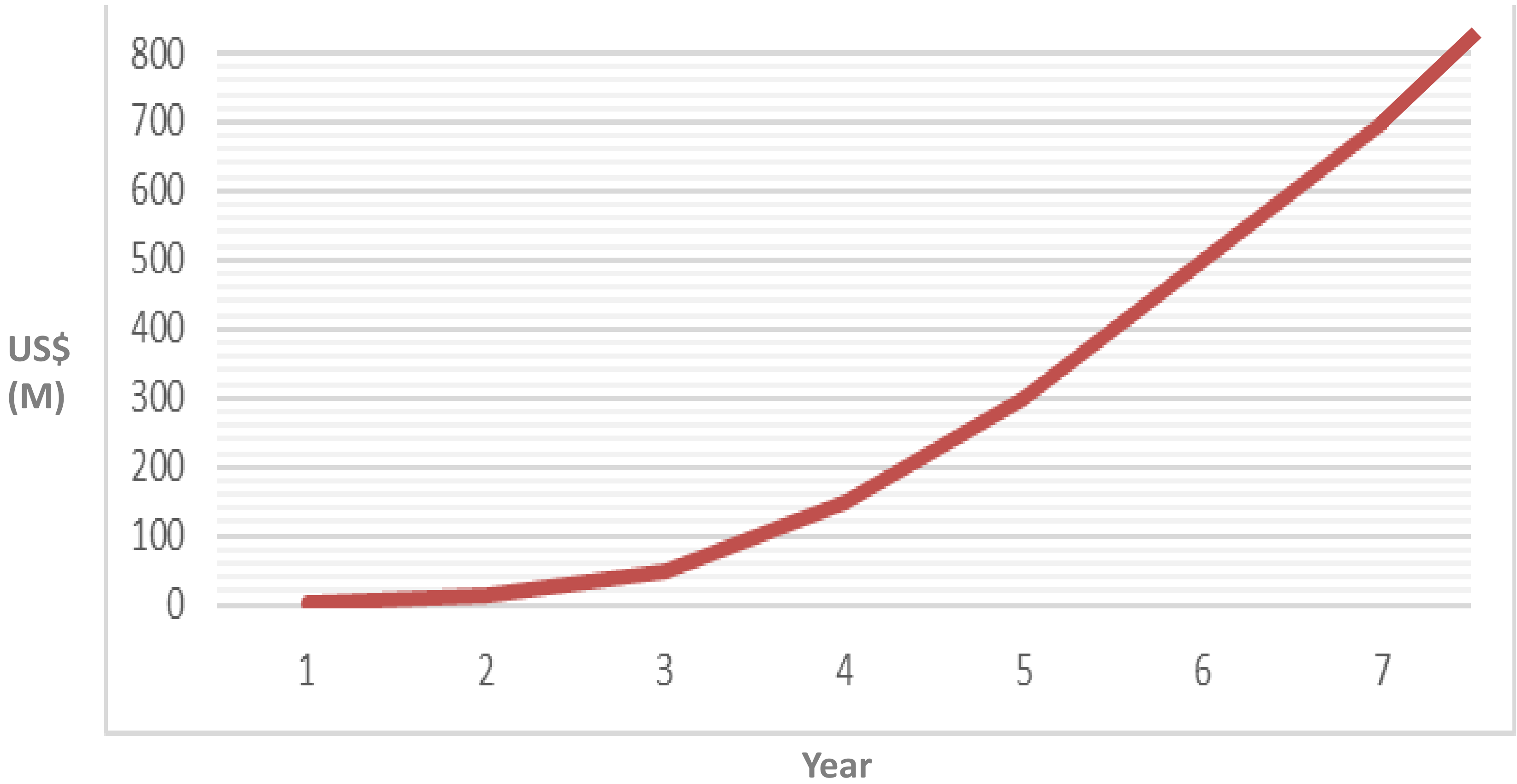
Conceptual Design | Preliminary Design | Product Development, Certification | In Service

Conceptual Design	Preliminary Design	Product Development, Certification		In Service
Trade study, Brainstorming, sketching	**Down select design**	**Detail Design**	**Build and fly prototypes for type certificate. Get production certificate.**	
0.5 to 1 year	**1 to 2 years**	**1.5 to 2 year**	**3 to 4 years**	

Schedule by James Wang

You have decided to start an eVTOL company or program

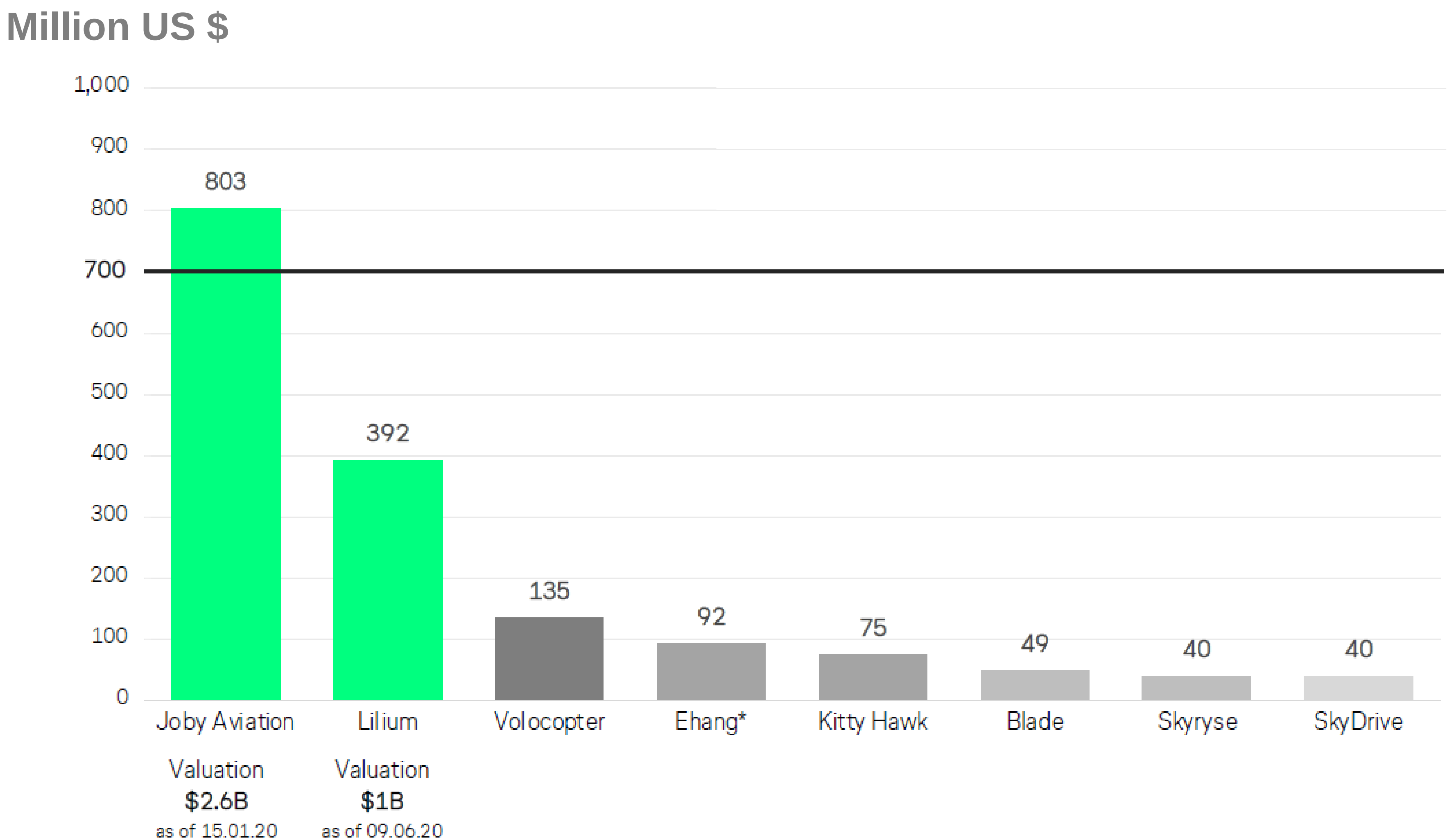
Investment Required to Develop an eVTOL Aircraft



Note, US $ will be used through out this short course in order to compare to other international programs

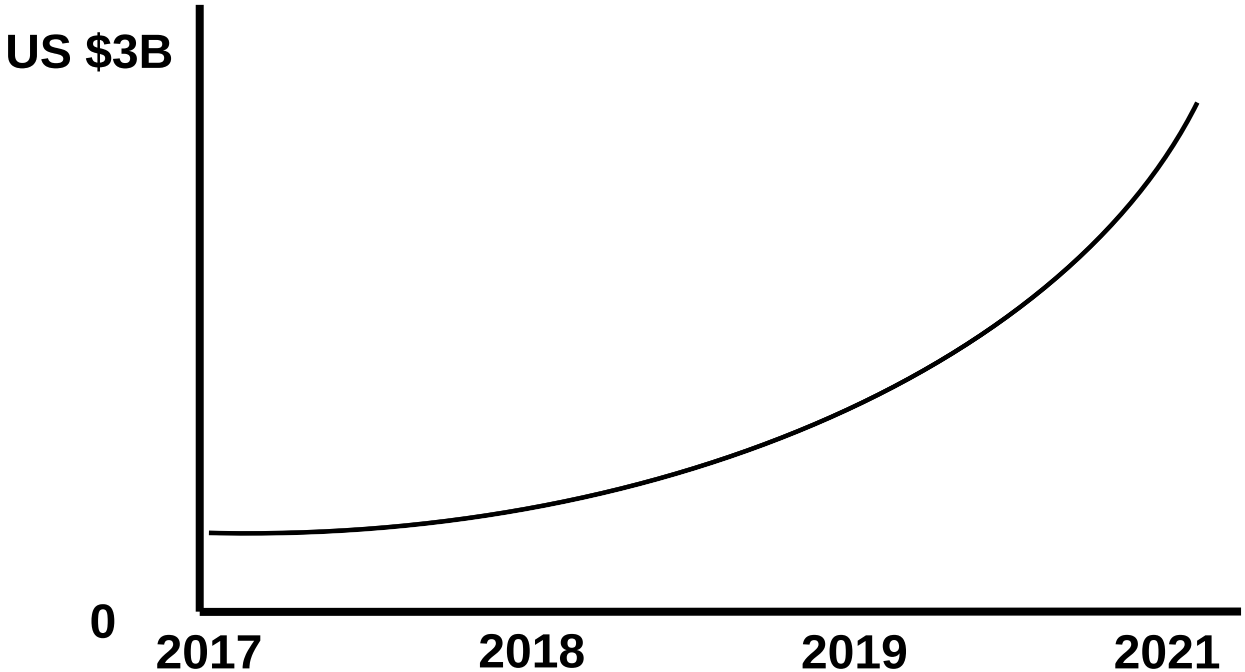
calculation by James Wang

Need > US $1 billion from Soup to Nuts



Source: Lufthansa Hub Report 2021, numbers have gone up in 2022

Amount of Investment Worldwide on eVTOL



VC and Corporate Ventures Invest in eVTOL

These are funding and not valuation

Start-ups	Funds	Investors
Joby	$1,800m	Toyota, Intel, JetBlue,... IPO Feb 2021
Lillium	$930m	Tencent, Freigest, Obvious, Atomico, Baillie Gifford, Qell,... IPO Sept 2021
Archer	$850m	Atlas Crest Investment,... IPO February 2021
Beta technologies	$510m	UPS, Amazon, FedEx, Fidelity, United Therapeutic,..
Eve	$500m	Embraer, Zanite, Azorra Aviation, BAE Systems,...
WISK	$480m	Google, Boeing, Porsche,...
Vertical Aerospace	$380m	RR, Am Airlines, Avolon, Honeywell,.. IPO Dec 2021
Volocopter	$380m	Daimler, Geely, Intel, DB Shenker,...
		Mitsui Sumitomo, MS&AD, Translink, Blackrock,...
EHang	$130m	United Therapeutic, Lung Biotech,... IPO Dec 2019
SkyDrive	$40m	Suzuki, DBJ, NEC, ENEOS, Itochu Corp, Obayashi, VeriServe, Sumitomo Mitsui Finance and Leasing,...
Overair	$25m+$145	Hanwah Systems

Note the numbers will change continuously

Many Cross-Industry Collaborations

- Archer + Fiat Chrysler + United Airline +…
- Boeing + Kitty Hawk + Porsche +…
- Airbus + RR/Siemens + Audi +…
- Joby + Toyota + Intel Capital + Uber + Agility Prime + Garmin +…
- Vertical + RR + Honeywell + GKN+ Solvay + Bristow + Leonardo +…
- Lilium + Ferrovial + Honeywell + ABB + Lufthansa + Customcell + Toray + City of Orlando + Azul + Aciturri + …
- Volocopter + Mercedes + Geely + Intel +…
- EHang + United Therapeutic + Lung Biotechnology +…
- Supernal + Hyundai + Uber +…
- Beta Technologies + United Therapeutic + Agility Prime + UPS +…

Note, the data change continuously

Good Time to Start eVTOL

2019 Dyson wanted to invest US$4.3B, but Dyson cancelled because that is a drop in the ocean compared to the wealth of the automotive giants who are waking up to the epochal shift away from internal combustion engines.

Volkswagen alone has announced plans to invest US$50 billion in electrification as it targets production of at least two million electric vehicles a year by 2025.

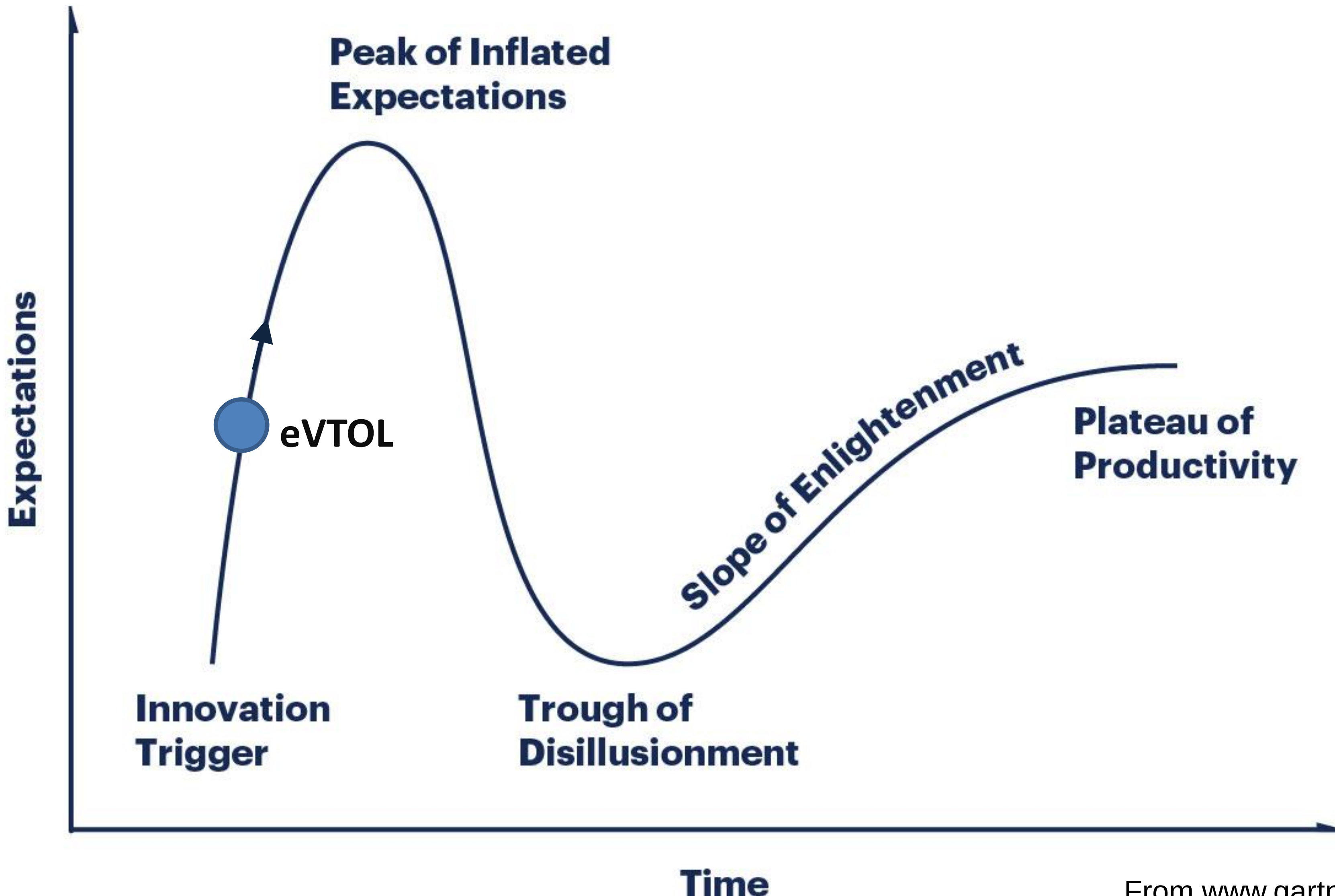
Look at 2019 Frankfurt Autoshow, its all about Electric.

Ford, Porsche, Toyota, Hyundai, Geely… All Wants in on Electric

Old Fashion Manufacturing in Small Quantity

Automatic Automotive Style Manufacturing

Gartner's Hype Cycle



From www.gartner.com

Requirements for Success

Primary

- Seed money (savings, or know rich friends)
- Leadership (Is that you?)
- Technical team (Hire the best experts, advisors)

Secondary

- Proprietary technologies, geography, partnerships, etc…

Requirements to Continue the Program

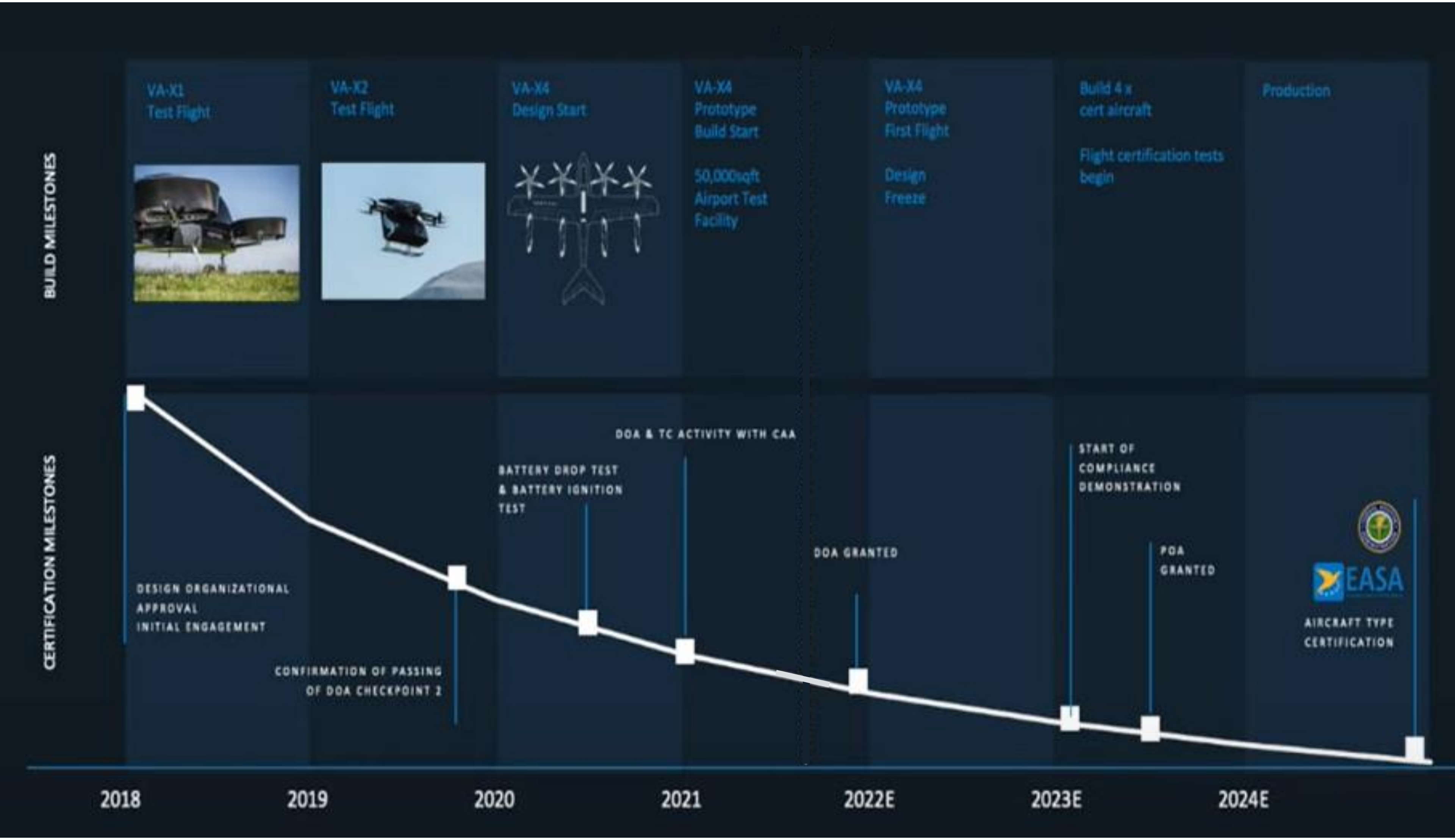
- *More funding*
- Testing and data for validation
- Grow certification expertise
- Grow manufacturing expertise

You Will Need More $$$
Investors will evaluate you on

- Leadership and technical team
- Your financial situation
- Design matureness
- Airworthiness/certification
- Business and industrial plan

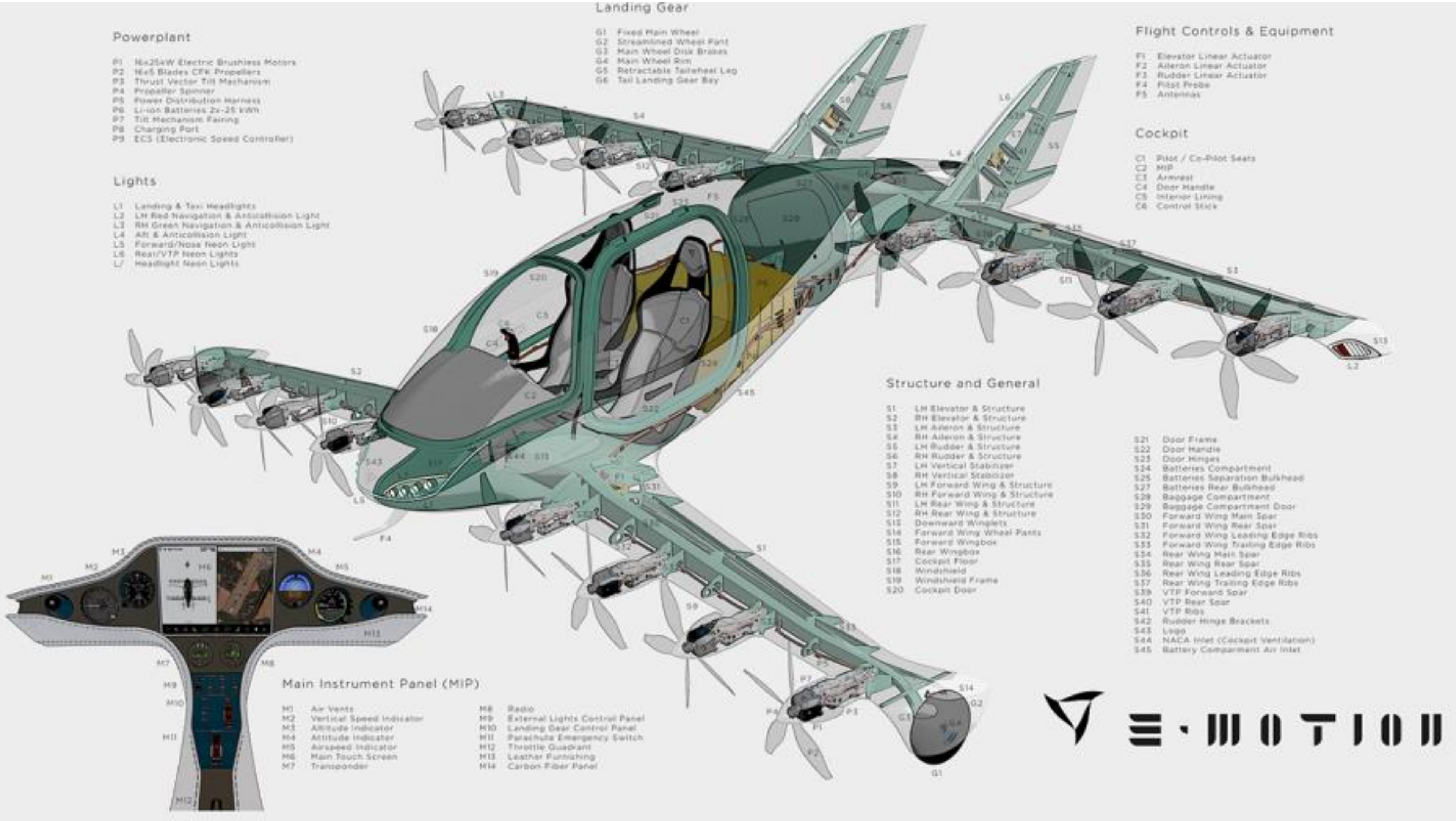
It takes longer than expected

Example of an Ambitious Schedule



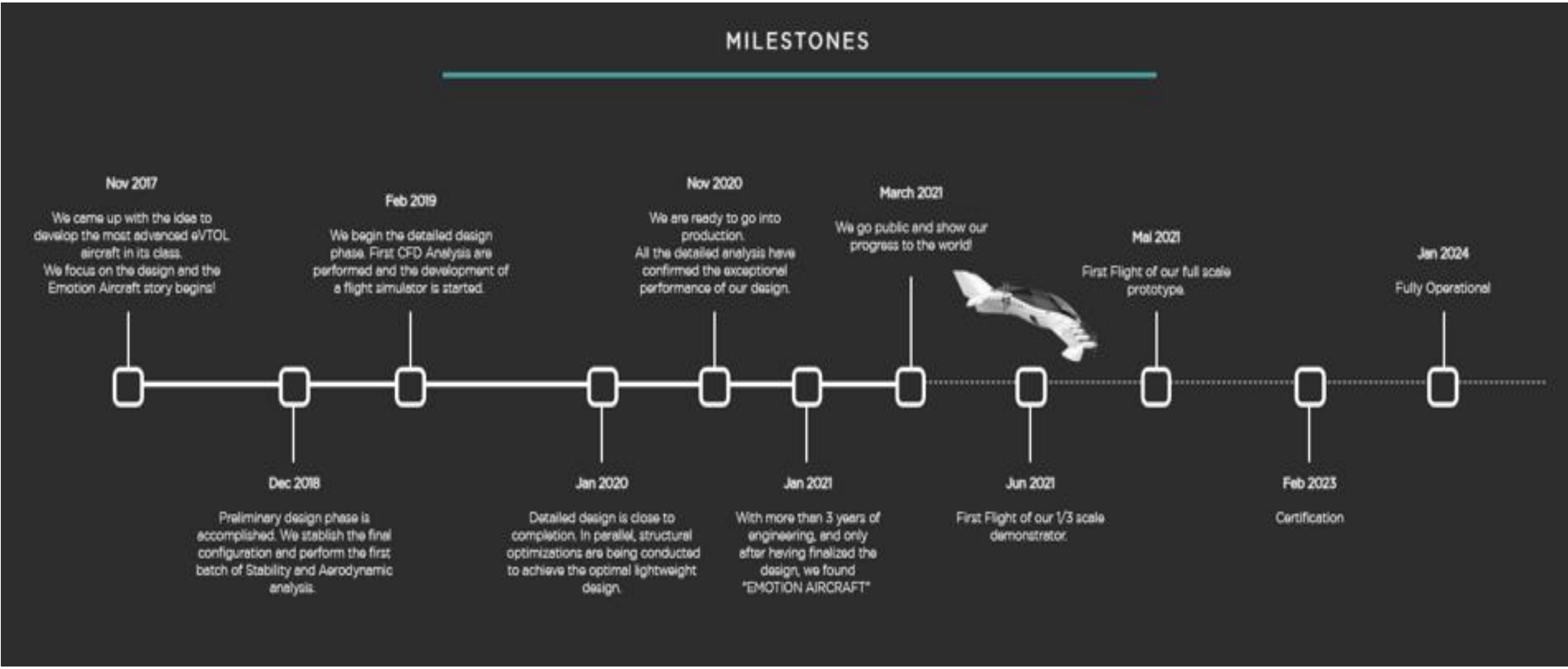
7 years from concept to receive certification

Example: an eVTOL from Emotion of Germany



Source: https://www.youtube.com/watch?v=MvE6tpf3060&ab_channel=EmotionAircraft
https://www.emotion-aircraft.com/

Example of the Schedule from Emotion

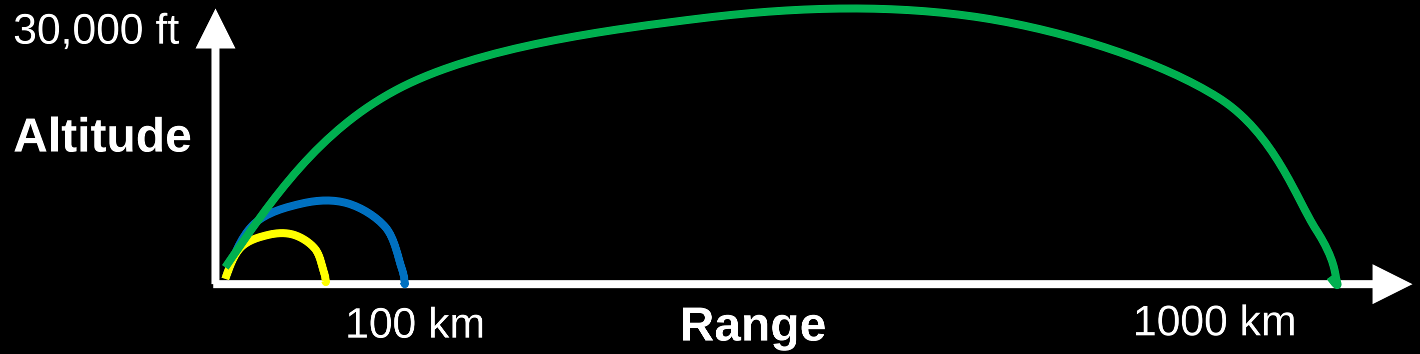


Total 8 years is reasonable

18 months from first flight to receiving certification is short

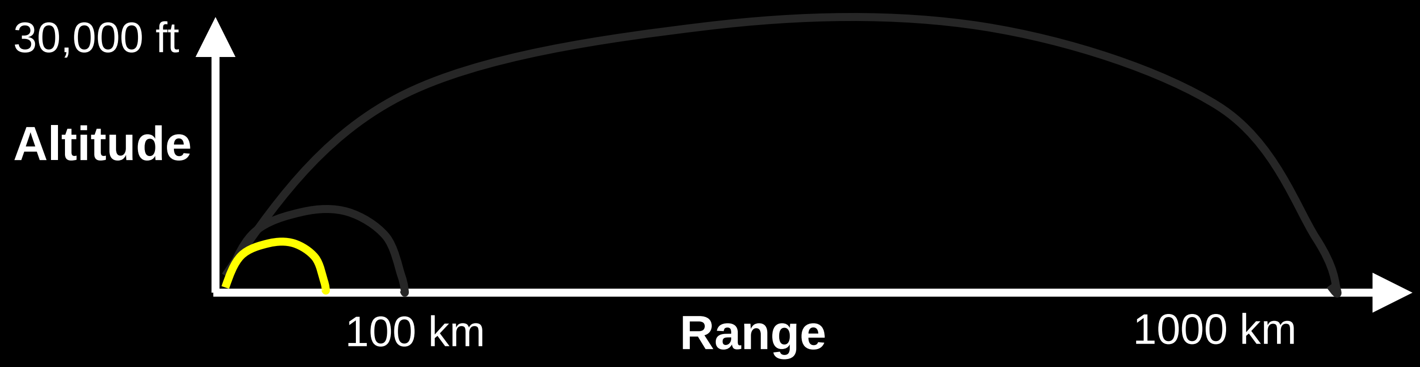
Three eVTOL Niches

- Personal eVTOL (GoFly competition)
- Short haul point-to-point business and inter-city (XTI TriFan)
- Public transport – urban air mobility (UAM)



First eVTOL Niches

- Personal eVTOL (GoFly competition)
- Short haul point-to-point business and inter-city (XTI TriFan)
- Public transport – urban air mobility (UAM)



Ten winners of GoFly Phase 1

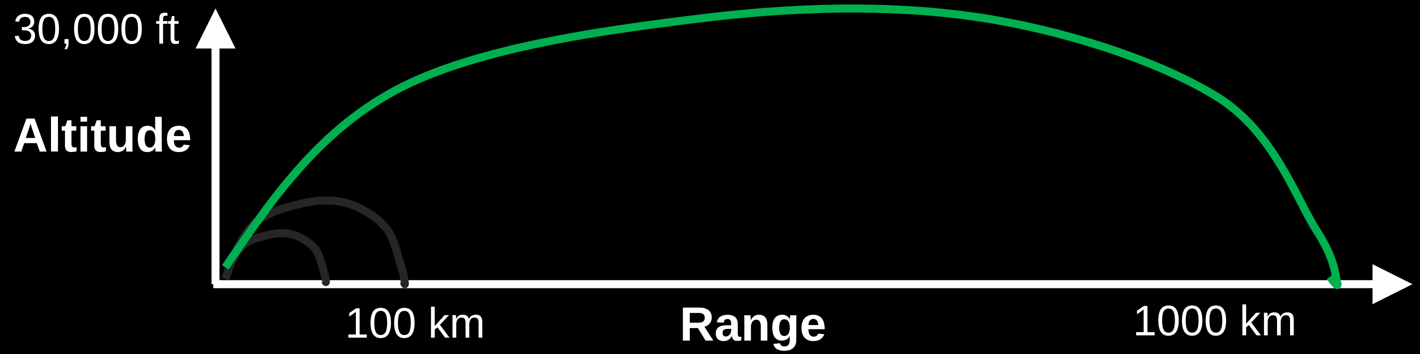
GoFly Final Flyoff at NASA Ames Feb 2020

No team completed the $1m prize requirements !

Team Tetra from Japan won Disruptor Award

Second eVTOL Niches

- Personal eVTOL (GoFly competition)
- Short haul point-to-point business and inter-city (XTI TriFan, Pegasus)
- Public transport – urban air mobility (Uber)



Trifan from XTI, USA

5. Efficient turboshaft engine

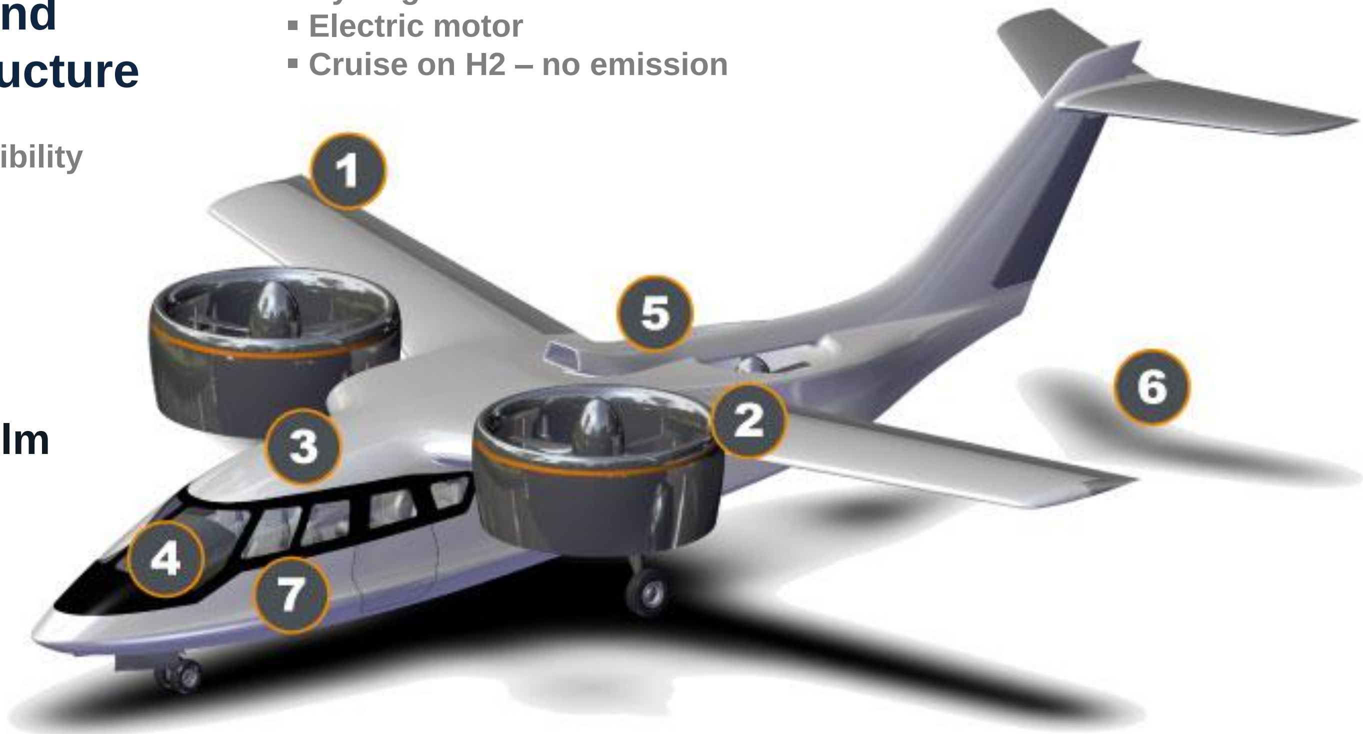
- 100% Sustainable Aviation Fuels (SAF) compatible
- Fuel efficient, highly reliable
- Supplemental power in vertical mode

2. Hybrid Energy System (HES)

- Hydrogen fuel cell
- Electric motor
- Cruise on H2 – no emission

1. Aluminum and composite Structure

- Lighter weight
- Greater design flexibility



3. Embedded Solar Film

- For ground power
- No noise pollution
- Zero emissions
- Low operating cost

4. Garmin 3000 Avionics

- Certified for single pilot operation
- Installed in hundreds of aircraft

7. 'Fly by wire' Flight Controls

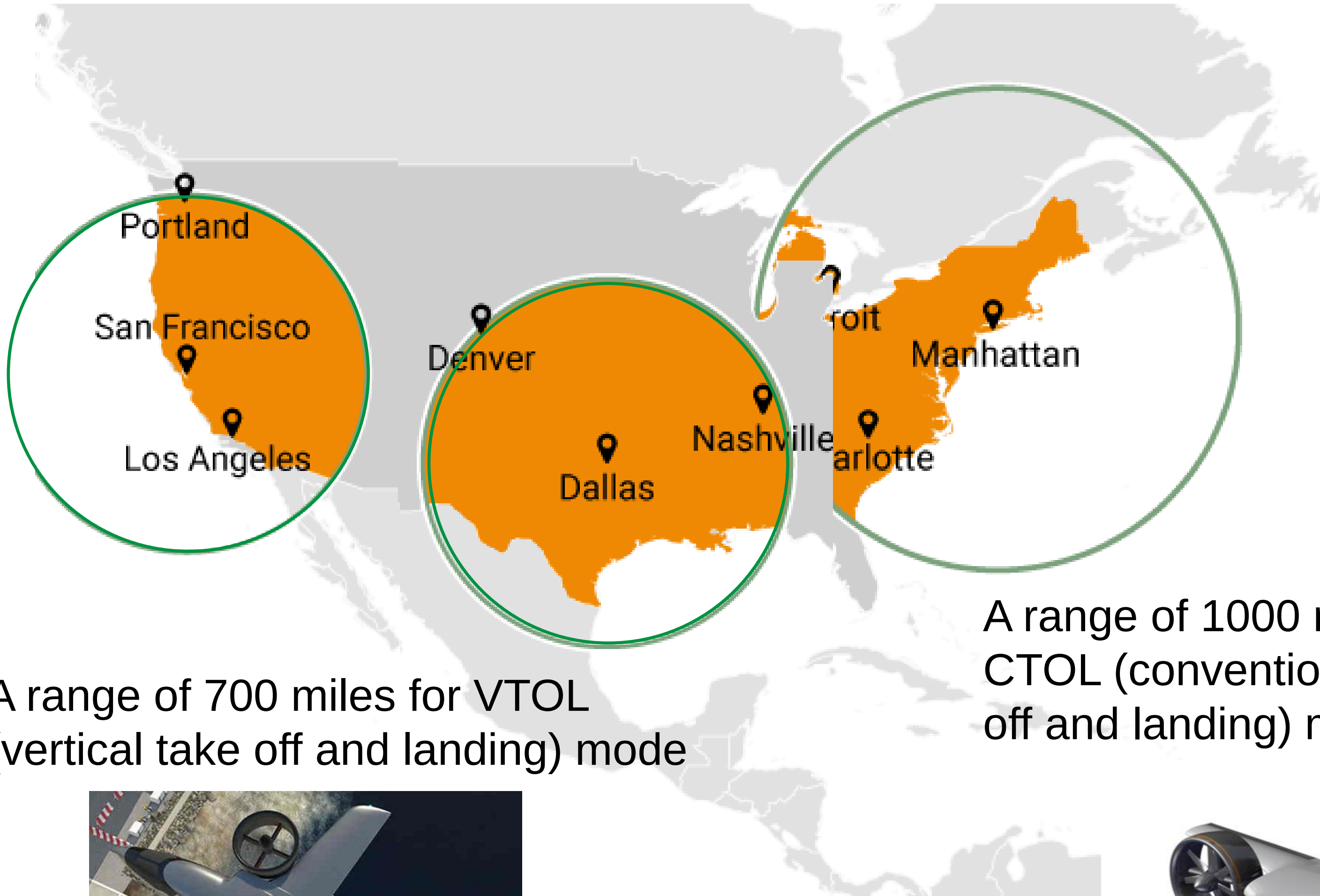
- Reduced pilot workload
- Stability enhancement

6. Digital Engineering

- 3D modeling
- Product Lifecycle Management
- Agility, efficiency

Source: from XTI public release 2022-02

Trifan from XTI, USA



A range of 700 miles for VTOL (vertical take off and landing) mode

A range of 1000 miles for CTOL (conventional take off and landing) mode

Source: from XTI public release 2022-02

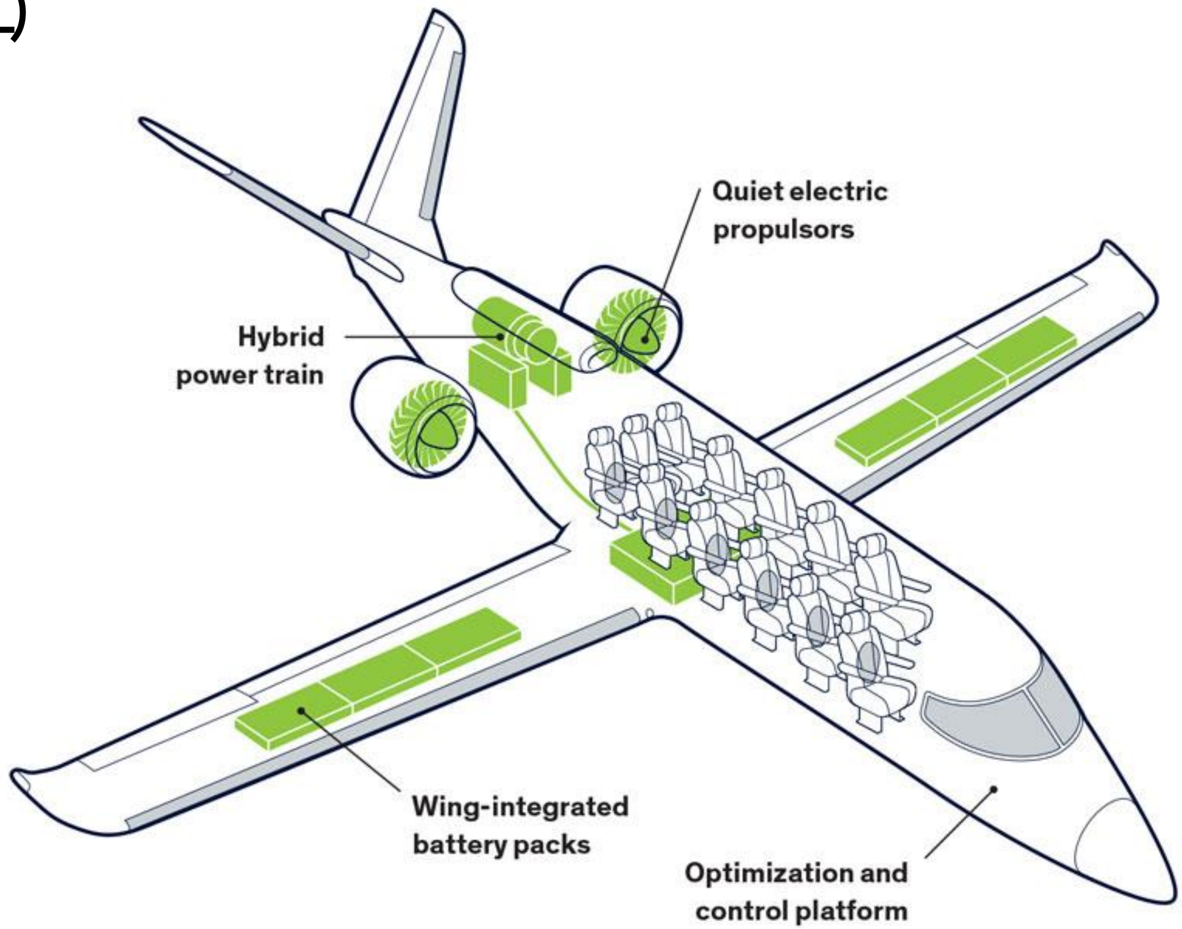
Example: Pegasus Universal Aerospace

Source: https://evtol.news/pegasus-universal-aerospace-vertical-business-jet/

Example: Eviation Alice Electric Airplane

(Non-VTOL)

Example: Zunum Hybrid-Electric Airplane
(Non-VTOL)

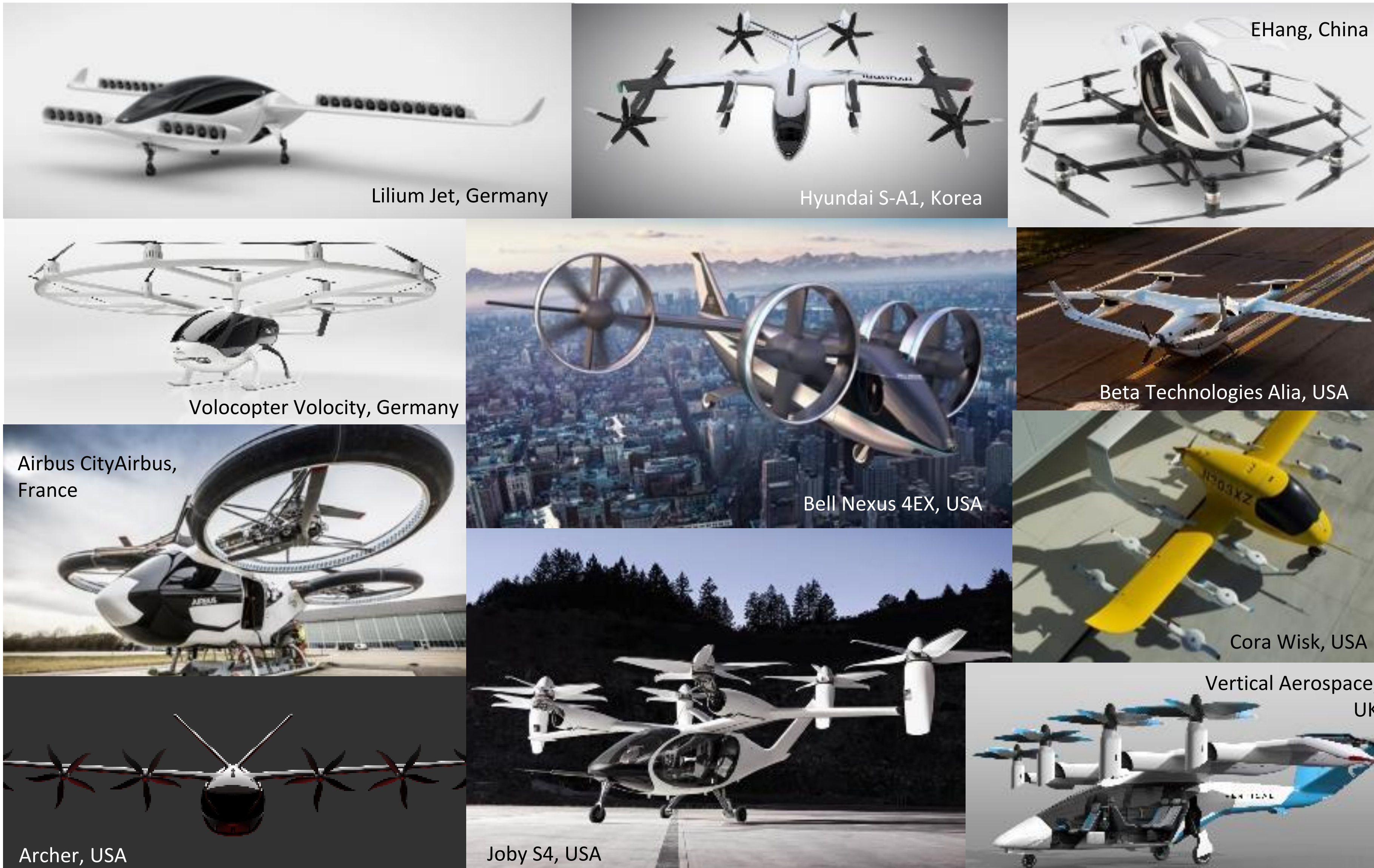


Source: https://spectrum.ieee.org/aerospace/aviation/zunum-aeros-hybrid-electric-airplane-aims-to-rejuvenate-regional-travel

Third eVTOL Niches

- Personal eVTOL (GoFly competition)
- Short haul point-to-point business and inter-city (XTI TriFan)
- Public transport – urban air mobility (UAM)

This is the Most Competed Niche



Often called Urban Air Mobility, it includes air taxi, shared ride, VIP transport, cargo delivery, organ transport, emergency services…

Why Share Ride Car is Successful?

- They provide additional transportation mean to help people

- A new user experience: on-demand, no cash.

- 30% of millennials do not plan to buy cars

- $215 billion revenue by 2025

- Can this be repeated for air mobility? Where to find thousands of pilots? Can they beat the regulation again?

Exponential growth of Uber car share-ride may be an indication for UAM

Uber's market	**End of 2019**	**Jan 2020**
Countries:	60	66
Daily trip:	15 millions+	19 millions+
Monthly active riders:	75 millions+	100 millions+
Total Rider served:	10 billions+	15 billions+

Data presented by Uber at VFS Jan. 2020

First, Set Up Intra-City Air Taxi Hubs

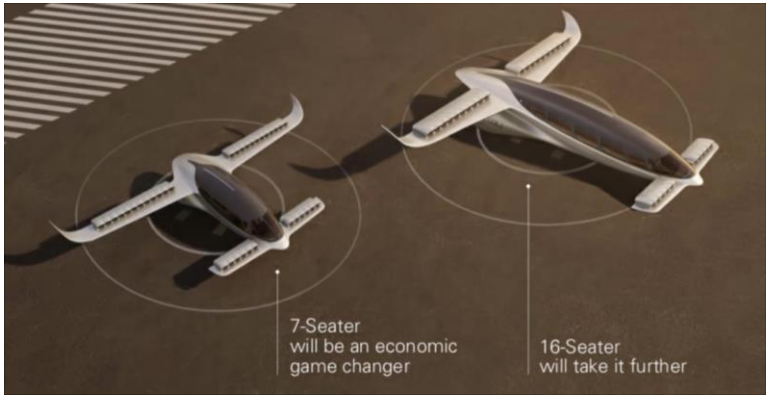
View of Dubai
Picture from Uber brief

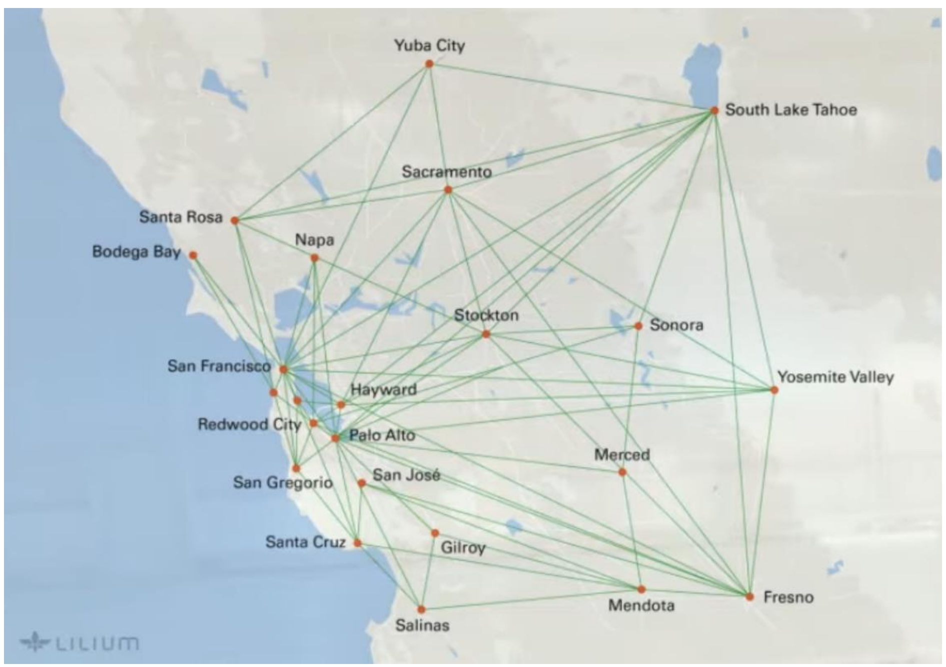
UAM Will Require Setting Up Many Air Taxi Hubs

View of Los Angeles
Picture from Uber brief

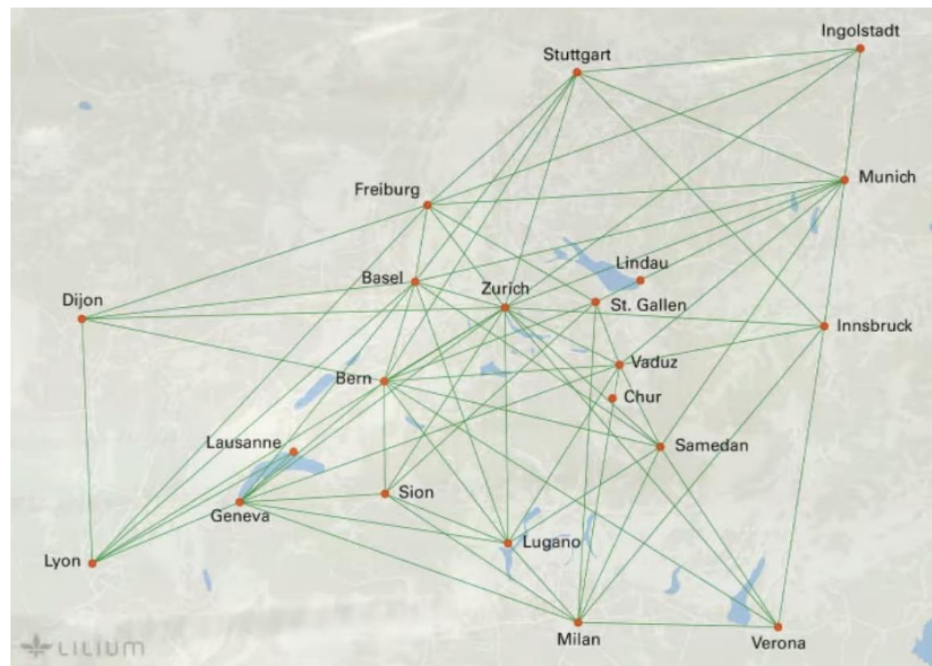
Expands to Inter-City

Example: Lilium's goal is 300 km/h speed and 300km range





Connecting Northern California cities



Connecting Germany, France, Switzerland, Austria, and Italy

Linking Singapore, Malaysia and Indonesia

Example of a Roof Top Vertiport

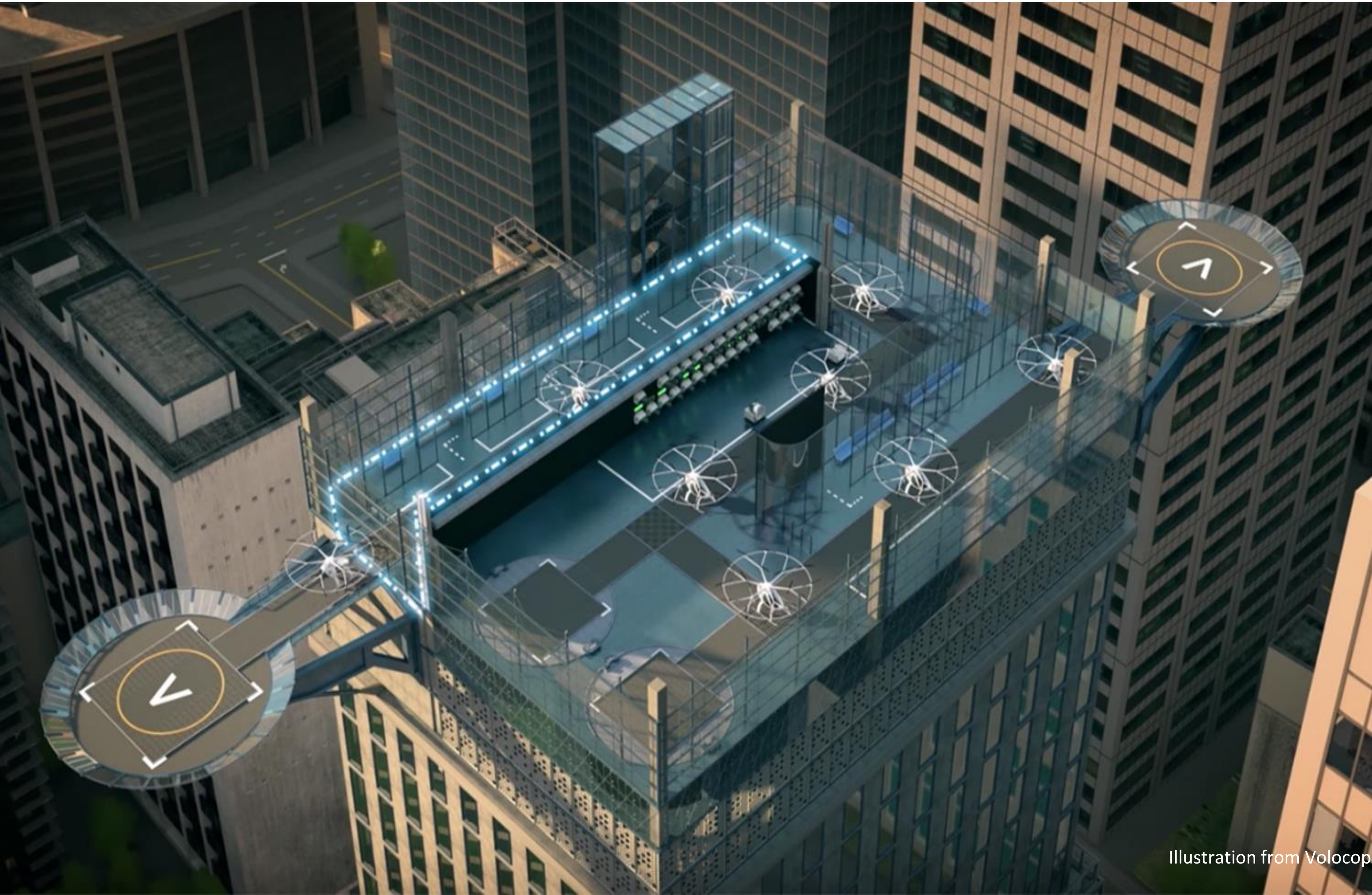


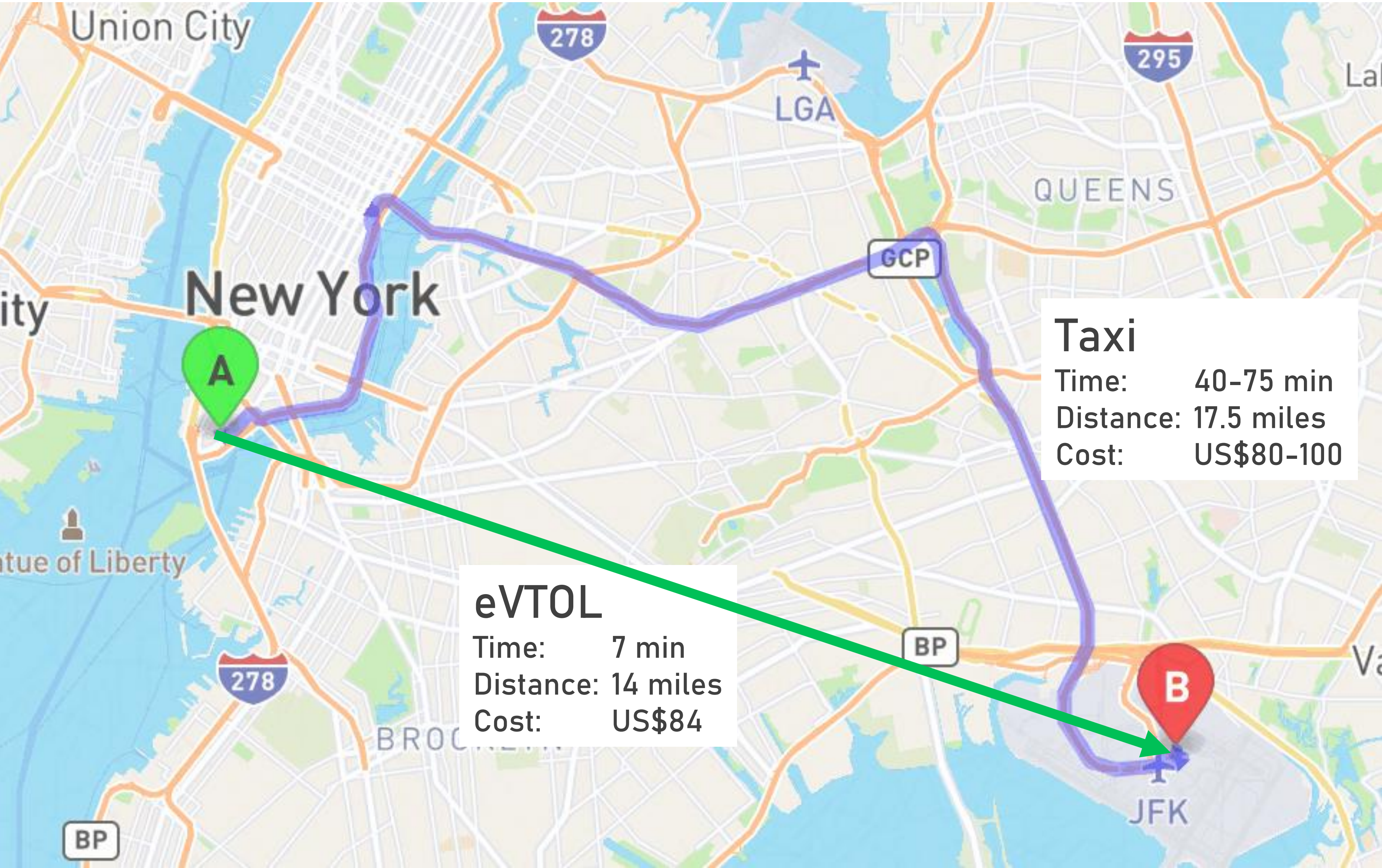
Illustration from Volocop

Over 50 Cities Are Exploring UAM for People and Cargo

- Los Angeles, Dallas, Melbourne, Dubai, Osaka, Rio de Janeiro,… want to launch UAM by 2025.
- Paris wants to debut air taxi at the 2024 Summer Olympic.
- Singapore may provide sight seeing rides by 2023

Price to Ride UAM

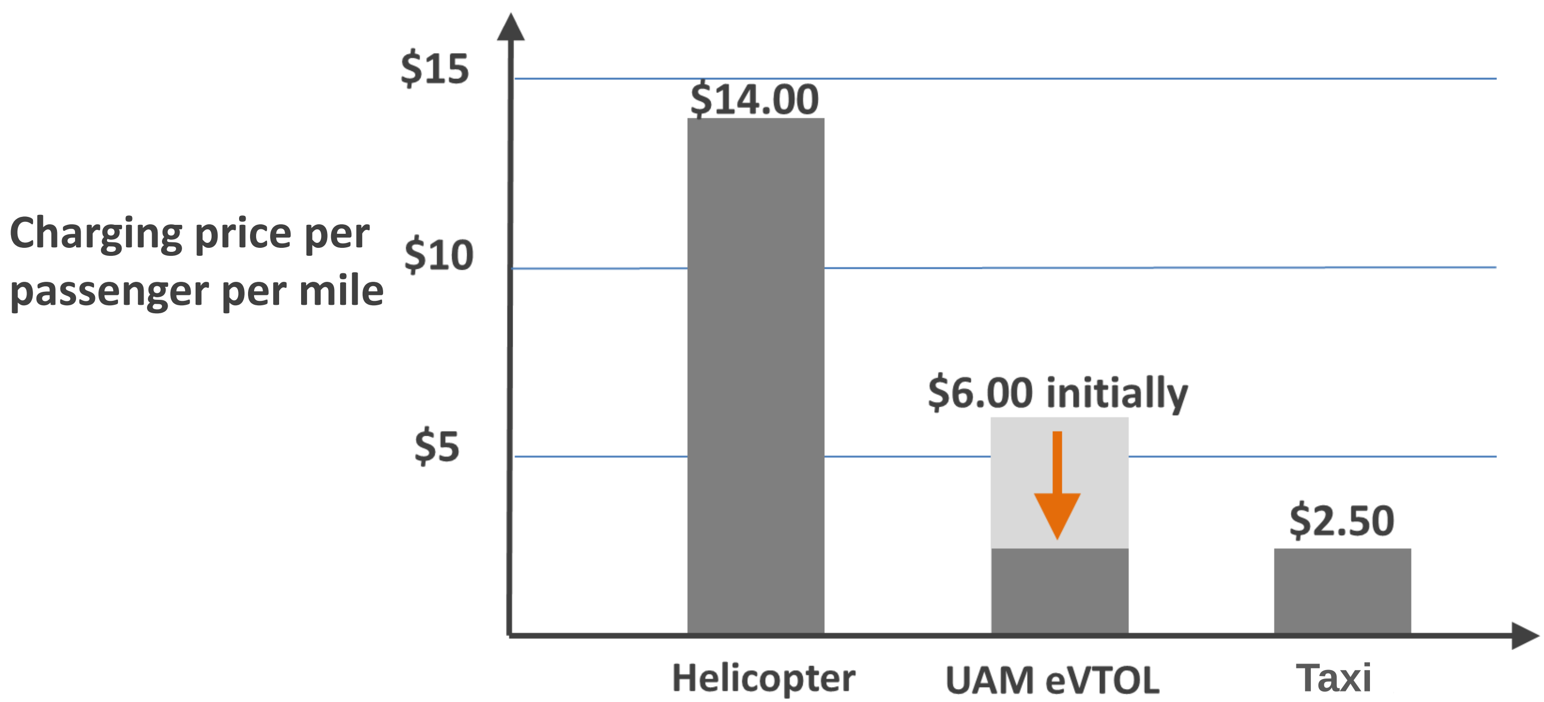
Example: NY Wall Street to JFK Airport



Today Blade operates helicopter flight from NYC to JFK Airport.
Only 7 minutes for 14 miles. Blade charges $195 per passenger

How Can eVTOL Reduces Air Taxi Price

- Goal is for eVTOL to cost less to buy & operate by 2027
- Further reduction through mass production by 2030 to 2035



eVTOL Reduces Hardware and Operating Cost

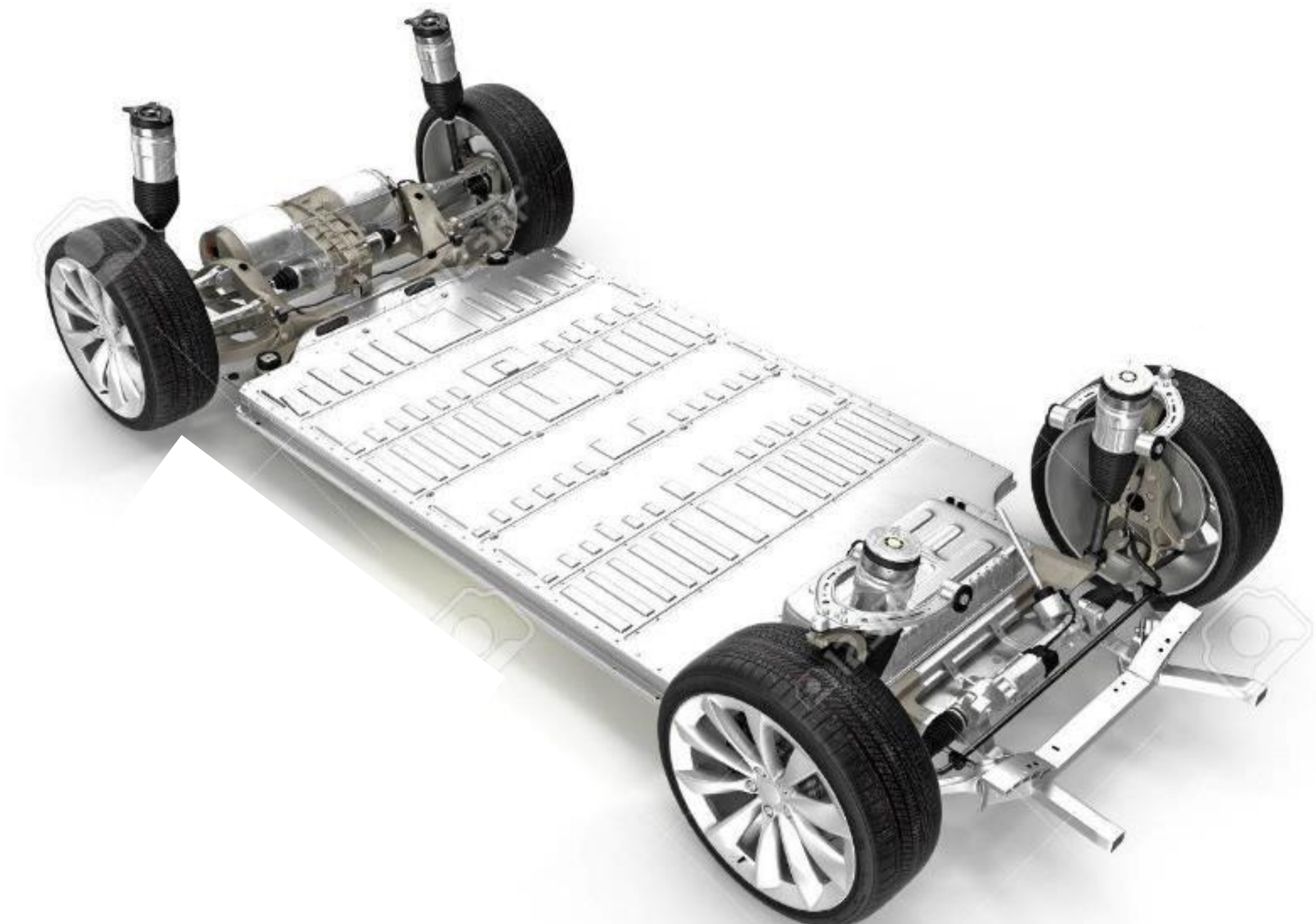
US $3.5 millions
2027

US $2.5m → US $2m
2027 → 2032

(Note, in 2027 $ value)


Helicopters Have Many Parts.   Expensive to Buy, Operate and Maintain

Electric Vehicles Have Much Fewer Parts

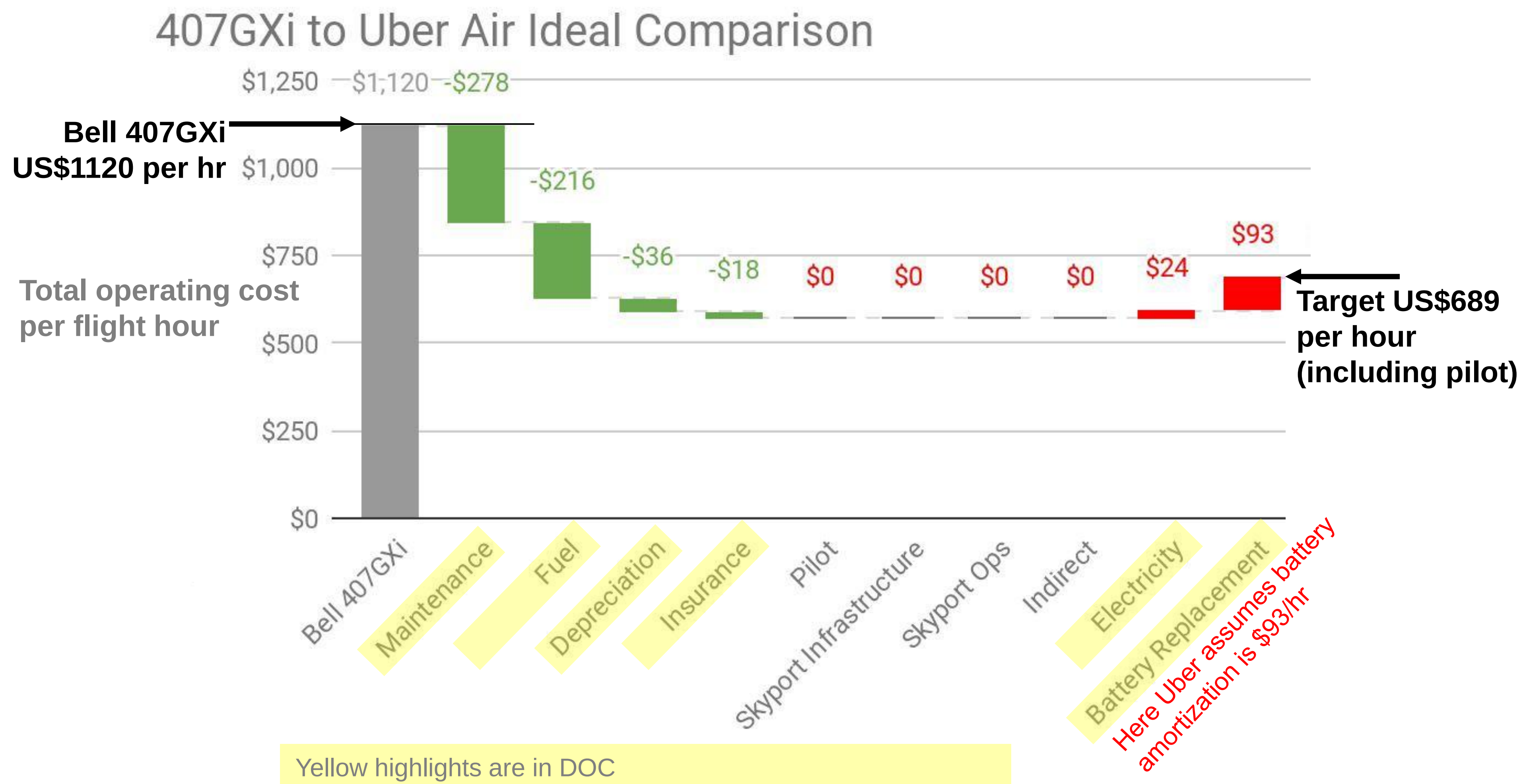


Electric Vehicles Reduces Parts Count

Whereas cars with a combustion engine need about 30,000 components, an electric vehicle needs just 11,000 parts, according to research from Goldman Sachs Group. That reduction in complexity has lowered the barriers to entry for the automotive market and caused a surge in the number of new electric carmakers.

We can also expect significant reduction from a light helicopter to an eVTOL aircraft.

UberAir Targets a Total Operating Cost for eVTOL to be 35% lower than operating helicopters



Yellow highlights are in DOC
Delta change in DOC = -$278-$216-$36-$18+$24+93= - $431

Source of graph: Uber presentation at 2019 VFS Forum, Philadelphia

Total operating cost =
indirect operating cost + direct operating cost

Lets find out the direct operating cost for eVTOL

Comparing Different Operating Cost Definitions

		ATA	AEA	+I	F41	TUB
Ownership	Depreciation	●	●	●	●	●
	Interest	○	●	●	○	●
	Insurance	●	●	●	●	●
Flight	Fuel	●	●	●	●	●
	Cockpit Crew	●	●	●	●	●
	Cabin Crew	●	●	●	●	●
	Fees, Landing	○	●	●	●	●
	Fees, Navigation	○	●	●	○	●
	Fees, Ground Handling	○	●	○	○	●
Maintenance	Airframe, Labor	●	●	●	●	●
	Airframe, Material	●	●	●	●	●
	Engine, Labor	●	●	●	●	●
	Engine, Material	●	●	●	●	●
	Burden	●	○	●	●	●
	Utilization Function	●	●	◐	○	●
	A/C Price Function	○	○	●	○	●

Source: https://www.researchgate.net/publication/322310413_Comparison_of_Direct_Operating_Cost_and_Life_Cycle_Cost-Benefit_Methods_in_Aircraft_Technology_Assessment/link/5ef1e895a6fdcc73be96e923/download

Direct Operating Cost for Helicopters and eVTOL

BASE AIRCRAFT PRICE (USD)	$3,225,000	$3,450,000	$3,200,000	$2,500,000
MANUFACTURER	Bell	Airbus Helicopters	Airbus Helicopters	Generic
AIRCRAFT TYPE	407GXi	H130	H125	eVTOL
DIRECT OPERATING COST	$ 589	$ 640	$ 627	<$300
DOC / NM	$ 4.43	$ 5.00	$ 4.61	$2.78 (for 108 nm)
DOC / NM / SEAT	$ 0.74	$ 0.71	$ 0.77	$ 0.56
MAX CRUISE SPEED (KTAS)	133	128	136	108
MAX RANGE (NM)	337	333	341	45
USEFUL LOAD (LBS)	2300	2299	2189	1100
TOTAL SEATS	6	7	6	5

Bell 407GXi's IOC = total op cost – DOC = US$1120/hr - $589 = $531/hr

eVTOL's DOC = total op cost – IOC = US$$689 - $531 = $158/hr Seems optimistic

Or eVTOL's DOC = DOC – changes = $589 - $431 = $158/hr

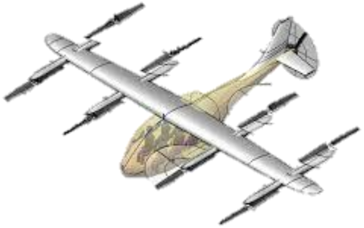
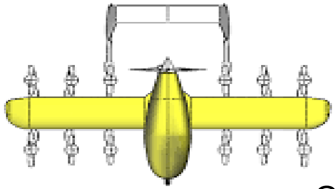
Types of eVTOL Aircraft

Name for different VTOL Aircraft Configurations

- Drone = UAV (unmanned air vehicle) = UAS (unmanned air system)
- Multirotor, multicopter



- Lift + cruise



Cora


- Tiltrotor


V22

AW609

- Tiltwing

CL-84

Vahana


- Tail sitter


Name for different VTOL Aircraft Configurations

- Helicopter

Bell-407

Kamov Ka27

Ch-47

- Compound

Piesecki

Sikorsky X2

Airbus X3

- Autogyro

eCavalon

- VTOL jet

Harrier

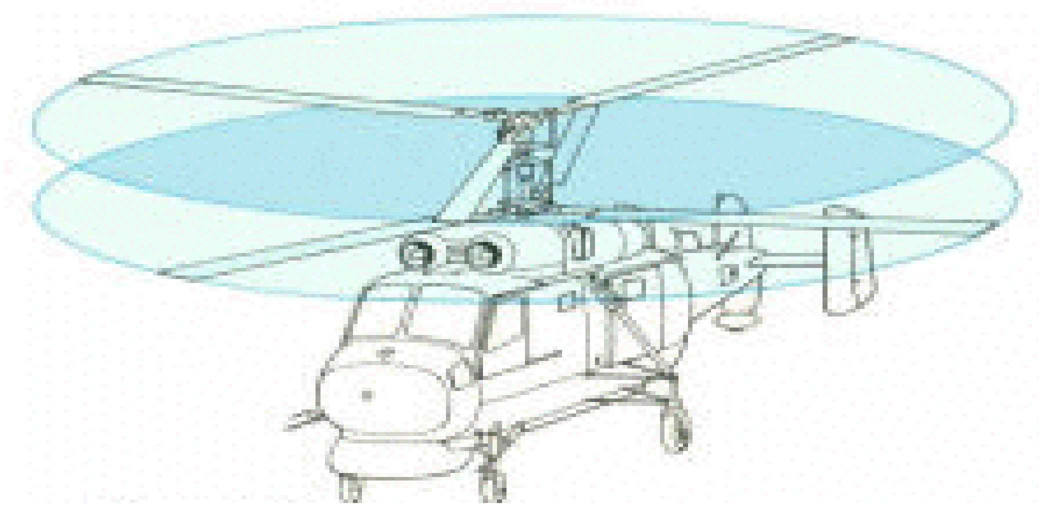
F35B

Definition

$$\text{Disk loading} = \frac{\text{Max Takeoff Gross Weight (lbs)}}{\text{Total rotor disks area (ft}^2\text{)}}$$

Coaxial Rotor

For coaxial rotor type when we calculate the disk loading, we typically use only the disk area of one set of rotors



Multirotor and Multicopter

Lift + Cruise

eHANG VT-30


Cargo drone

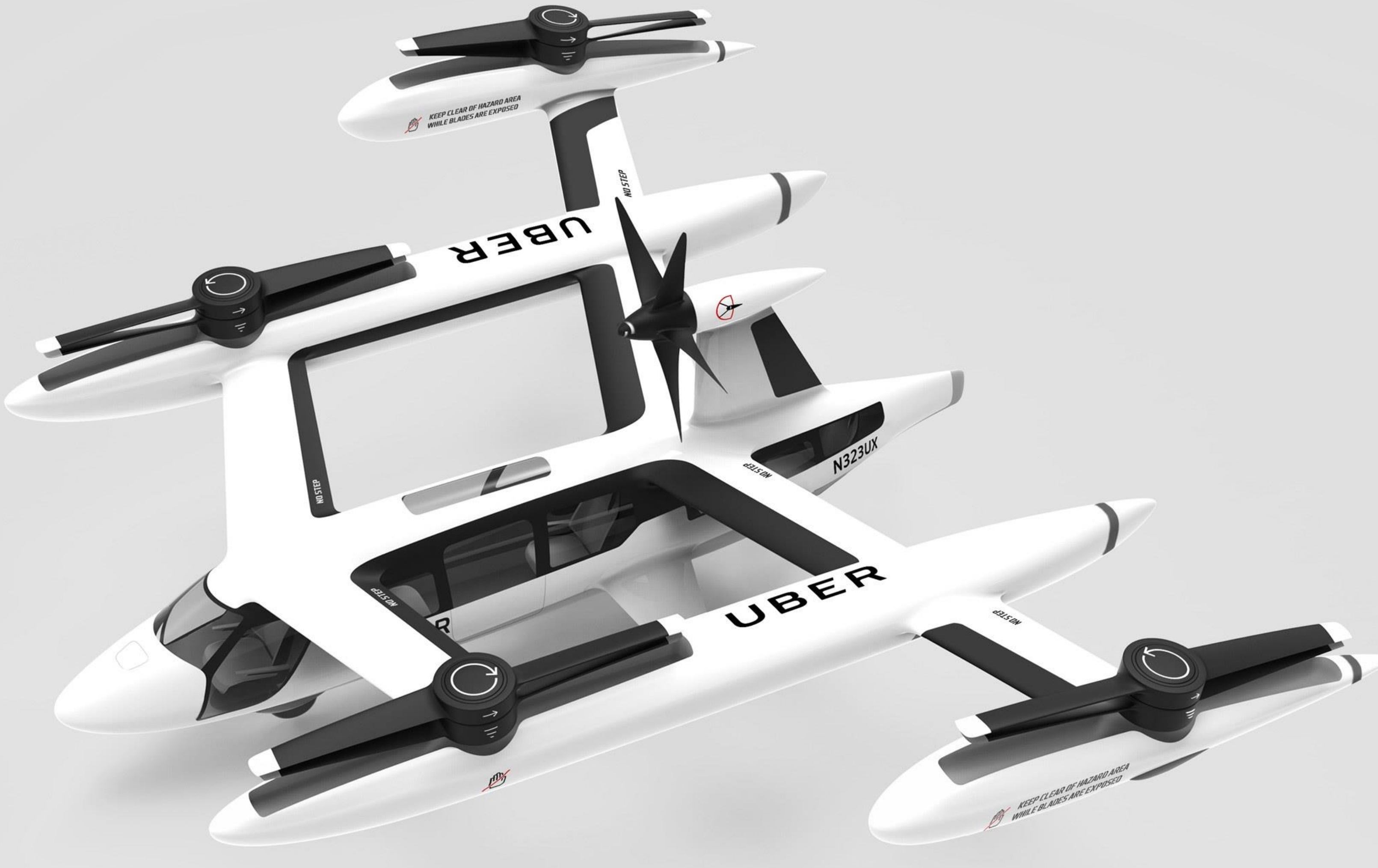

Boeing PAV


Beta Alia

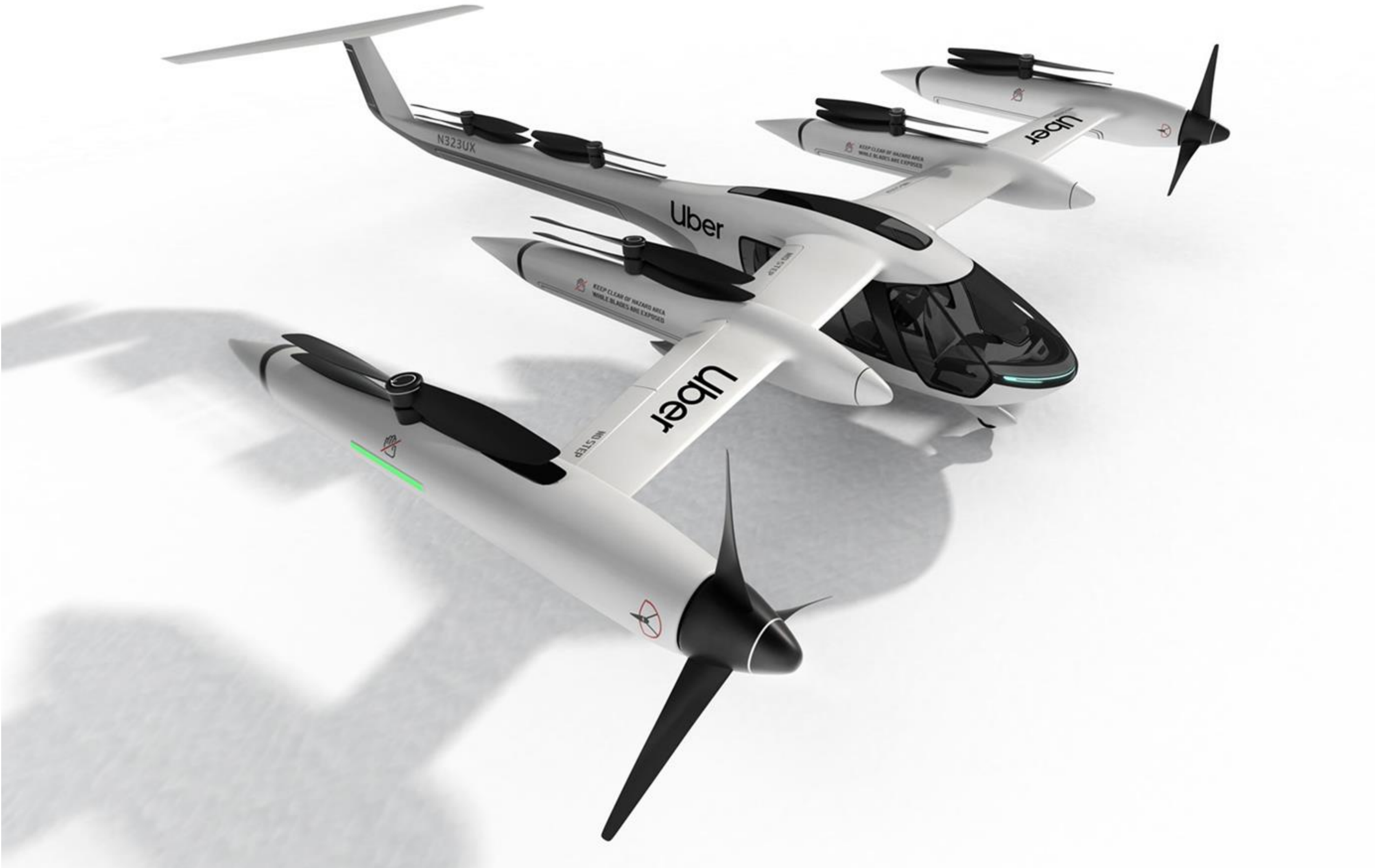
Lift + Cruise

https://www.droneassemble.com/product/long-endurance-drone-3-hours-vtol-v-tail-for-mapping-surveillance-vtol-frame-kit/

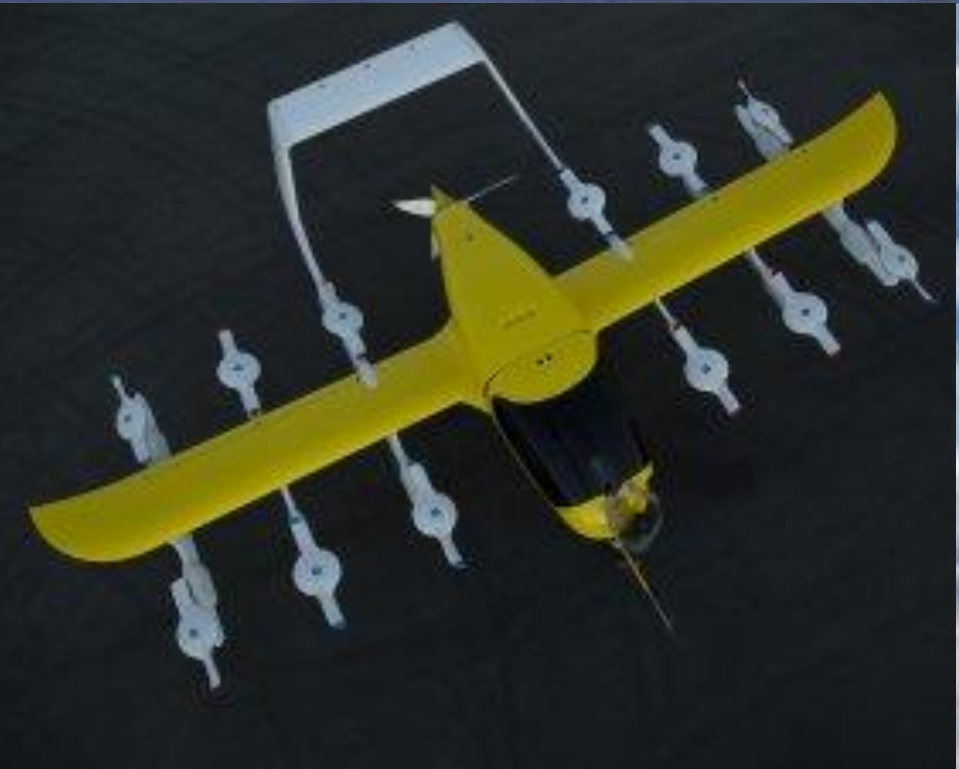
Lift + Cruise


UBER
UBER
N323UX
NO STEP
KEEP CLEAR OF HAZARD AREA
WHILE BLADES ARE EXPOSED

Lift + Cruise



Kitty Hawk Cora (Lift + Cruise Type)



Tiltrotor


V22


AW609


AW609


Bell Nexus

Tiltrotor (vector thrust)

25 mile mission repeated indefinitely
4 passengers + pilot (1,100 lb payload weight)
9-minute, 2C charge
6-mile reserve

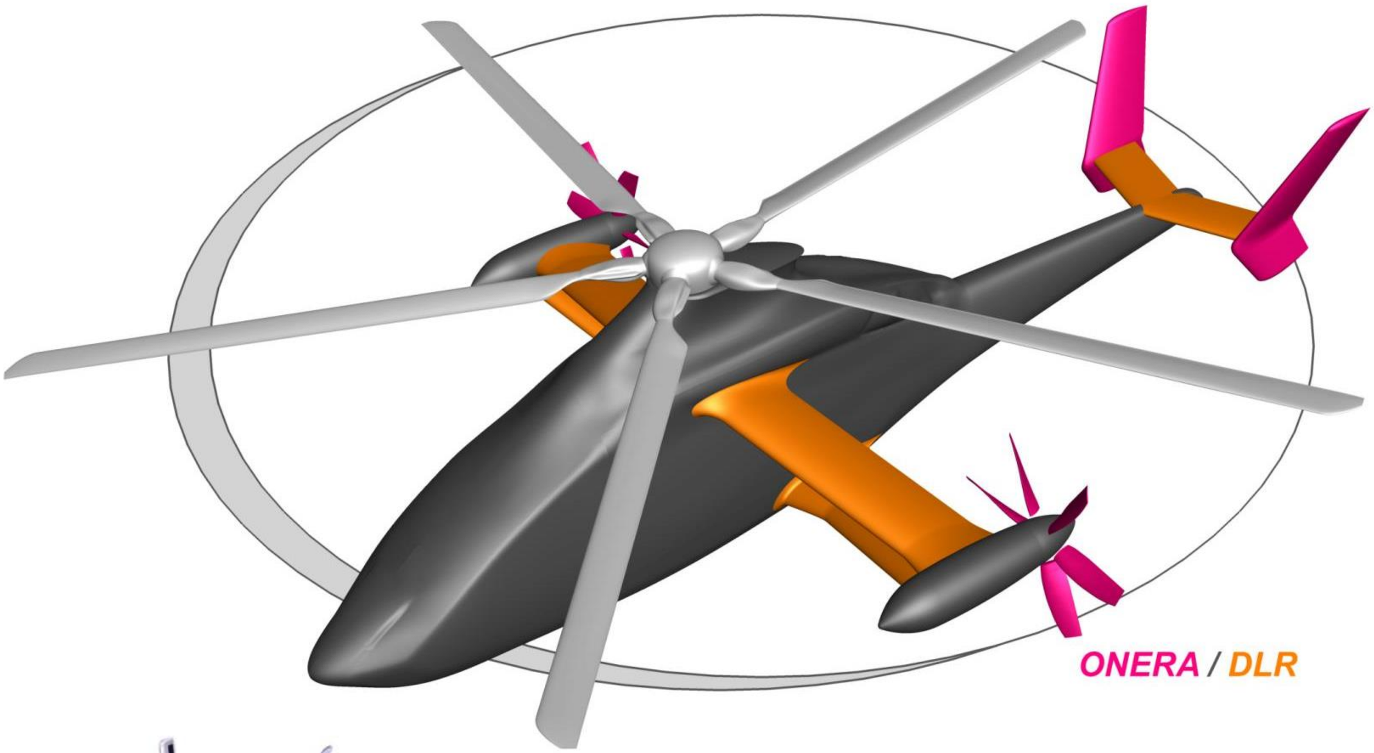
Unlimited operations during peak time

Tiltwing

Canadair CL-84

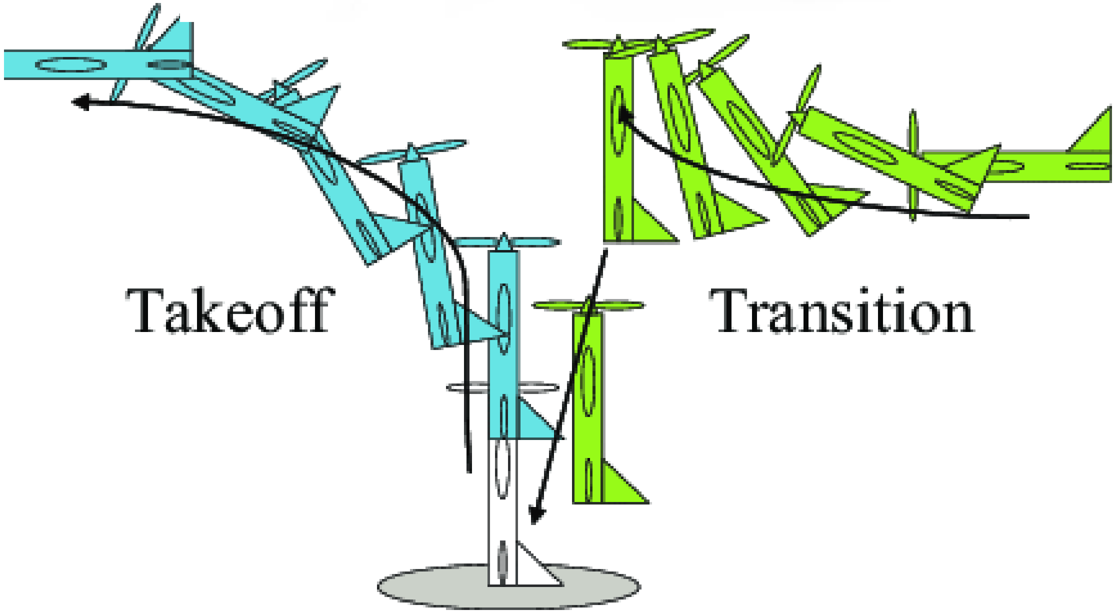
Airbus Vahana

Compound Helicopter - Airbus X3



Tail Sitter

Drawbacks: visibility and passenger comfort



Autogyro (eSTOL)

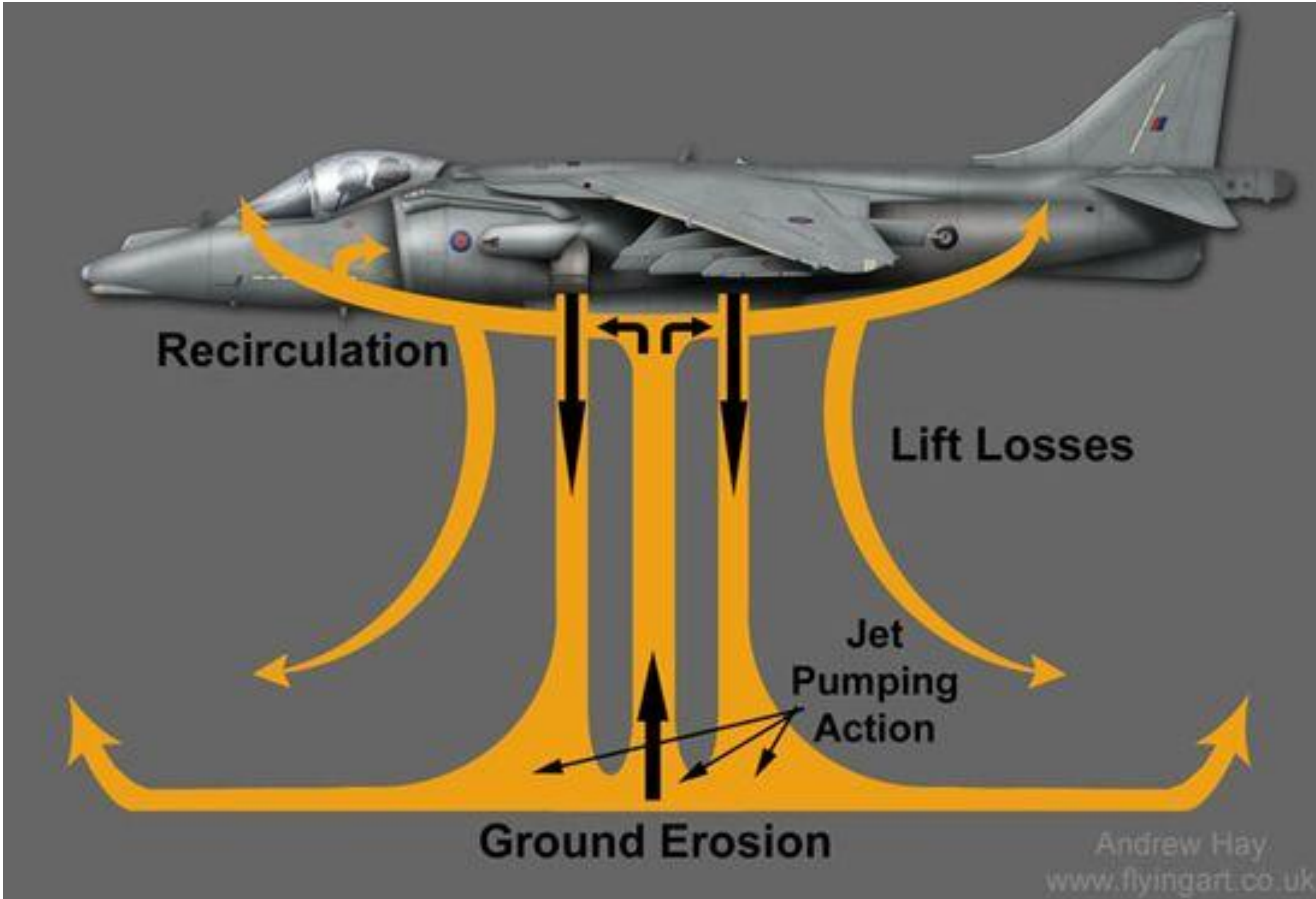
Characteristics:

- Passengers: 2
- Empty weight: 300 kg (661 lb)
- Gross weight: 500 kg (1,102 lb)
- Powerplant: 1 × Siemens motor 107hp (80 kw)
- Main rotor diameter: 8.4 m (27 ft 7 in)
- Propellers: 3-bladed composite
- Endurance: 30 minutes
- Cruise speed 90 mph (145 km/h), top speed is 99 mph (160 km/h)

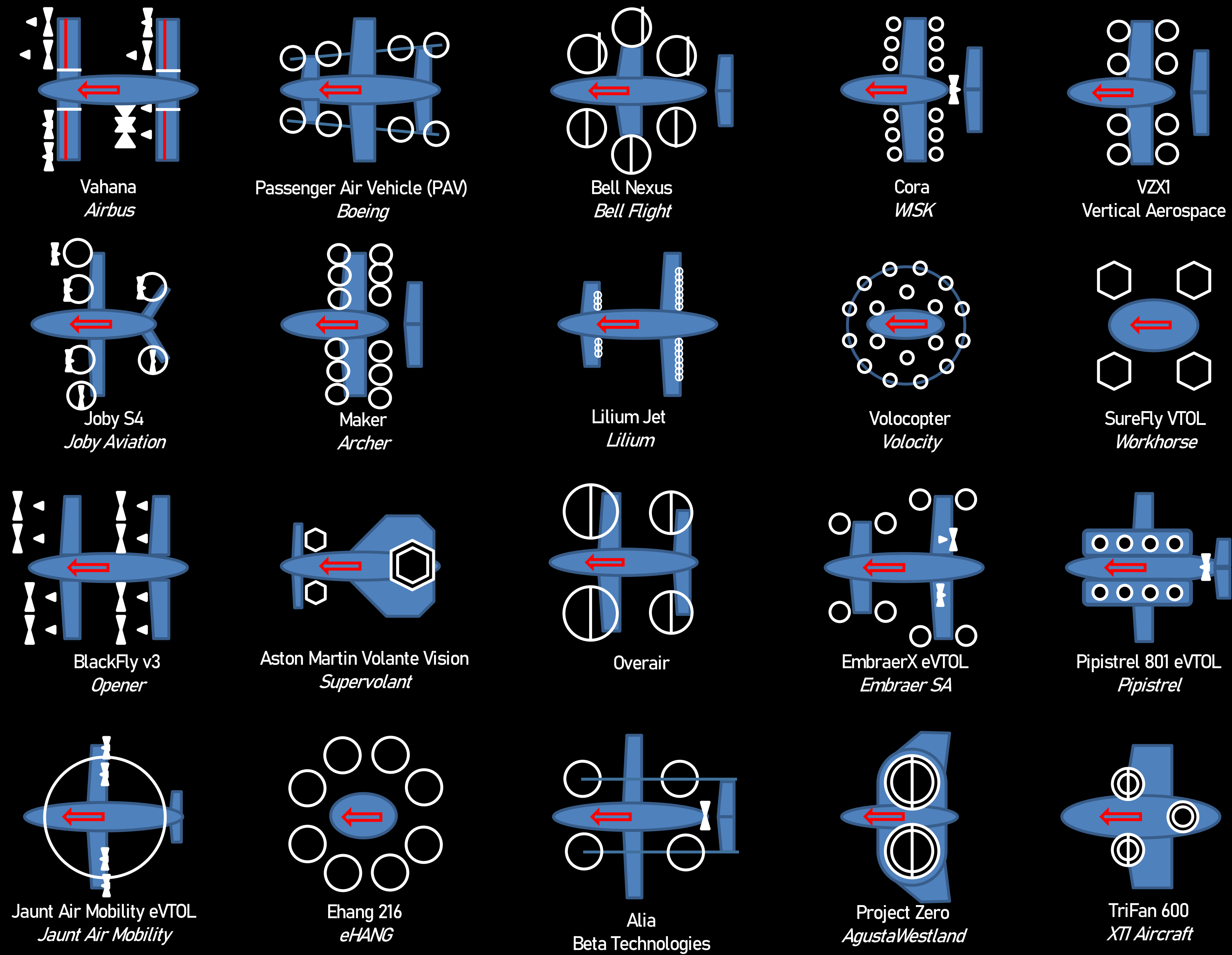
AutoGyro GmbH
Hildesheim, Germany
www.auto-gyro.com

Autogyro (R-Evolution, a Swiss study)

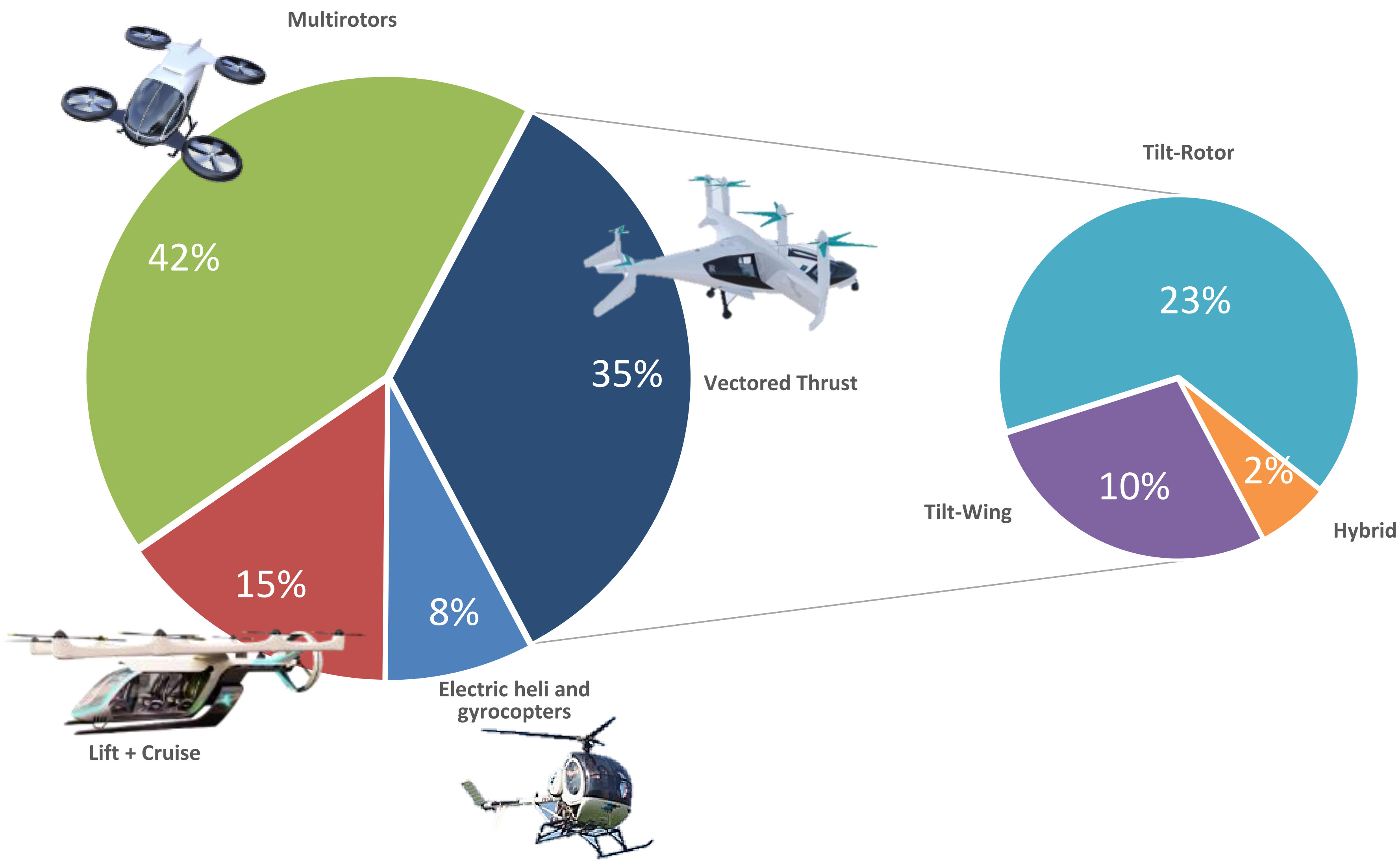
VTOL Jets



Recirculation
Lift Losses
Jet
Pumping
Action
Ground Erosion
Andrew Hay
www.flyingart.co.uk


Vahana
Airbus
Passenger Air Vehicle (PAV)
Boeing
Bell Nexus
Bell Flight
Cora
WISK
VZX1
Vertical Aerospace
Joby S4
Joby Aviation
Maker
Archer
Lilium Jet
Lilium
Volocopter
Volocity
SureFly VTOL
Workhorse
BlackFly v3
Opener
Aston Martin Volante Vision
Supervolant
Overair
EmbraerX eVTOL
Embraer SA
Pipistrel 801 eVTOL
Pipistrel
Jaunt Air Mobility eVTOL
Jaunt Air Mobility
Ehang 216
eHANG
Alia
Beta Technologies
Project Zero
AgustaWestland
TriFan 600
XTI Aircraft

Types of eVTOL Aircraft in Development



Compiled by James Wang

Trend is Multirotor Replaced by Lift+Cruise

Volocity 2019

Voloconnect
May 2021

EHang 216 2019

Ehang VT-30
May 2021

Rotor Comparison

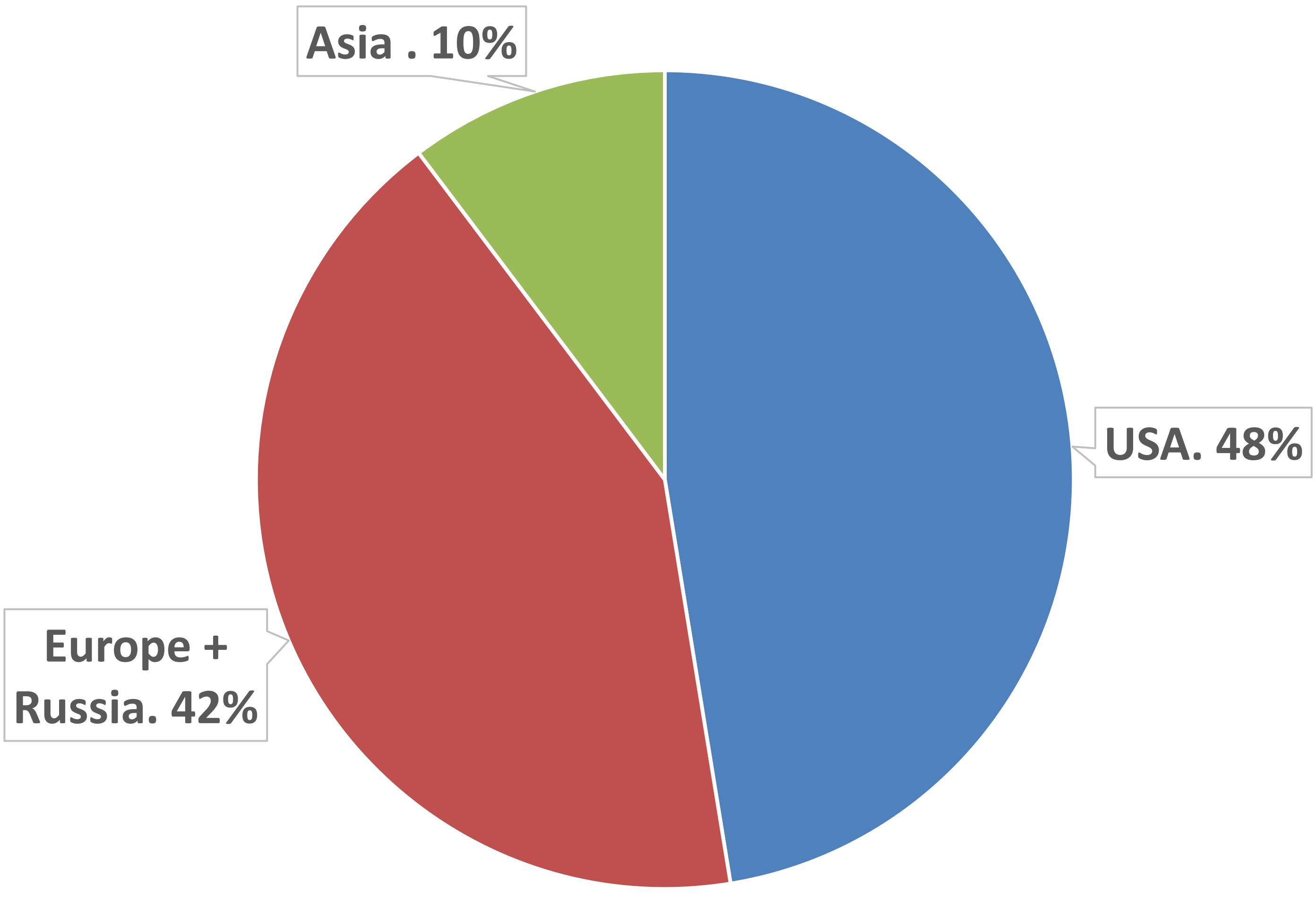
Lower disk loading <10 lbs/ft^2 — Higher disk loading >20 lbs/ft^2

Lower L/D <4 — Higher L/D >8

Better hover, less range — Better cruise, more range

Less rotors, lower redundancy — More rotors, greater redundancy

eVTOL Developmental Regions



Recent Technology Enablers for eVTOL

- Better rechargeable batteries
- More powerful electric motors
- Silicone carbide inverters
- Lower cost sensors and autonomous flight control
- Light weight composite structure
- Distributed propulsion architecture
- Better computation tools

Key Challenges to eVTOL and UAM

- Fine tuning the technologies
- Creating appropriate infrastructures
- Collaboration and partnerships
- Regulating an entirely new industry
- Overcoming public psychological barriers
- Public acceptance and affordability

1. Design Phases for a New Aircraft Program Different types of eVTOL

by Dr. James Wang

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