

2. Battery and Energy Source

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For students to use in the 2022 eVTOL Design Short Course at SNU,
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Some Electrical Engineering Definitions

Current is measured in Amps (A)

Voltage is measured in Volts (V)

Power is measured in watts (W) or kilowatts (kw)

Power equals current x voltage

Battery capacity is measured in amp-hour (Ah)

Energy is measured in watts-hour (Wh)

Amp Hour

Ah (amp hour) is a measure of battery capacity for a given voltage

Examples:

a **1 Ah 12 volt battery** => Can supply

1 amp current for one hour at 12 volt, or

0.5 amp current for 2 hours at 12 volt, or

2 amps current for half hour at 12 volt

Amp Hour

Class question:

A 50 Ah 12 volt car battery with its 200 watts head light left on, how many hours will the battery last?

Answer:

Current draw = 200 watts / 12 volt = 16.67 amps

Duration = 50 Ah / 16.67 amps = 3 hours

Watt Hour

Wh (Watt hour) is measure of energy or battery energy capacity

$$\text{Wh} = \text{Ah} \times \text{Voltage}$$


Example:


a 5 Ah 12 volt battery can provides 60 Wh energy

Watt Hour

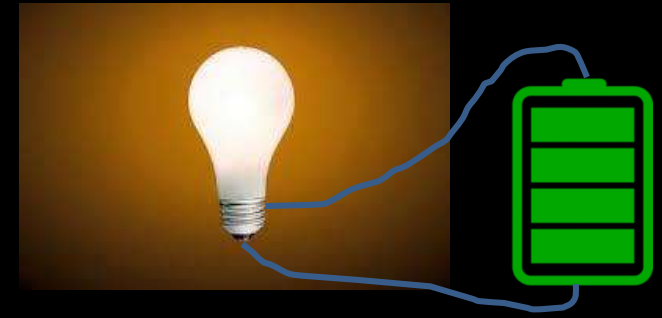
Wh (Watt hour) also tells you how long you can draw power from battery

$$\text{Wh} = \text{Ah} \times \text{Voltage}$$


$$\text{Wh} = \text{A} \times \text{V} \times \text{time}$$


$$\text{Wh} = \text{power} \times \text{time}$$

Watt Hour



Class question:

How long can a 100 watts lightbulb stay on when connected to a 500 Wh battery?

Answer:

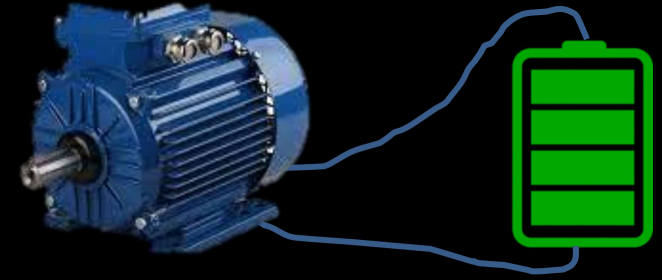
Wh = power x time

time = Wh / power

= 500 Wh / 100 watt

= 5 hours

Watt Hour



Class question:

How long can a one horsepower motor run when connected to a 750 Wh battery?

Answer:

Wh = power x time

time = Wh / power

= 750 Wh / 1 hp ← (Note: 1 hp = 746 watts)

= 1 hour

Watt Hour



Class question:

If this one-person eVTOL draws 100 amps at 600 volt and can fly for 30 minutes with no reserve left, then its battery must store how much energy?

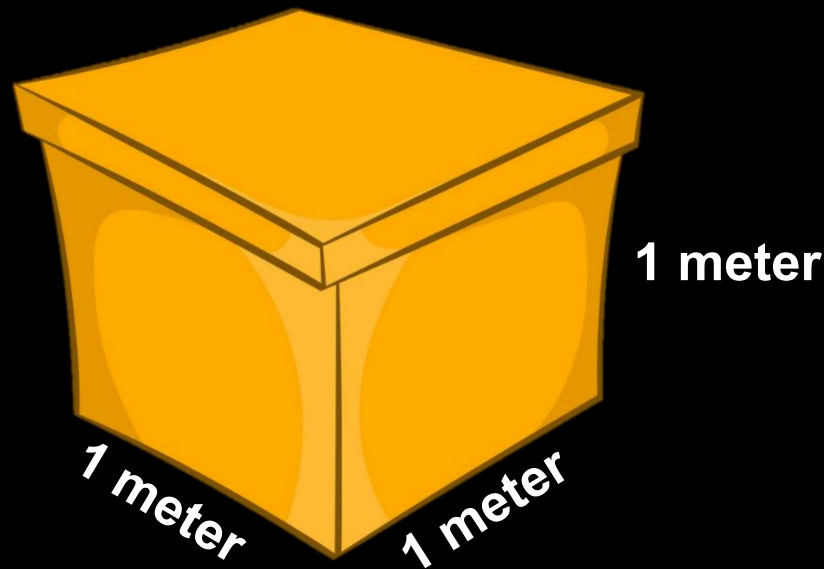
Answer:

Energy = Watt hour

= A x V x time

= 100A x 600V x 0.5hr = 30,000 Wh or 30 kWh

Energy density is the energy per unit volume of a fuel or a battery (MJ/m³)
The higher the better.

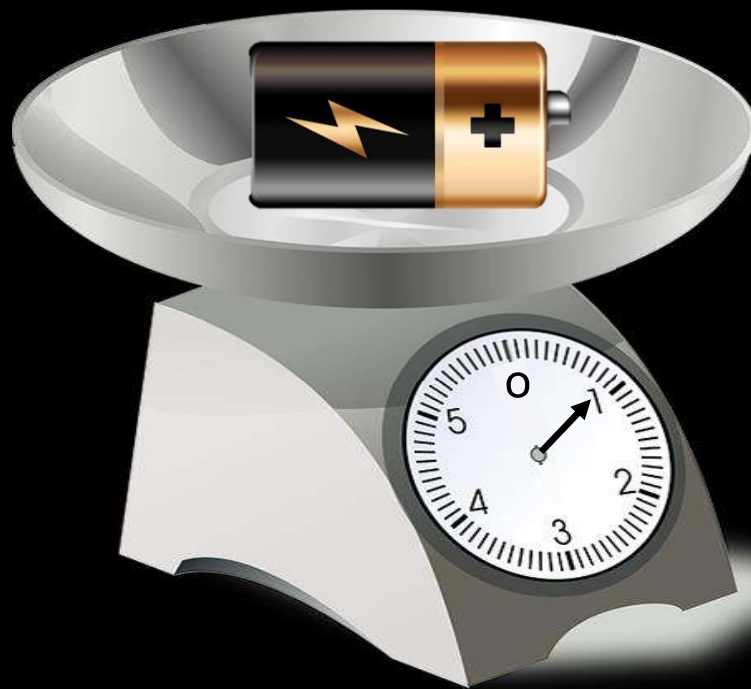


Note: MJ = mega joules, it's a measure of energy

Energy density and **Specific Energy**
are not the Same !

**For eVTOL, the useful measurement
for battery is Specific Energy**

Specific energy is the energy per unit mass of a fuel or a battery (MJ/kg or Wh/kg). The higher the better.

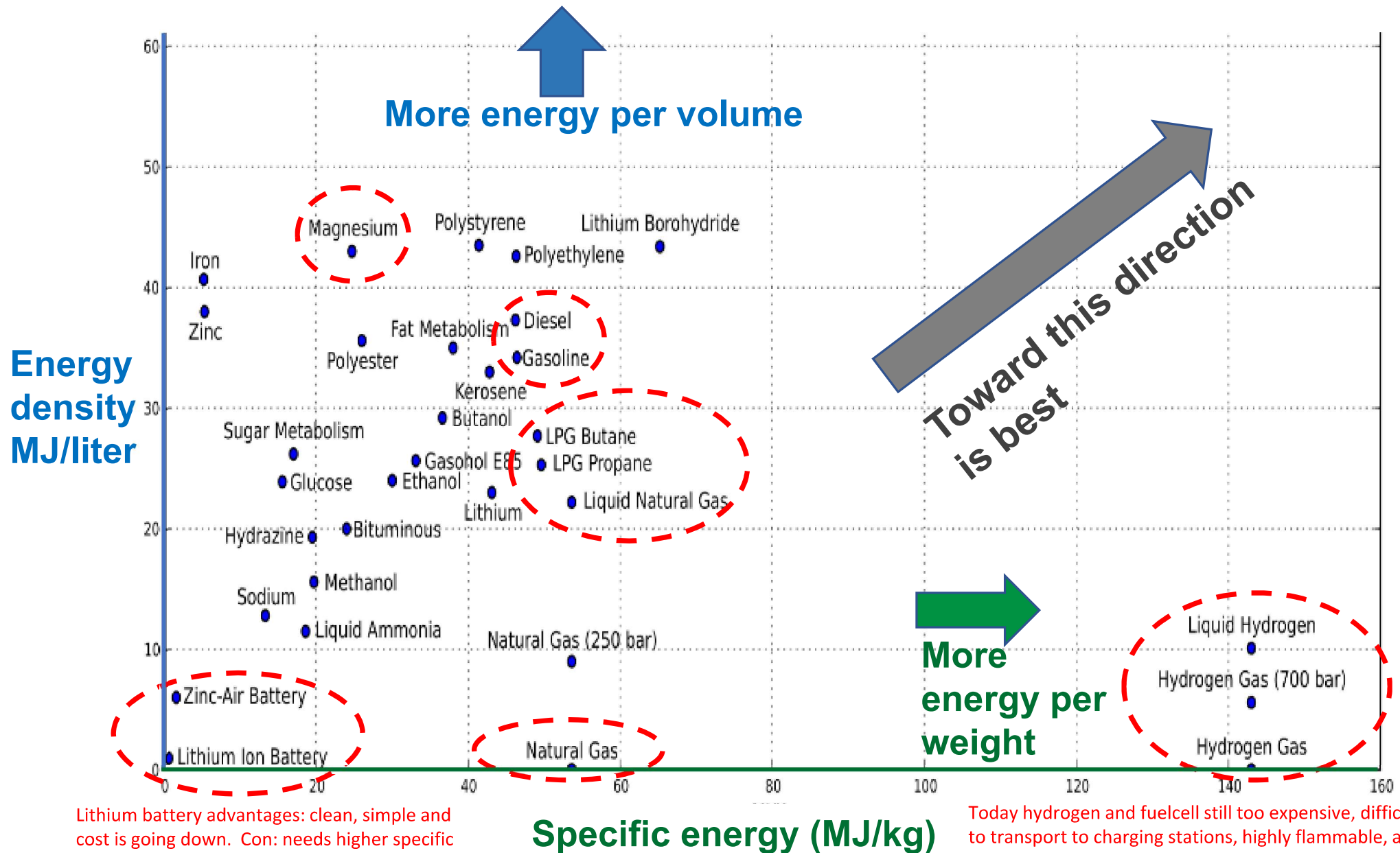


Note: for eVTOL we usually use specific energy and not energy density

Comparing Energy Sources

	<i>Energy density</i>	<i>Specific energy</i>
Diesel fuel	37,184 MJ/m³	45 MJ/kg
Coal	36,450 MJ/m³	27 MJ/kg
Wood	9,000 MJ/m³	15 MJ/kg
Propane	29,449 MJ/m³	50 MJ/kg

Want High Specific Energy & High Energy Density



Comparing Specific Energy for

(MJ/kg) or (Wh/kg)

Propane	50 MJ/kg	13,890 Wh/kg
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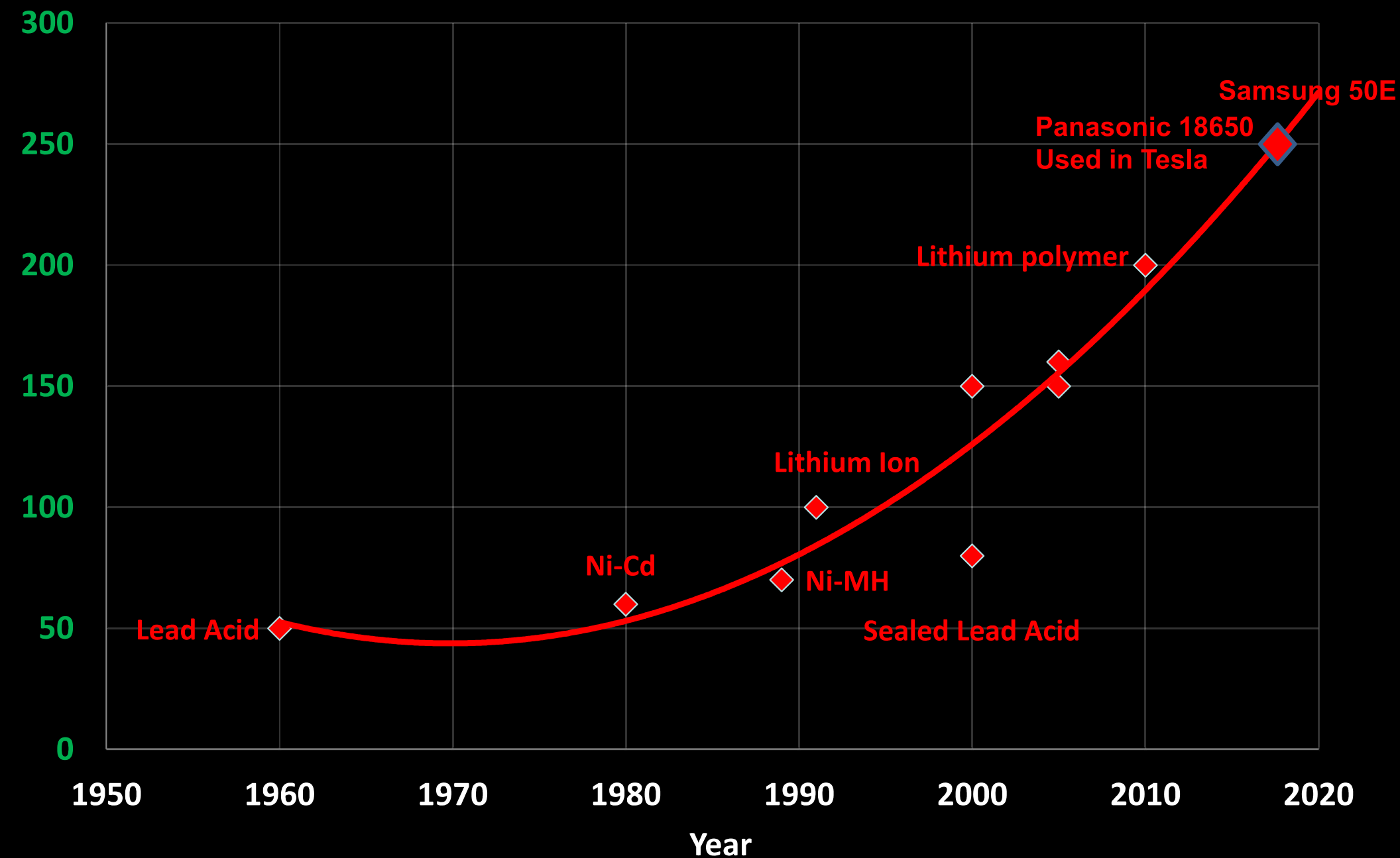
Diesel fuel	45 MJ/kg	12,501 Wh/kg
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Coal	27 MJ/kg	7,500 Wh/kg
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Wood	15 MJ/kg	4,167 Wh/kg
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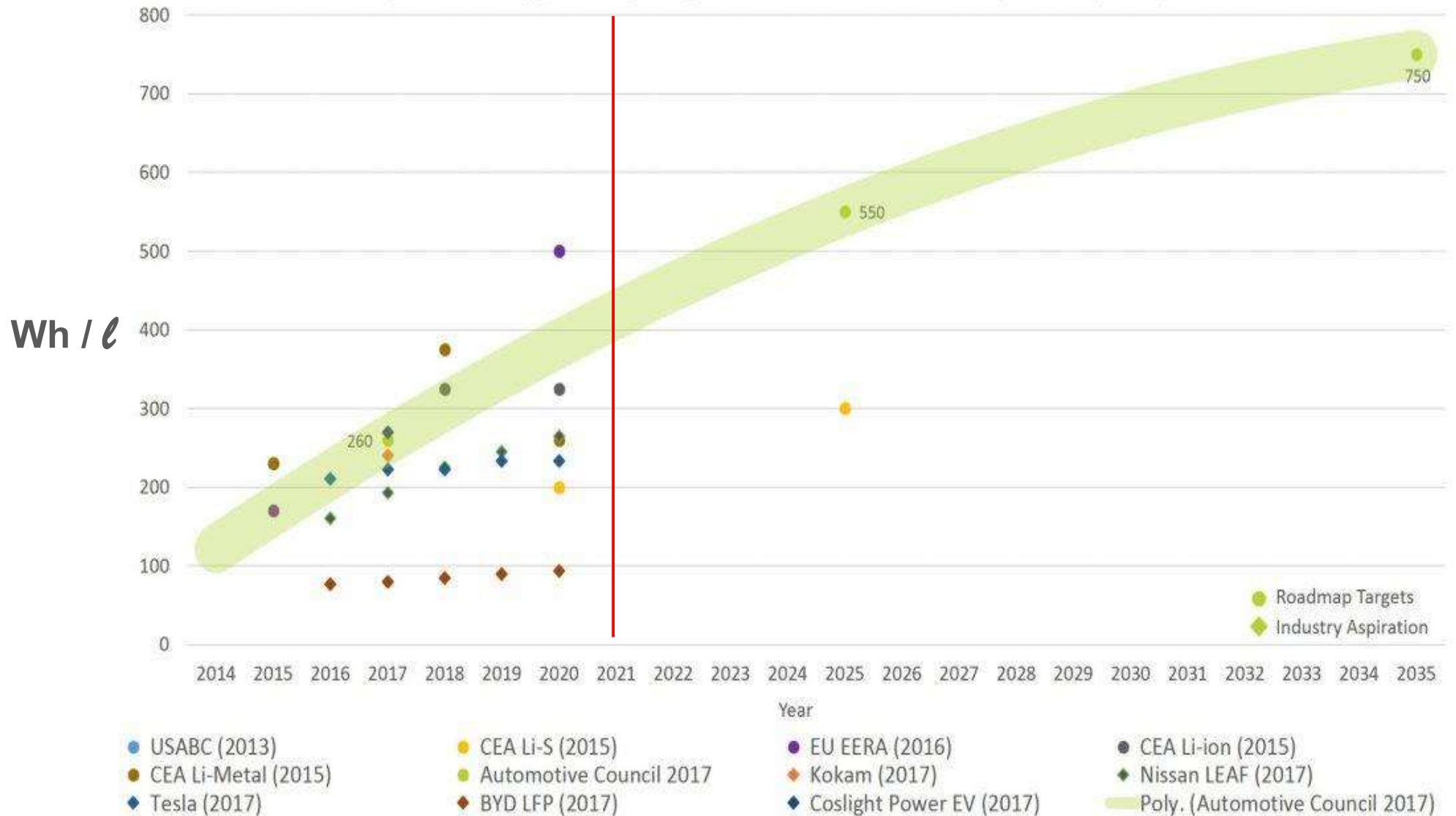
Lithium battery	0.72MJ/kg	250 Wh/kg
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Specific Energy Trend for Rechargeable Batteries (at the cell level)



Energy Density Trend

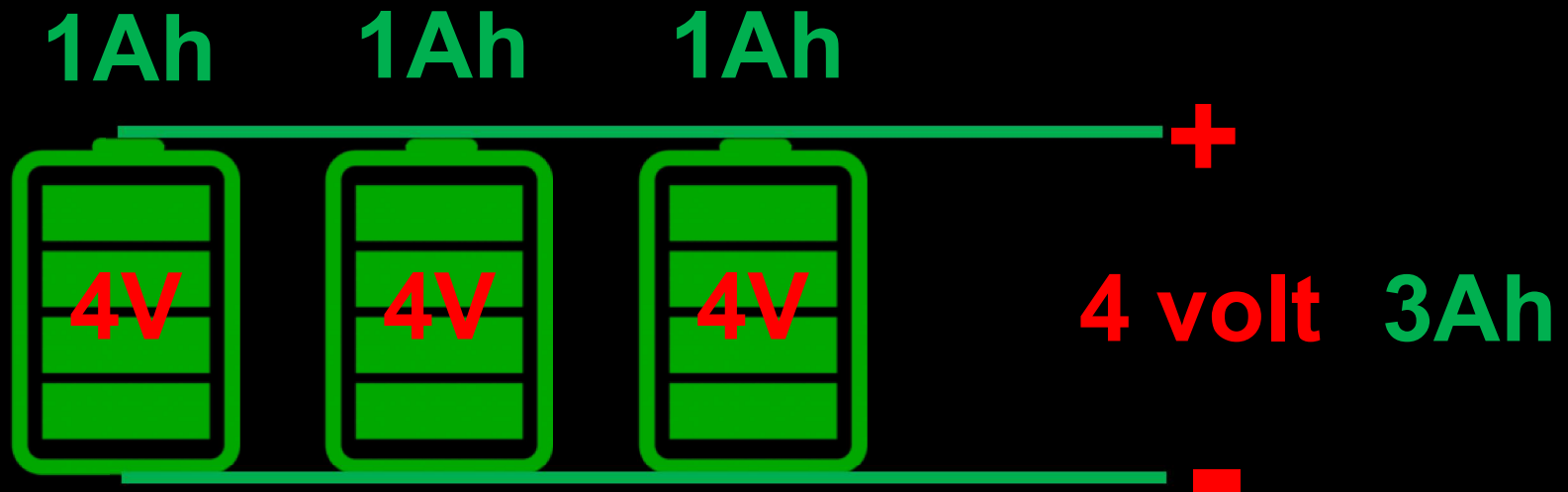
Rechargeable Automotive Lithium Batteries at Cell Level



Note, 400 Wh = 1.44 MJ

Battery Jargon

Connect in **parallel** => voltage remains the same, but Ah capacity increases.



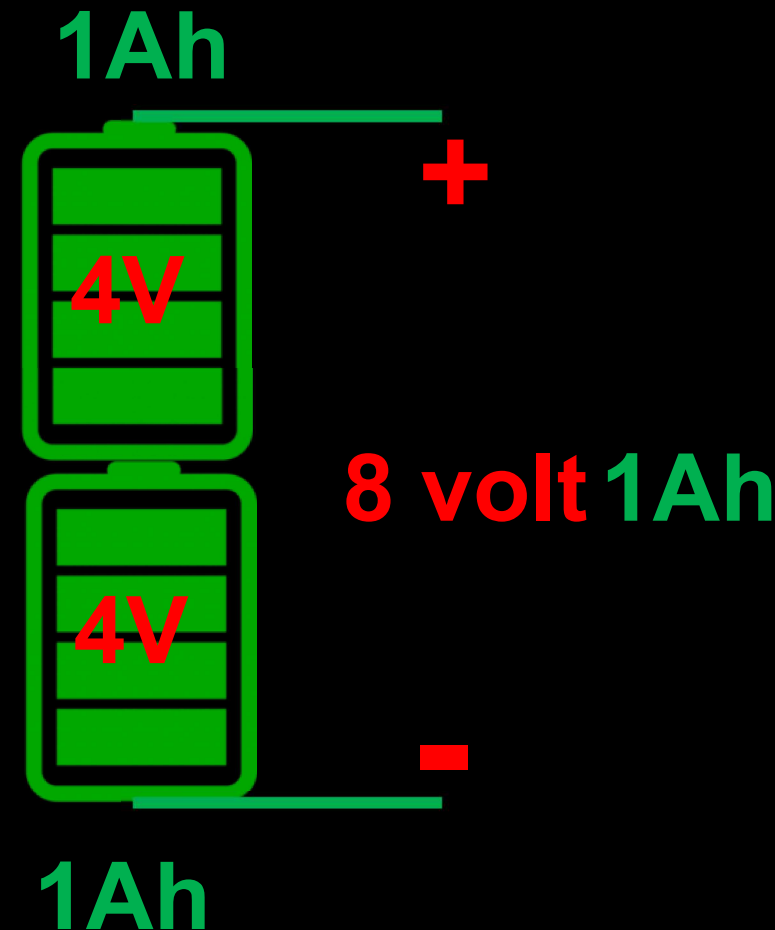
Example: this is a “3P”

(A fully charged lithium cell is around 4.2 volts. During use it is around 4 volts.)

Battery Jargon

Connect in **series** => voltage increases, but the Ah capacity remains the same.

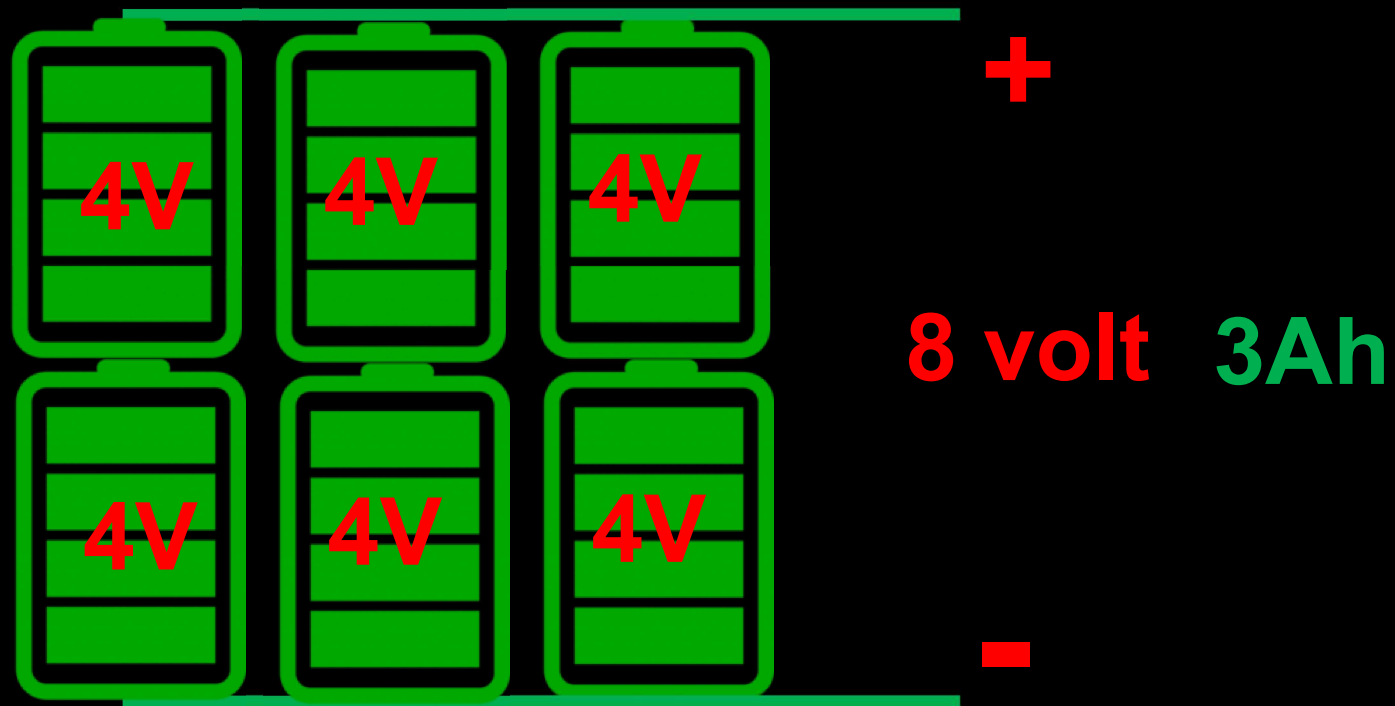
Example: this is a “2S”



Battery Jargon

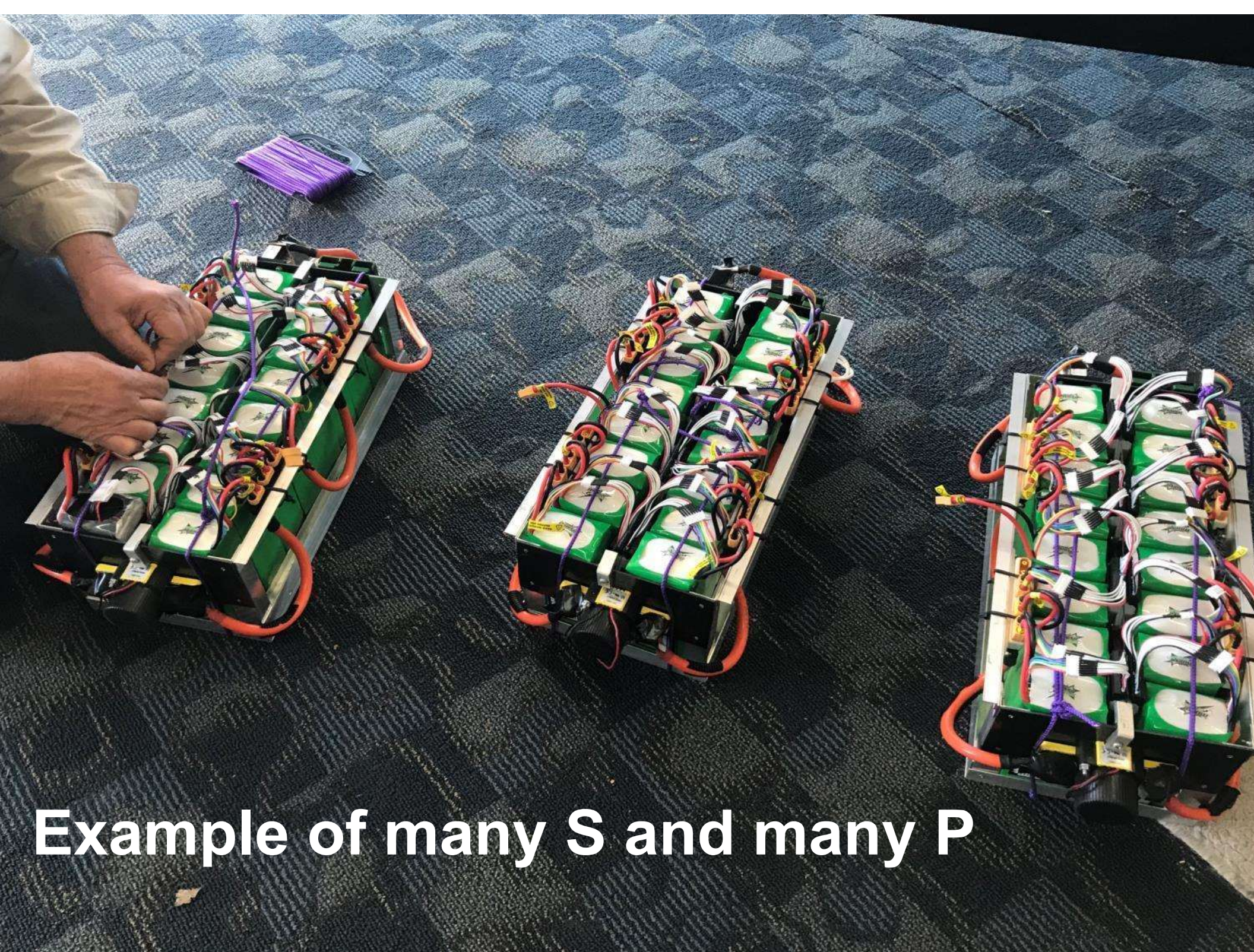
Connect in **series and parallel** =>
voltage increases, and Ah increases.
=> allows more power and endurance

“2S3P”



A photograph of a 5S LiPo battery pack. The battery is rectangular and has a silver, ribbed metallic casing. It is oriented diagonally from the top-left towards the bottom-right. A red cable and a black cable are connected to the top of the battery. The background is a dark, textured surface.

Example of a 5S pack



Example of many S and many P

Design Rule

- 1. Use as high a voltage as possible.**
- 2. i.e. 800 volts (=200 cells in series).**
- 3. Then increase the number of cells in parallel so the continuous current draw will not exceed 5C.**

(I will explain later what 5C means)

In the future for electric vehicles and eVTOL, we probably use 800 volts instead of 400 volts to reduce current draw and wire weight.

If we need 800 kW of power to hover, then $800\text{kW} / 800\text{V} = 1,000$ amps of total current draw during hover.



That's a lot of current!

To reduce the current through the wires, we use distributed architecture for eVTOL. Use 6 rotors and 6 motors, then each motor only needs to produce $800\text{kW} / 6 = 133\text{kW}$ of power



Then $133\text{ kW} / 800\text{V} = 166$ amps of steady current draw per motor during hover.

That's more manageable

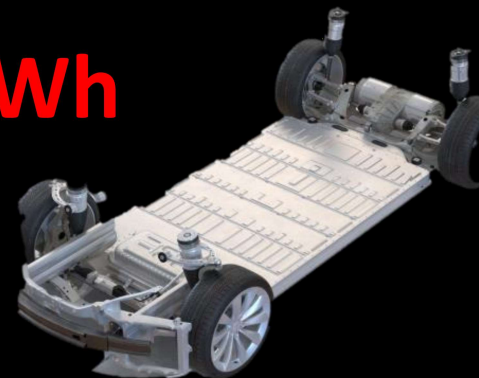
Can even use 6 separate battery packs for safety

How big a battery this eVTOL requires if it has to hover for 15 minutes with no reserve?

Answer

800V x 1,000 amp x ¼ hour = 200 kWh

Compare to a Tesla car has only 85 kWh





One 18650 cell




***For Tesla Model-S car
Each cell 4v, 3200 mAh***

***444 cells per module in
6S74P (24v, 233 Ah)***

***16 modules in series
(384v, 7104 cell, 85 kwh
of energy, 1000 lbs)***



You Can Buy This Battery Module on eBay



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Tesla Model S battery module, 24V, 233Ah, 5.2kWh, 444 Panasonic 18650 3200mAh

🔥 226 viewed per day

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Nissan Leaf Uses Pouch Type Lithium Ion Cells

Source: 2 hrs video dissecting Nissan Leaf battery <https://youtu.be/vYQJatWpBXy>



Nissen Leaf's 225 Amps, 450 Volt Fuse

Source: 2 hrs video dissecting Nissen Leaf battery <https://youtu.be/vYQJatWpBXY>

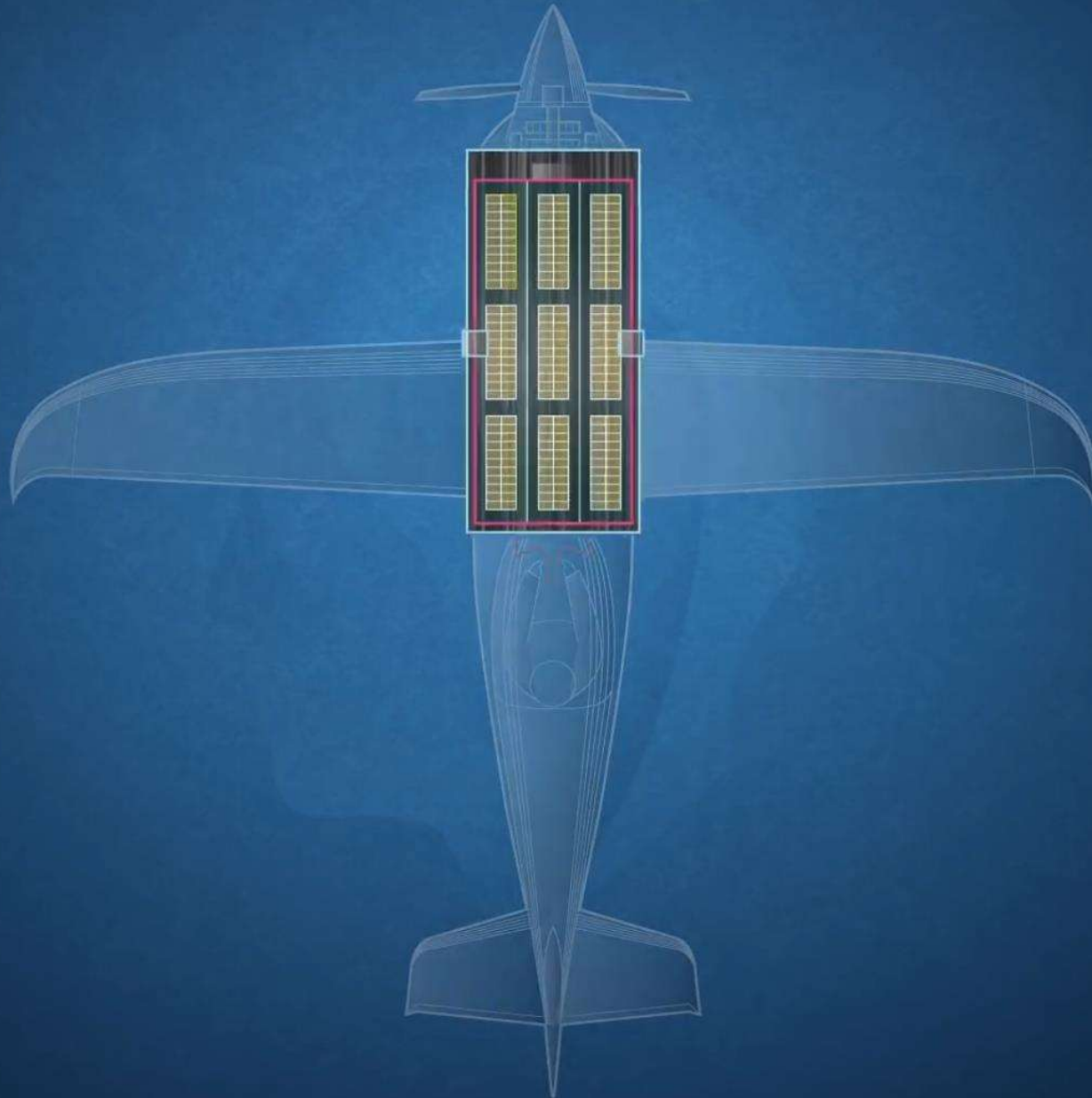


Example: An Electric Airplane

RR Spirit of Innovation Clocks 387 MPH



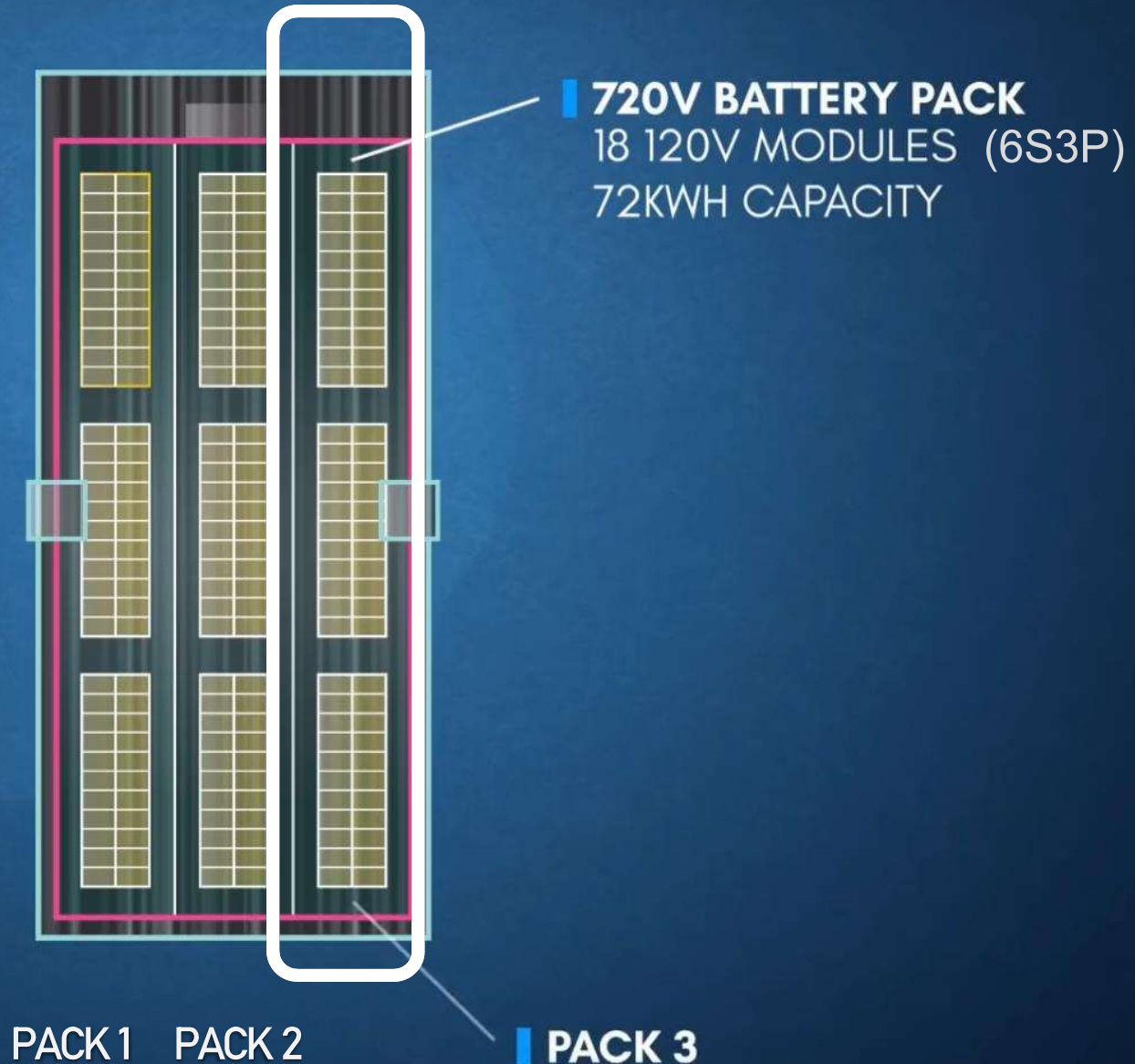
RR Spirit of Innovation has 216 kWh Battery



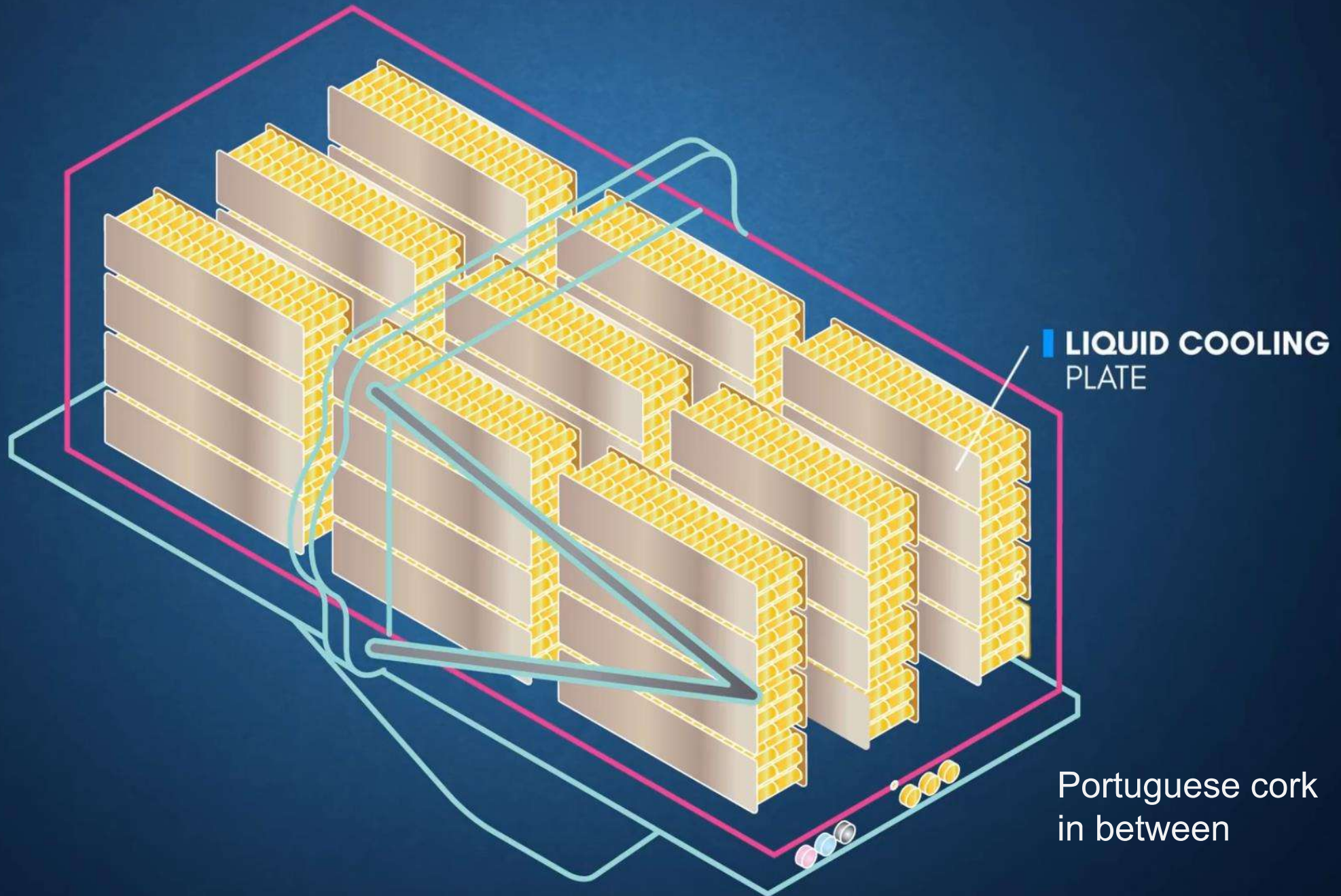
RR Spirit of Innovation has 216 kWh Battery

Using 18650 cylindrical type cells

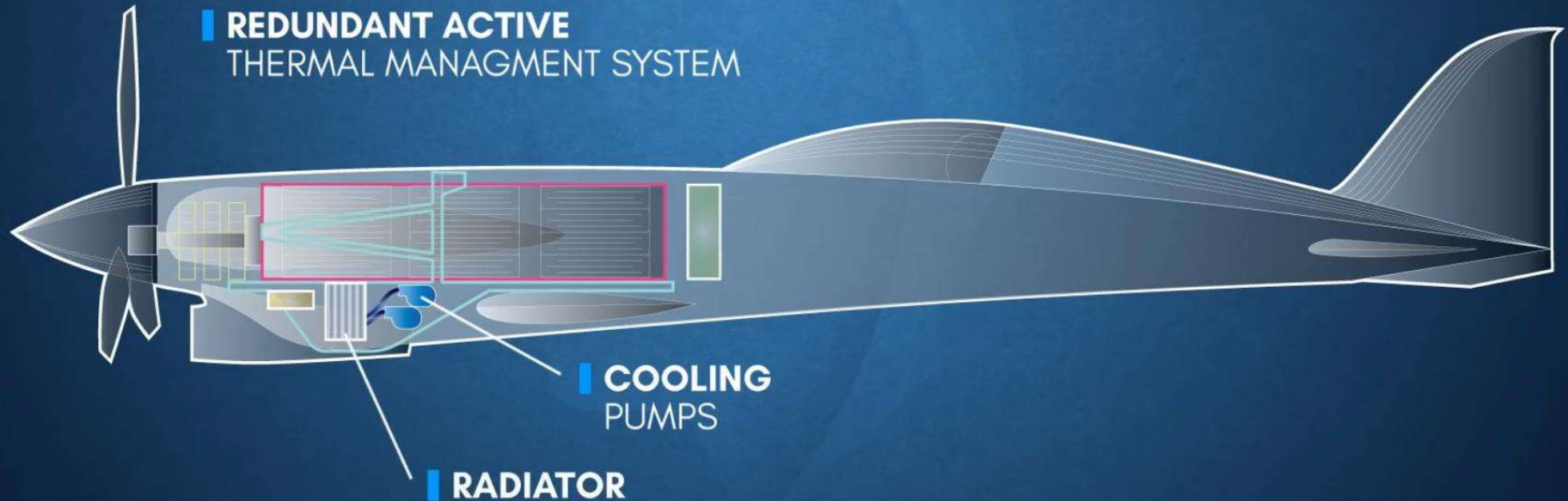
216 KWH
TOTAL CAPACITY



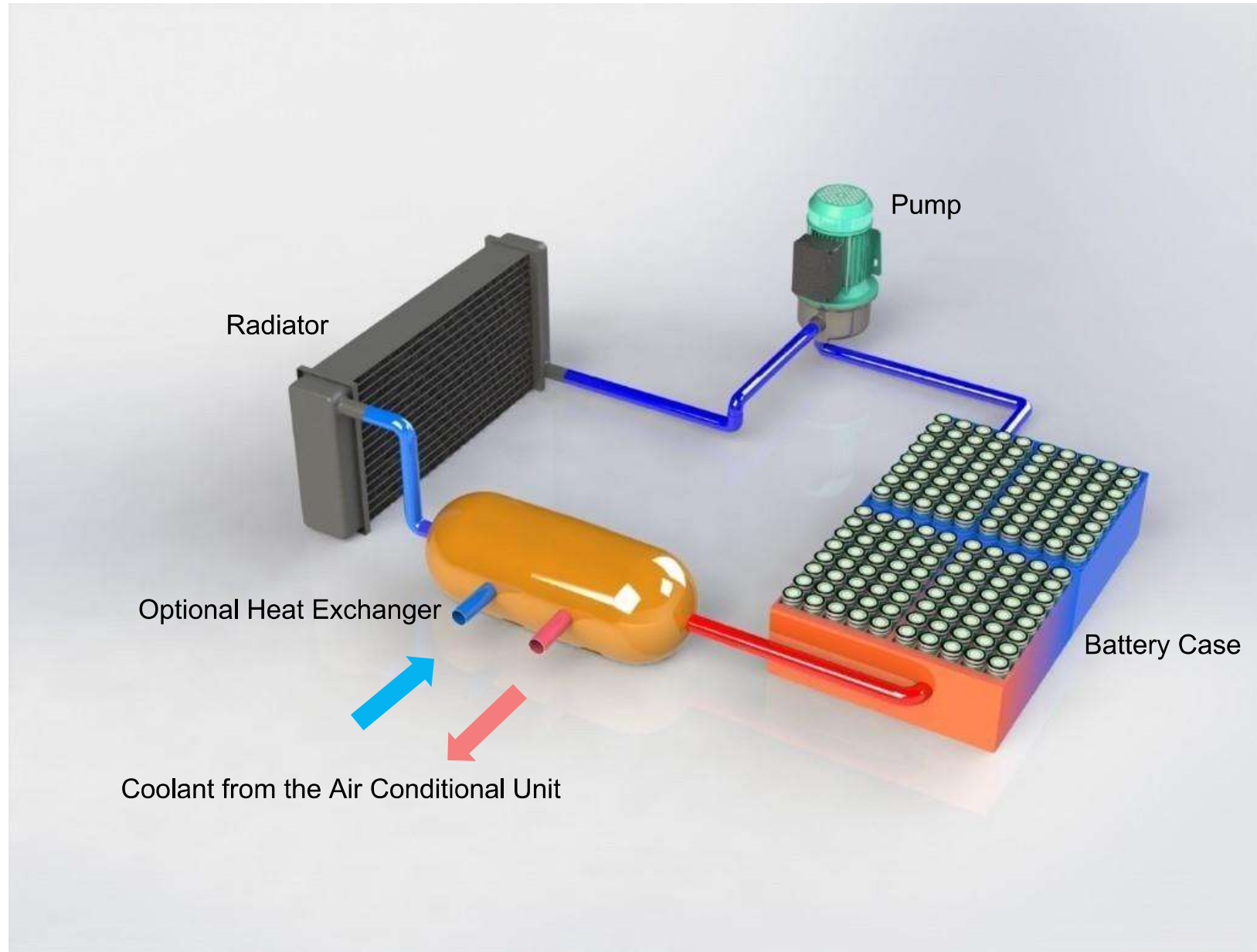
Liquid Cooled Battery Pack



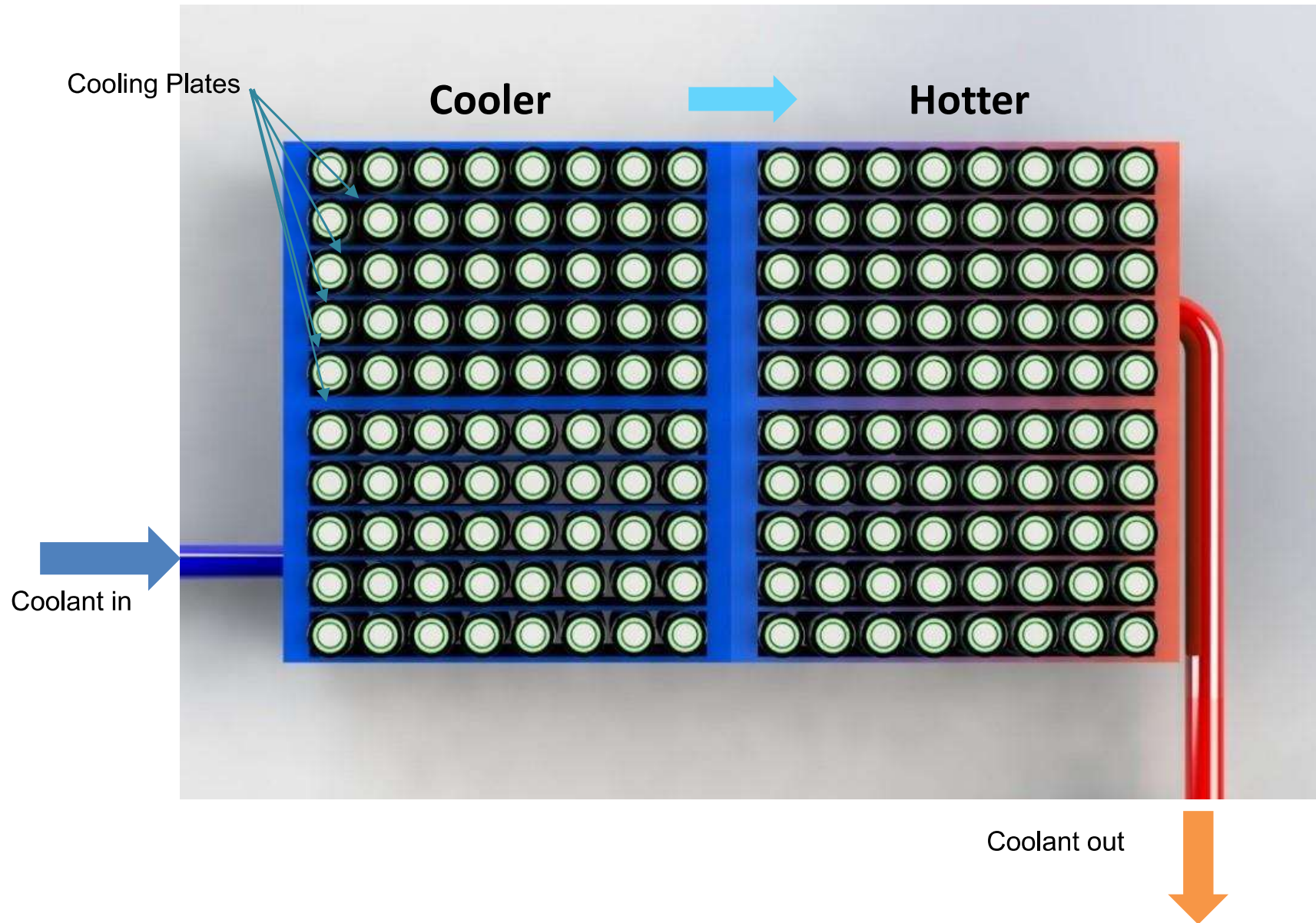
RR Spirit of Innovation Cooling System



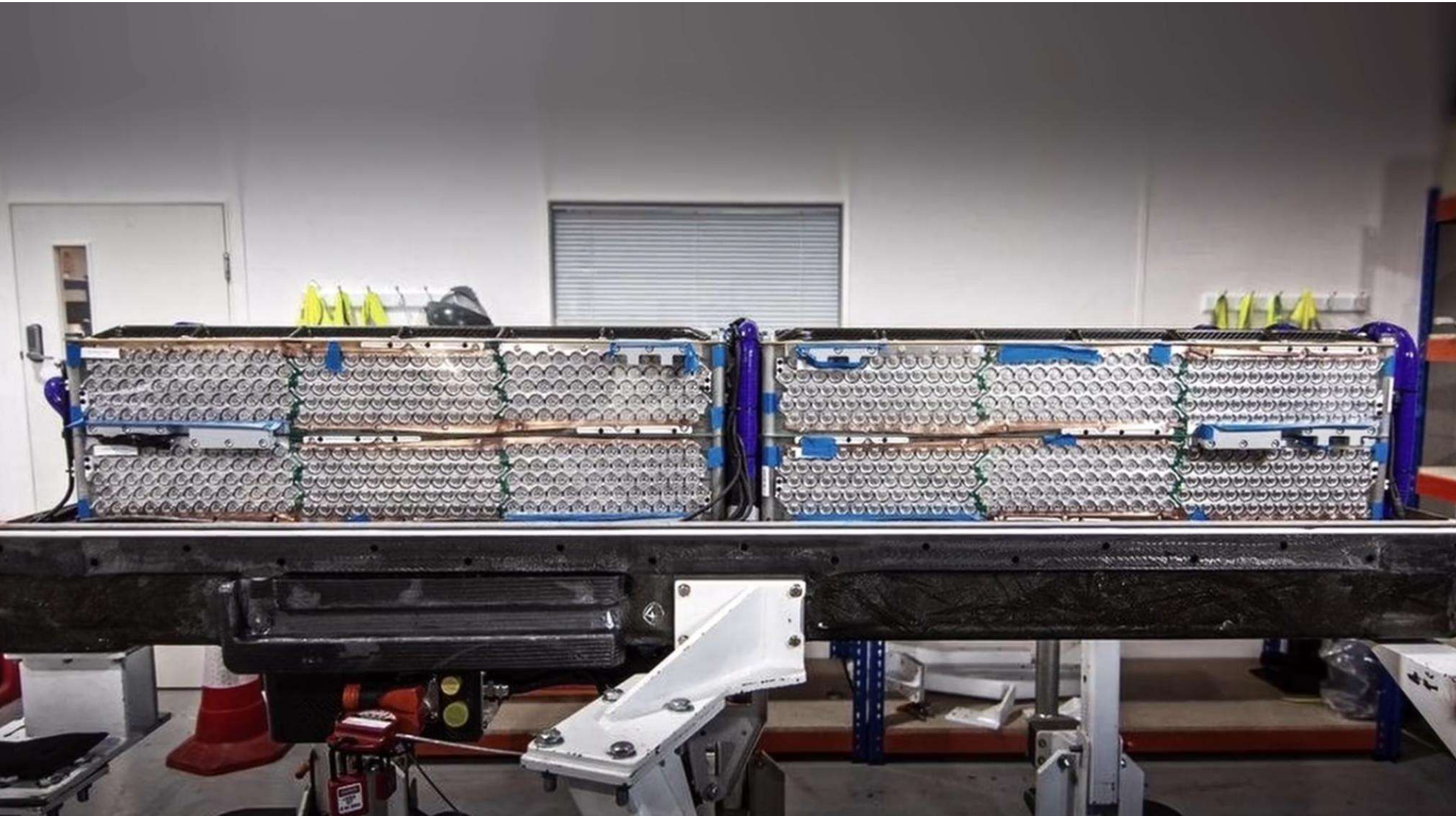
Liquid Cooling of Lithium Cells



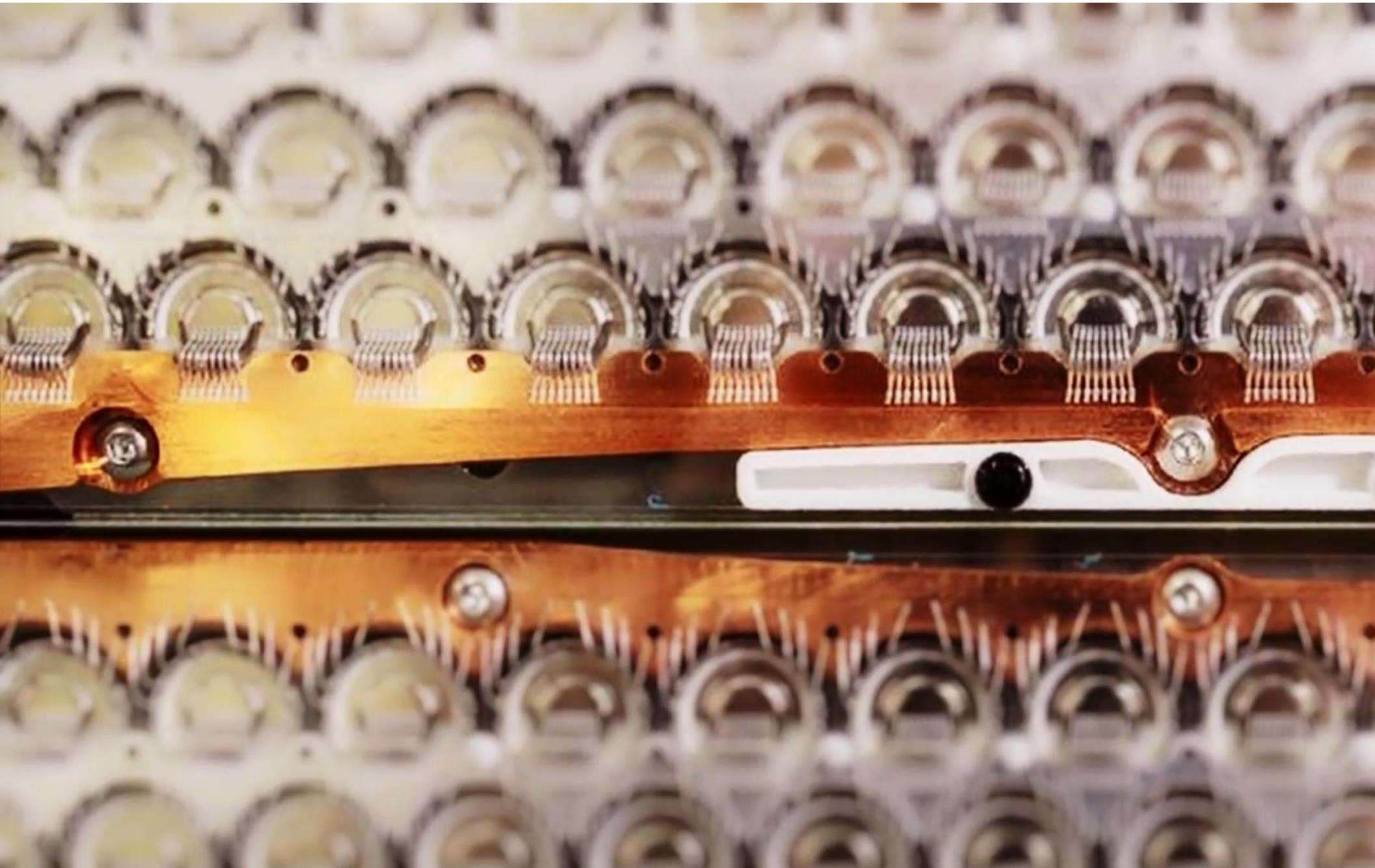
Thermal Gradient Problem



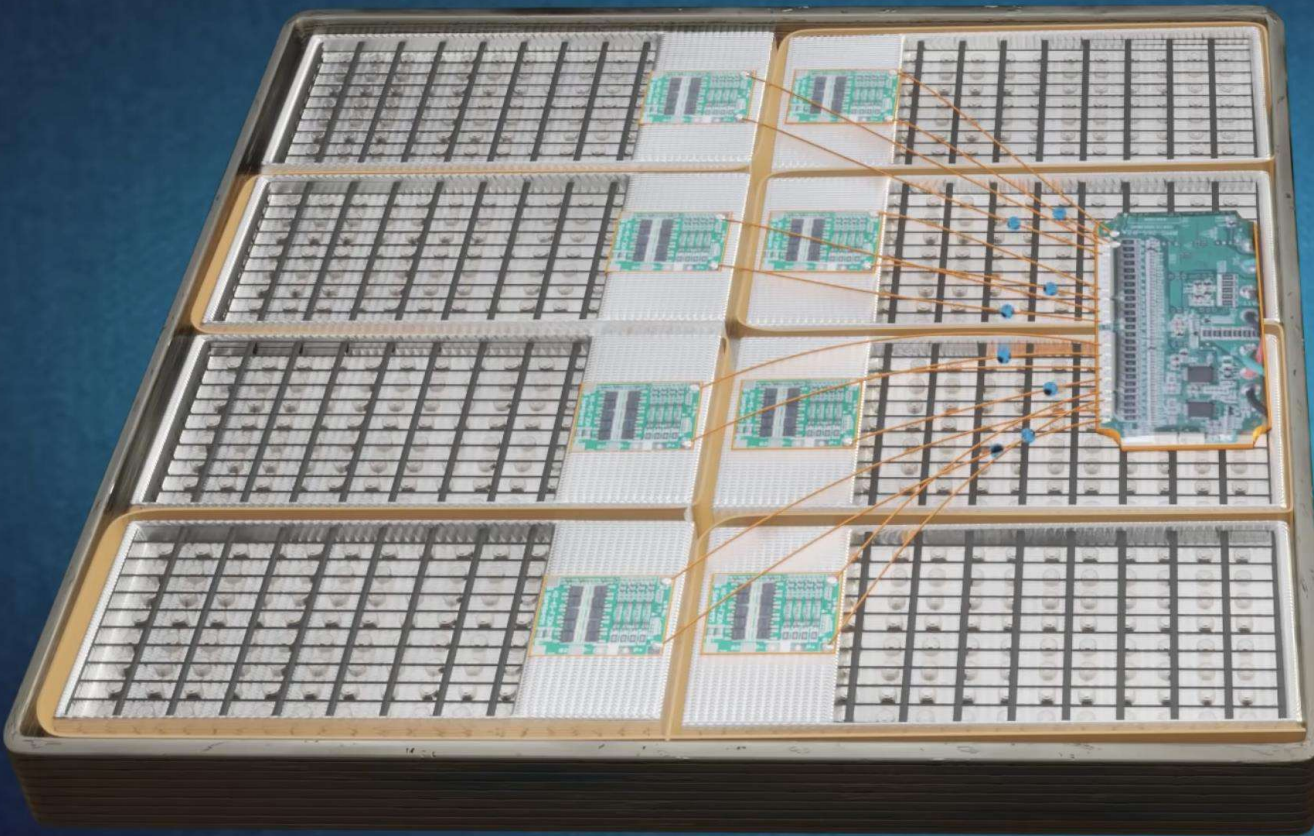
RR Spirit of Innovation Uses 18650 Type Cylindrical Cells



Each Cell is Connected to the BMS (Battery Management System)



BMS Monitors Each and Compares Every Cell



BMS helps prevent

- OVERLOADING
- OVERCHARGING
- UNDER DISCHARGING



LITHIUM-ION BATTERY

3S battery pack without BMS



**Single lithium
pouch cell
200wh/kg**



3S battery pack with BMS

Importance of Balancing Cells When Charging

Example of checking the cell voltages on a 6S battery pack.

The voltage difference between cells should be less than 0.01 volt

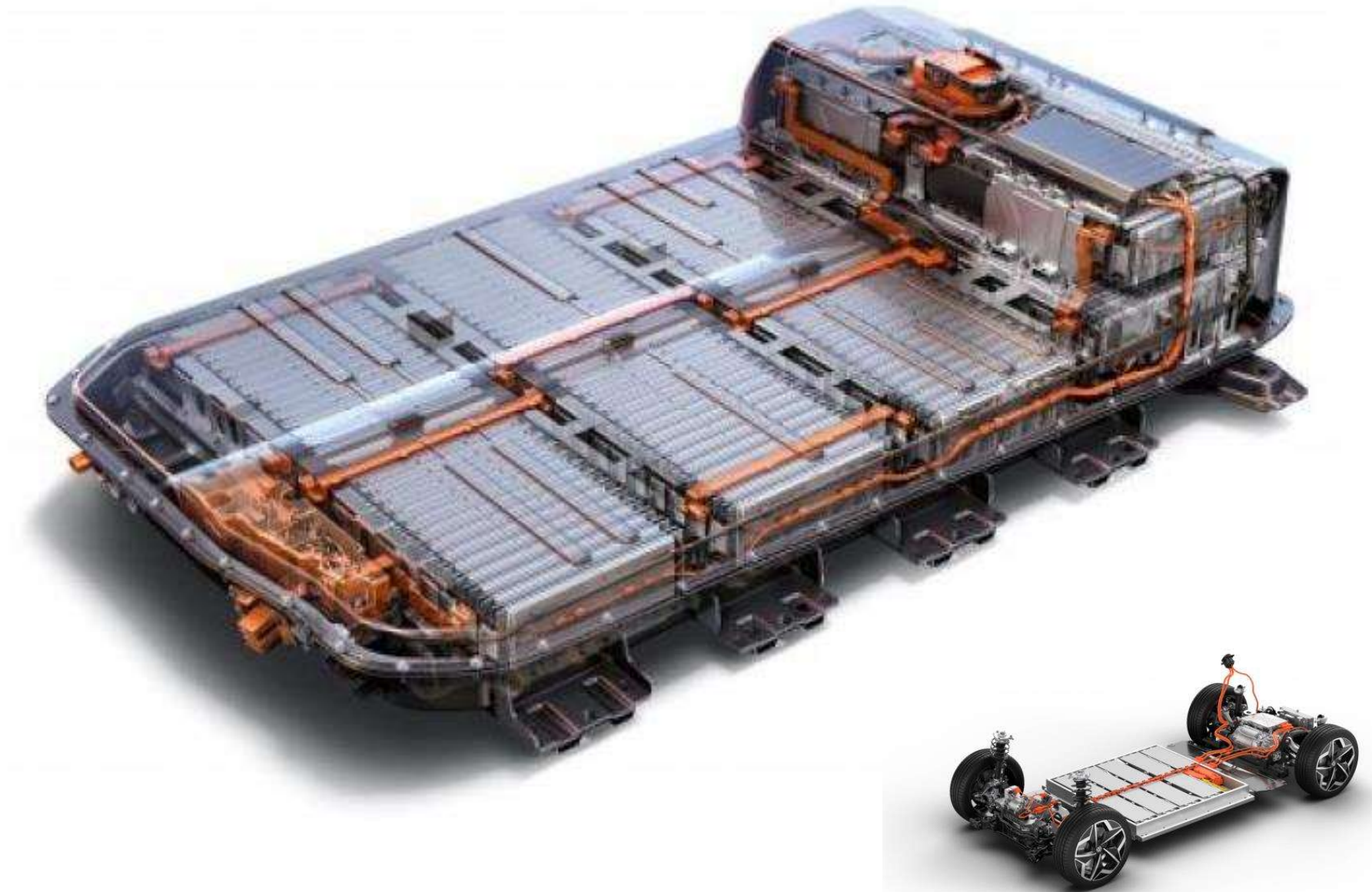
All eVTOL battery pack should have a built-in battery managing system (BMS) to check and compare the health of every cell. There could be thousands of cells in an eVTOL.



Don't Let This Happen !

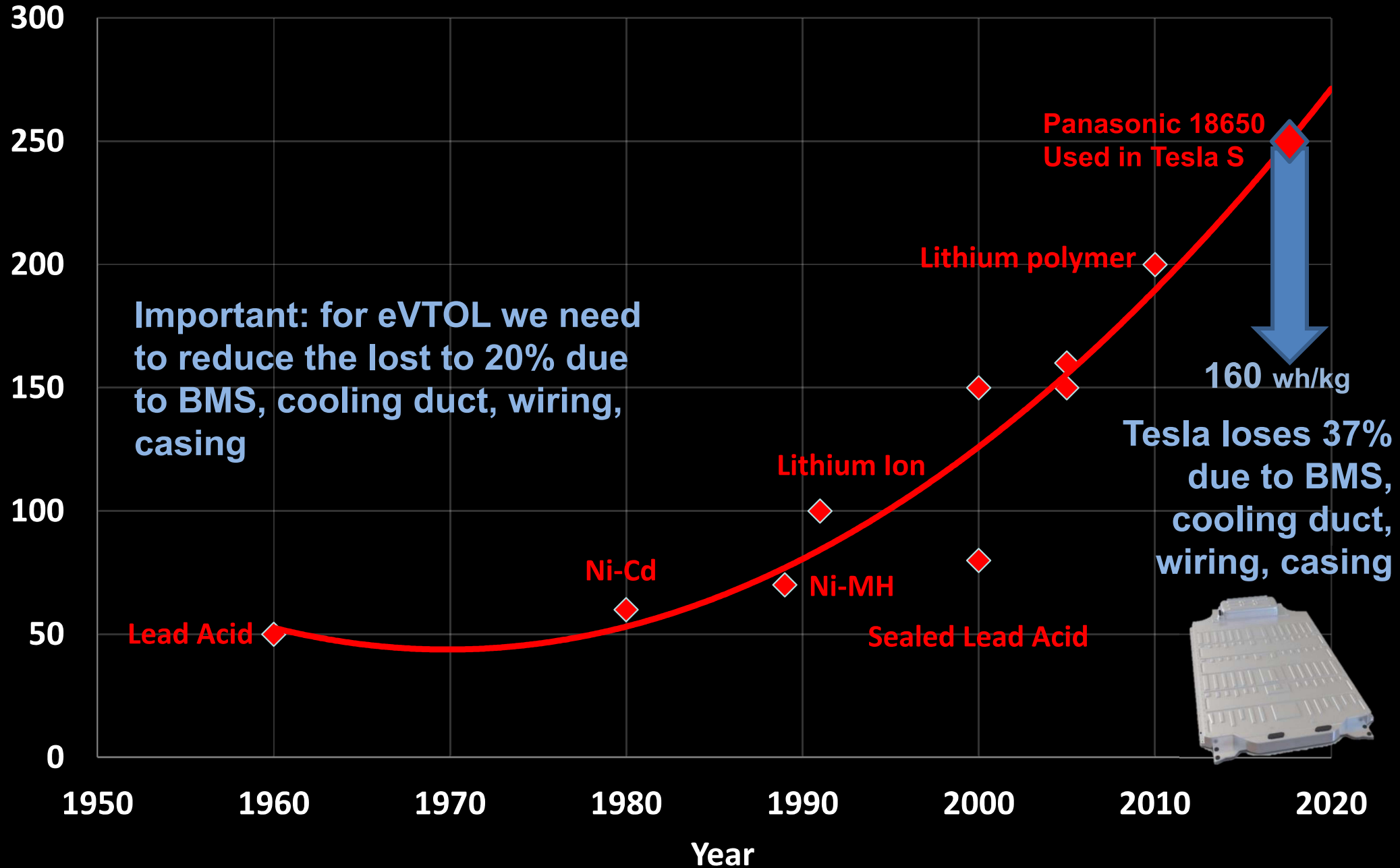


Example: Finished Car Battery Pack with BMS

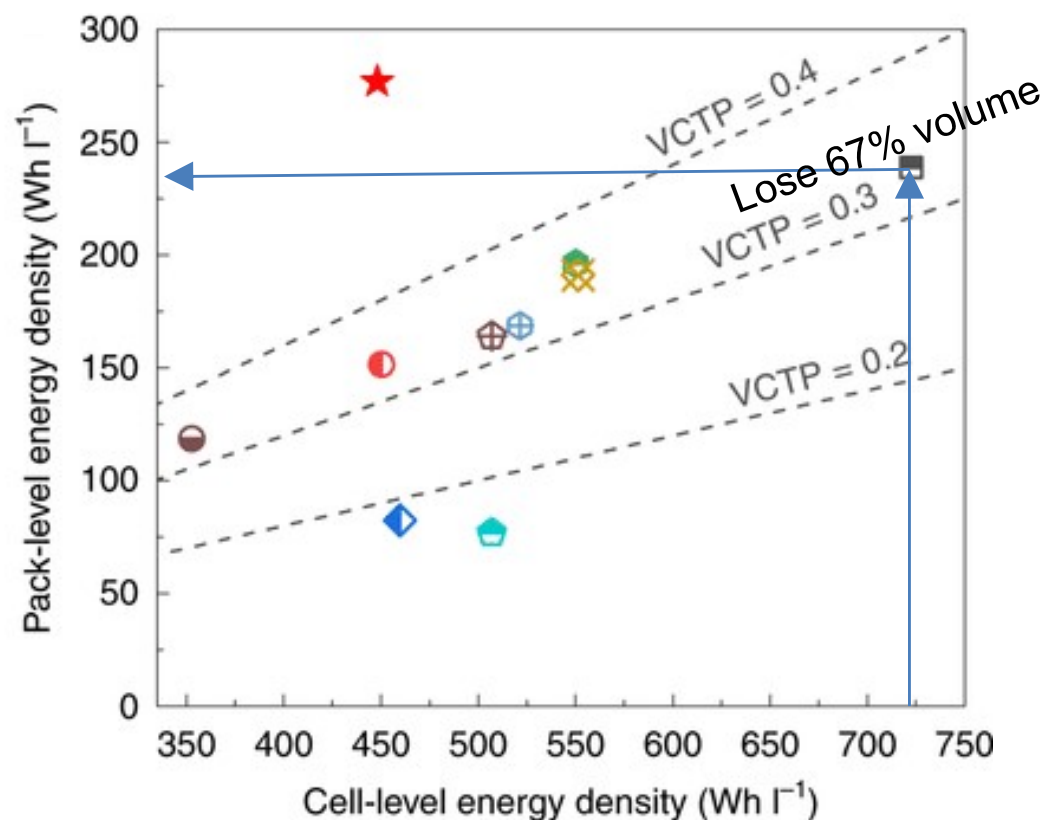
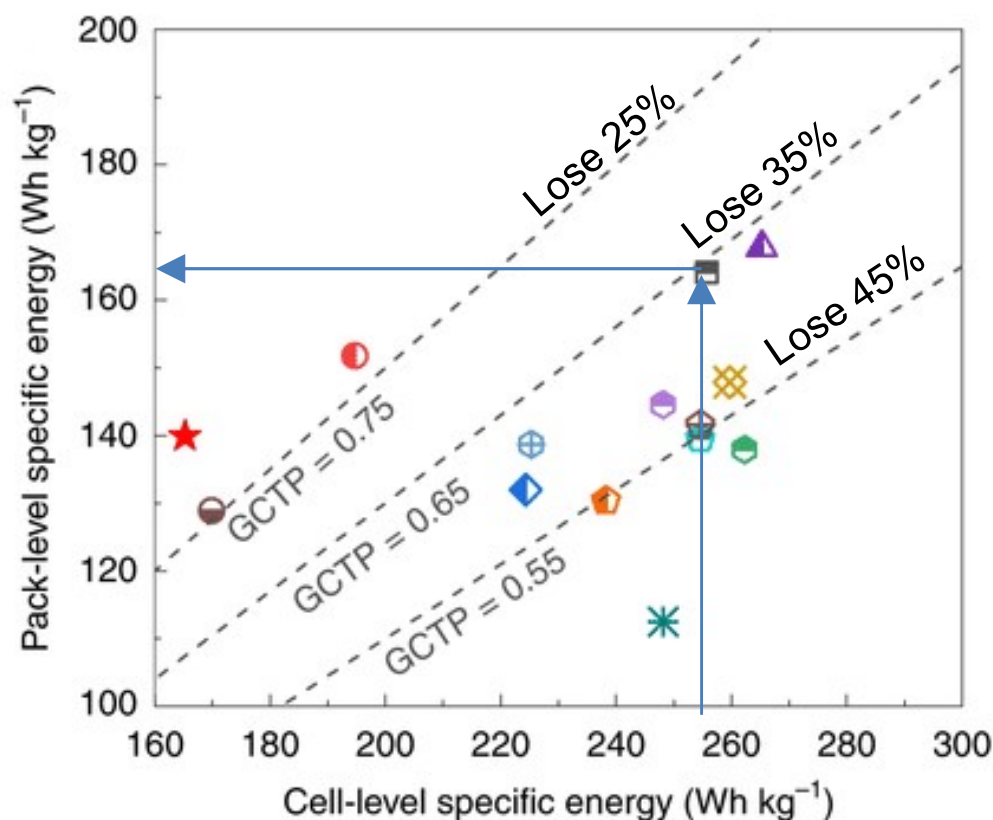


Specific Energy Trend for Rechargeable Batteries (at the Cell Level)

Specific Energy
(Watt-Hour/Kg)



When Going from Cell Level to Pack Level Can Lose 45% to 25% in Specific Energy



■ Tesla Model 3 LR (2018)

● BMW i3 (2018)

● BMW i3 (2019)

◆ Nissan Leaf (2018)

● Chevy Bolt (2018)

● Renault ZE40 (2018)

● Renault ZE50 (2019)

● Audi E-Tron (2018)

● Hyundai Kona (2018)

● Jaguar I-PACE (2019)

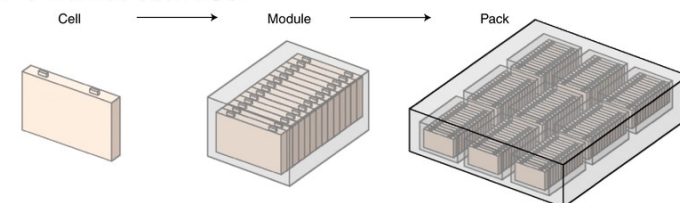
● Mercedes EQC (2019)

● NIO ES8 (2018)

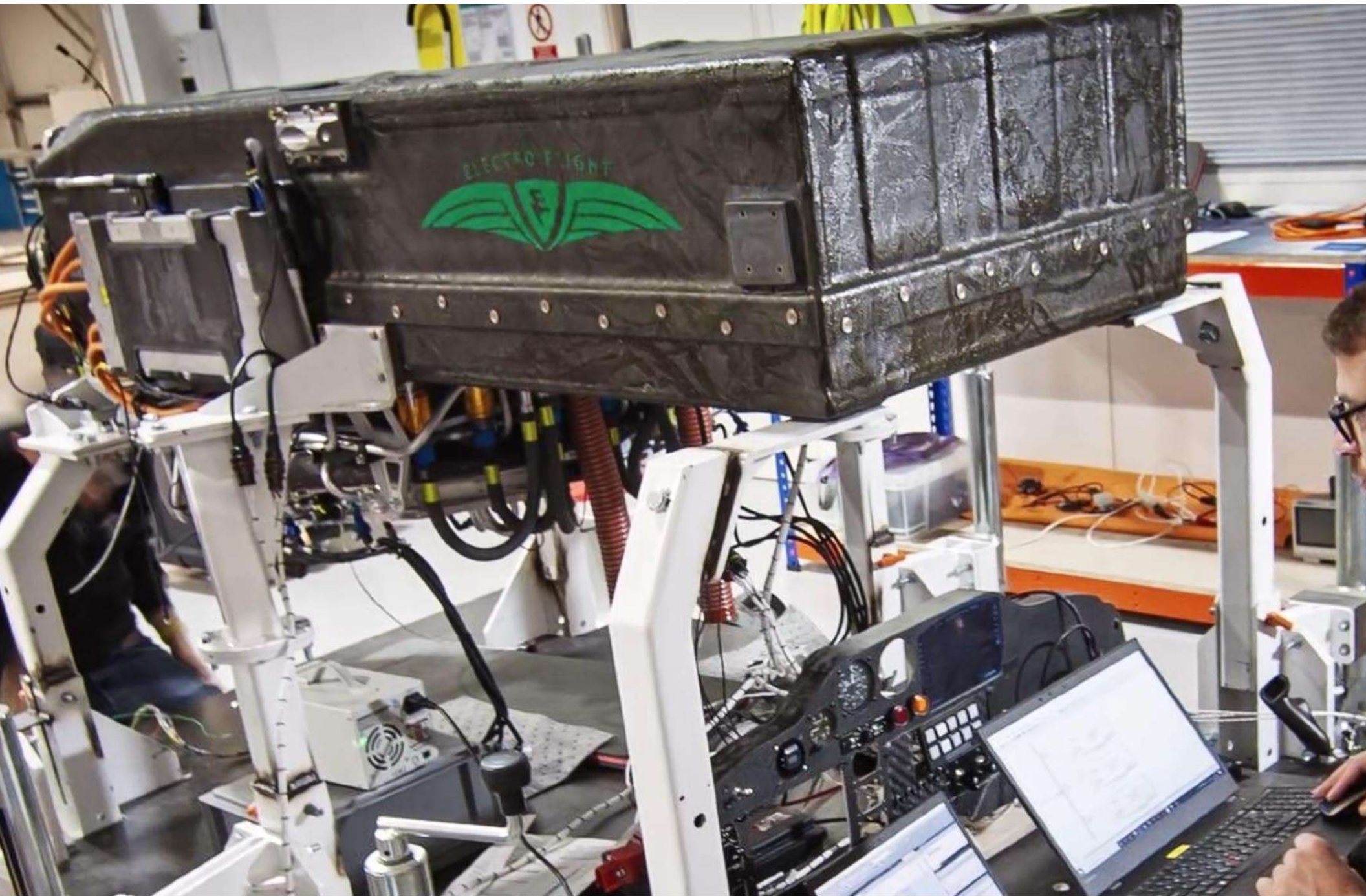
● Hyundai Ioniq (2018)

★ BYD Han (2020) (LFP blade battery)

Source: https://www.researchgate.net/figure/Cell-to-pack-technology-a-b-A-schematic-illustration-of-a-conventional-battery-pack-a_fig1_348584577



RR Airplane Achieves 168 Wh/kg at Pack Level



Advantage of Using Battery Modules for cars and electric aircraft

- **Ease of manufacturing**
- **Safety in manufacturing**
- **Can distribute around the aircraft**
- **Safety in failure/crash**
- **Serviceability**

What is C Rating

Definition of C Rate

0.1C = fully discharge or fully charge in 10 hour

1C = fully discharge or fully charge in 1 hour

10C = fully discharge or fully charge in 1/10 hour

100C = fully discharge or fully charge in 1/100 hr

Example: a 50 Ah battery discharging at 50 amps, will be fully emptied in 1 hour. That is called *discharged at 1C rate*

Example: a 50 Ah battery charging at 50 amps, will be fully charged in 1 hour. That is called *charging at 1C rate*

Definition of C Rate

Can also calculate C Rate if we know the power usage in watts.

Example: a 50 Ah 100 volt battery = 5000 Wh battery

A 5000 Wh battery discharging at 5000 Watts, will be fully emptied in 1 hour. That is called **discharged at 1C rate**

More Examples of C Discharge Rate

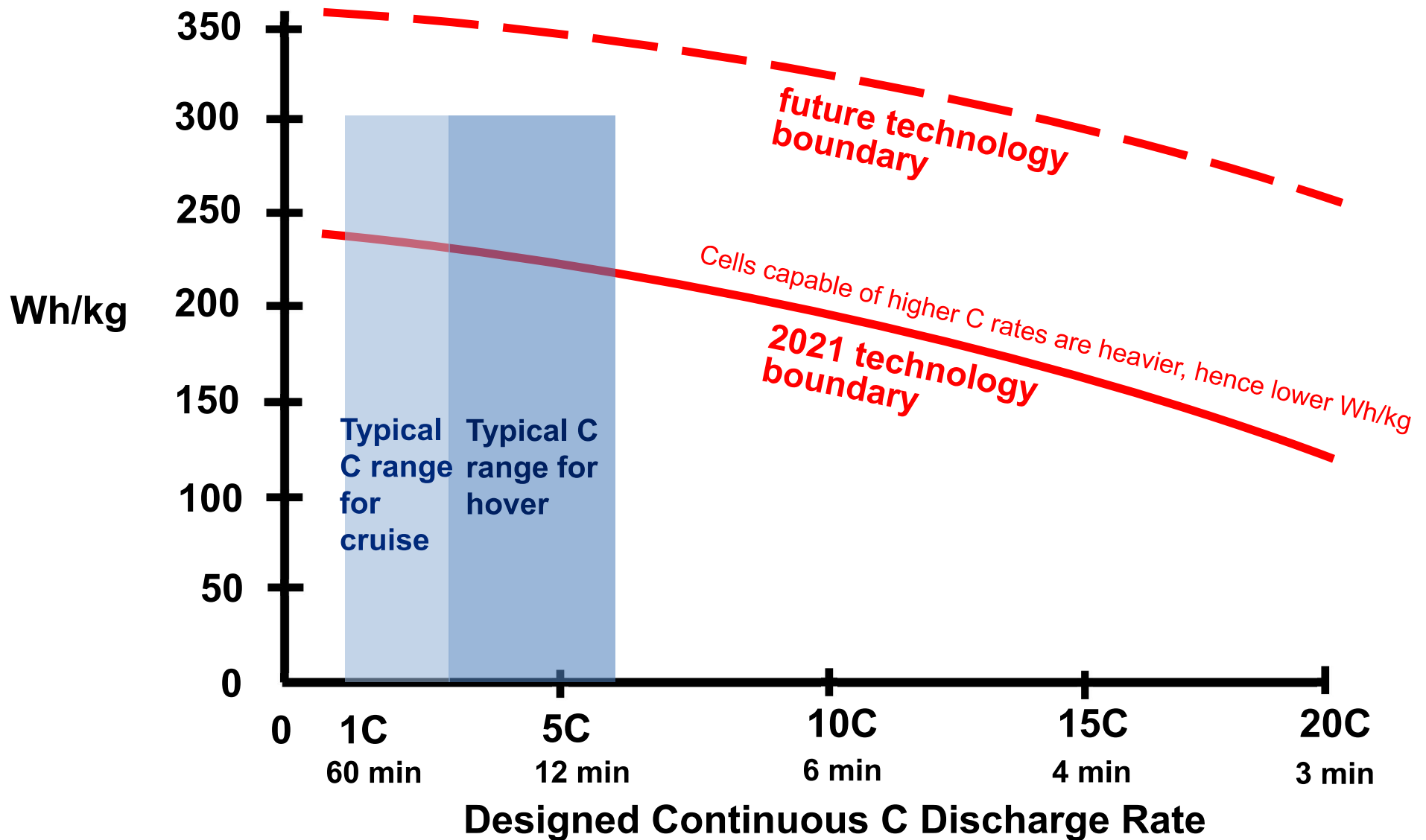
Example: a 50 Ah battery discharging at 500 amps (@10C) will be fully emptied in **1/10 hour** (= 6 min)

Example: a 50 Ah battery discharging at 100 amps (@2C) will be fully emptied in **1/2 hour** (= 30 min)

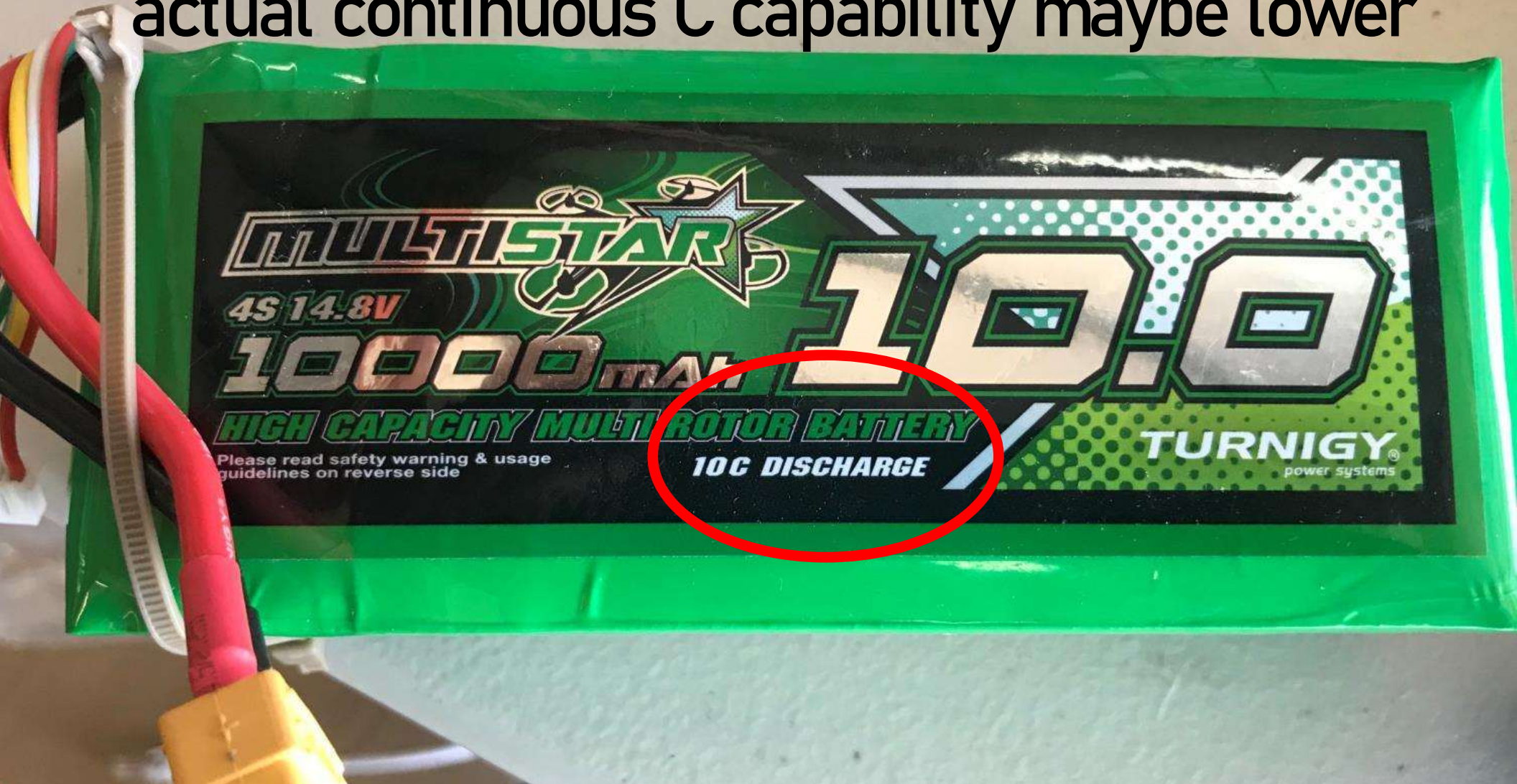
Example: a small eVTOL with a fully charged 800 volt, 50 Ah battery (40 kWh) discharging at 250 amps (@5C), it can fly for **12 minutes**.

***Warning: lithium battery should never be fully emptied!
Avoid draining down to below 25% of its total capacity.***

C Discharge Rate Affects Cell's Specific Energy



Regardless what the advertising says, the actual continuous C capability maybe lower

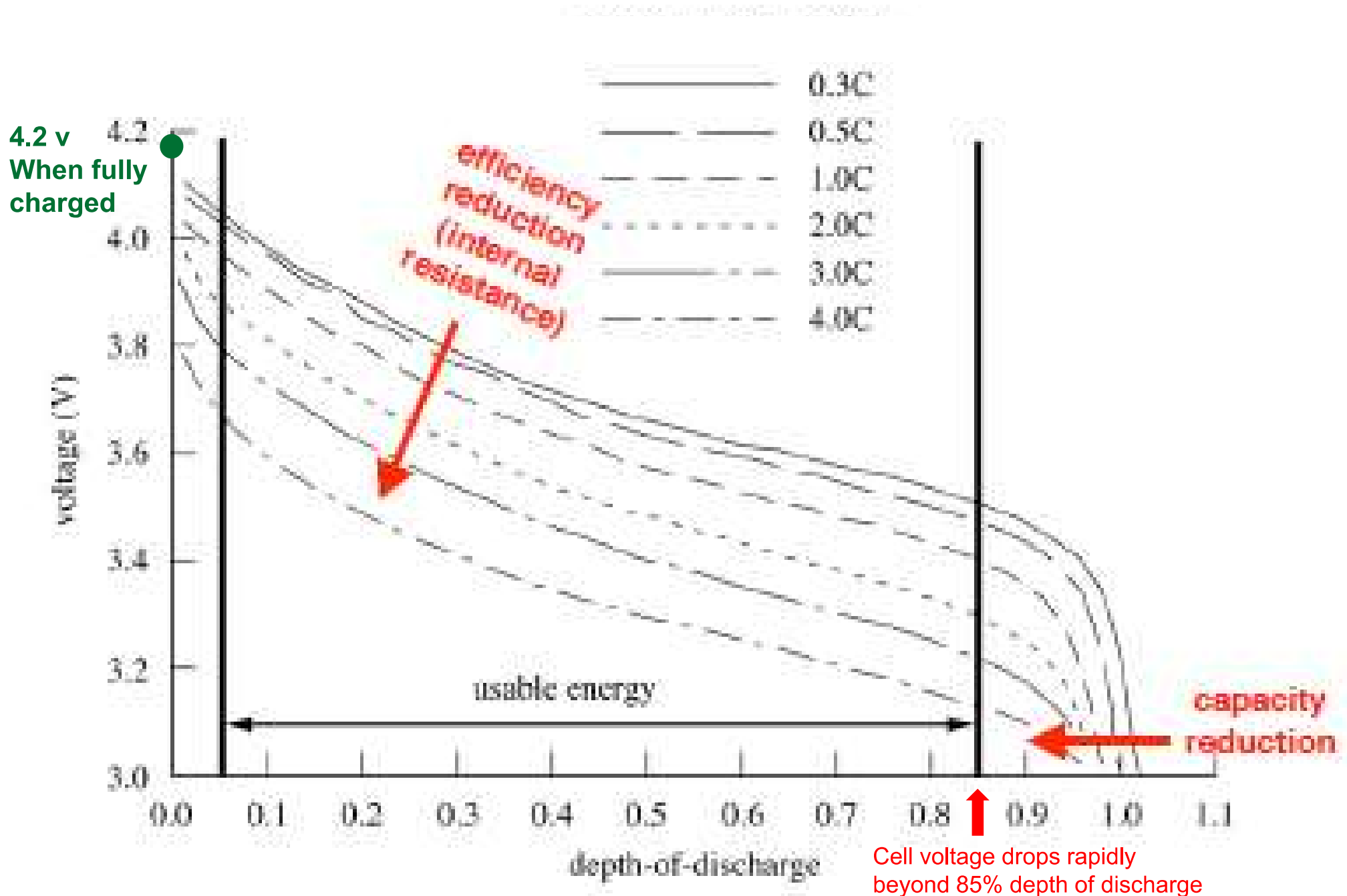


For today's lithium battery technology, it is best to keep your discharge rate under 5C.

A fully charged lithium cell is around 4.2 volts.
Minimal usable voltage 3.7 volts. Hence $3.7\text{V} \times 4 = 14.8\text{V}$



Lithium Cell Discharge Characteristics



Examples of C Charging Rate

Example: a 50 AH battery charging at 100 amps (@2C) will be fully charged in 1/2 hour (= 30 minutes)
Called fast charge, feasible today

Example: a 50 AH battery charging at 500 amps (@10C) will be fully charged in 1/10 hour (= 6 minutes) *Super fast charge! Not popular yet !*

Example: a 50 AH battery charging at 5 amps (@ 0.1C) will be fully charged in 10 hour
Called slow charge. If even lower rate, then it is called trickle charge

To permit high C charge and discharge rates, the cell is designed to have a lower internal impedance. This also helps prevent heat built up inside the cell.

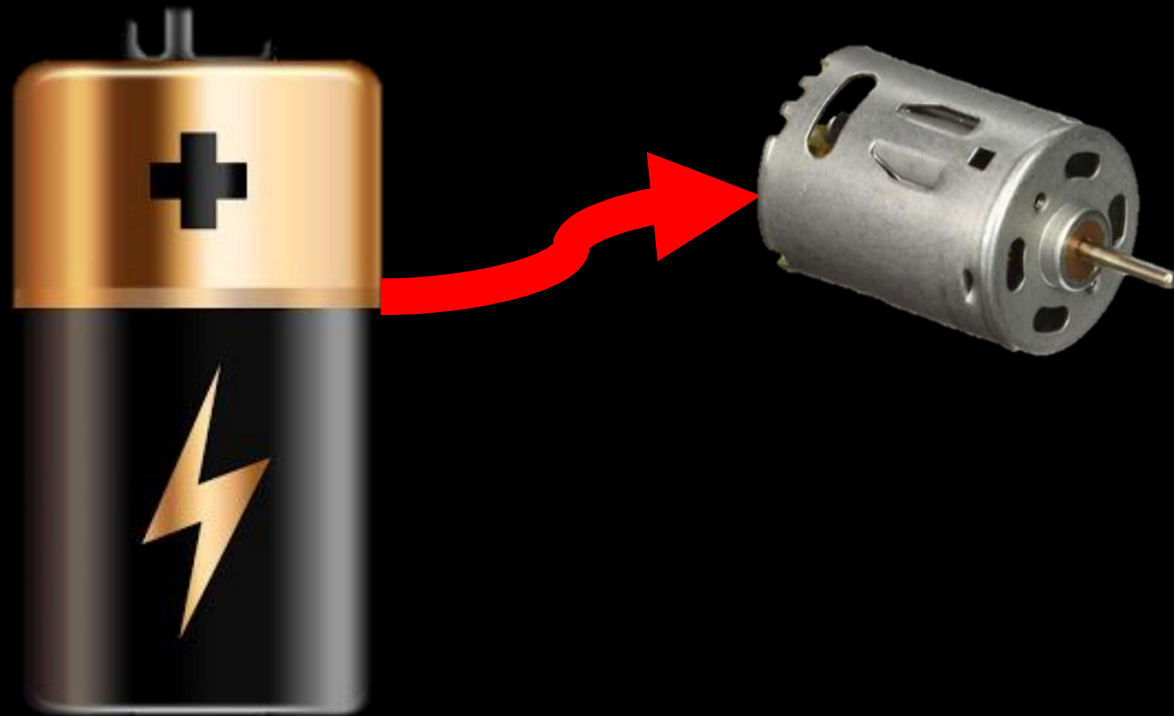
Higher-C cells are 10 to 20% heavier.



Super DC Charger Charges at 1C to 2C Rate

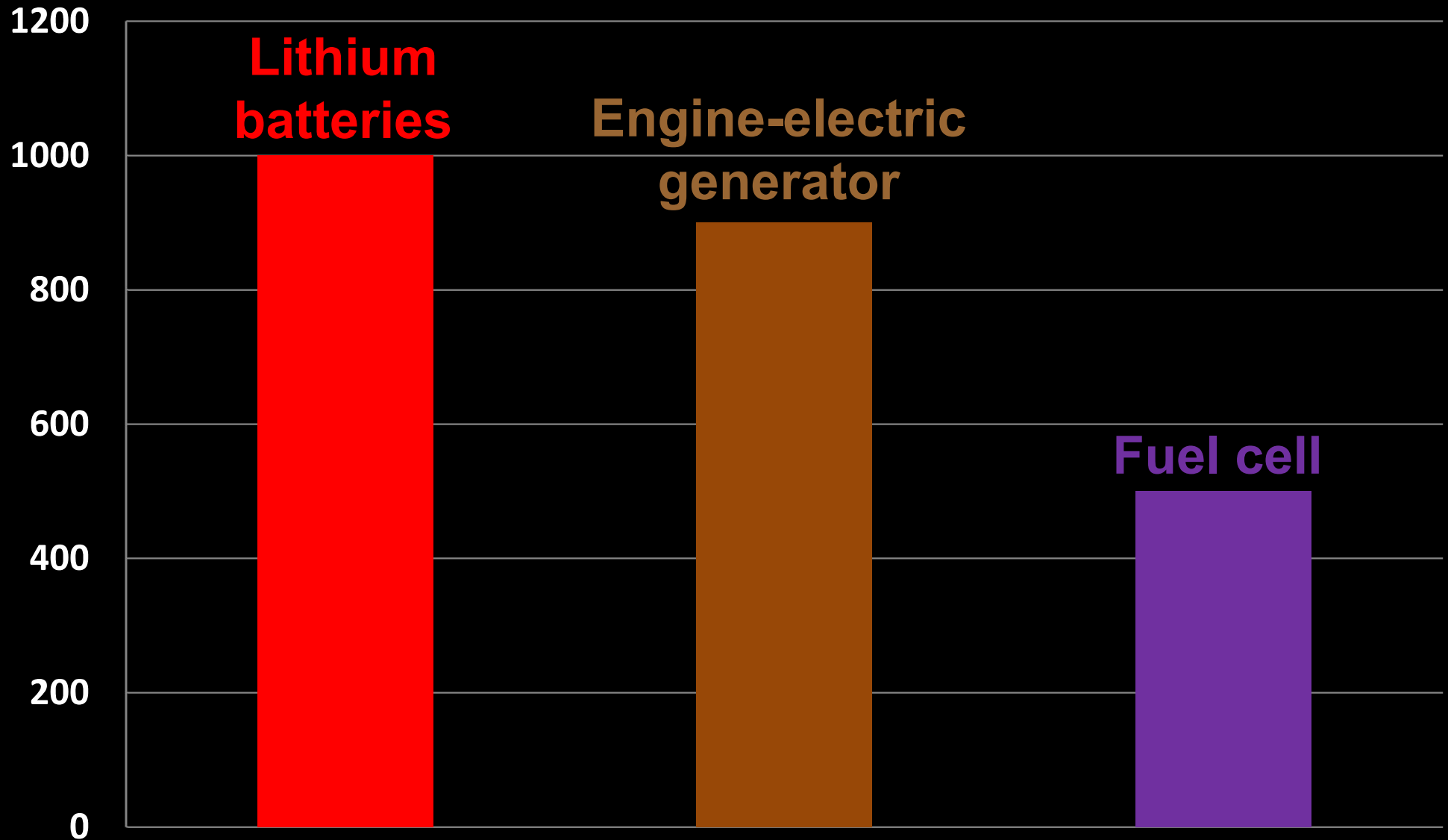
Specific Power

Specific Power is a measure of how quickly
an energy source can supply power

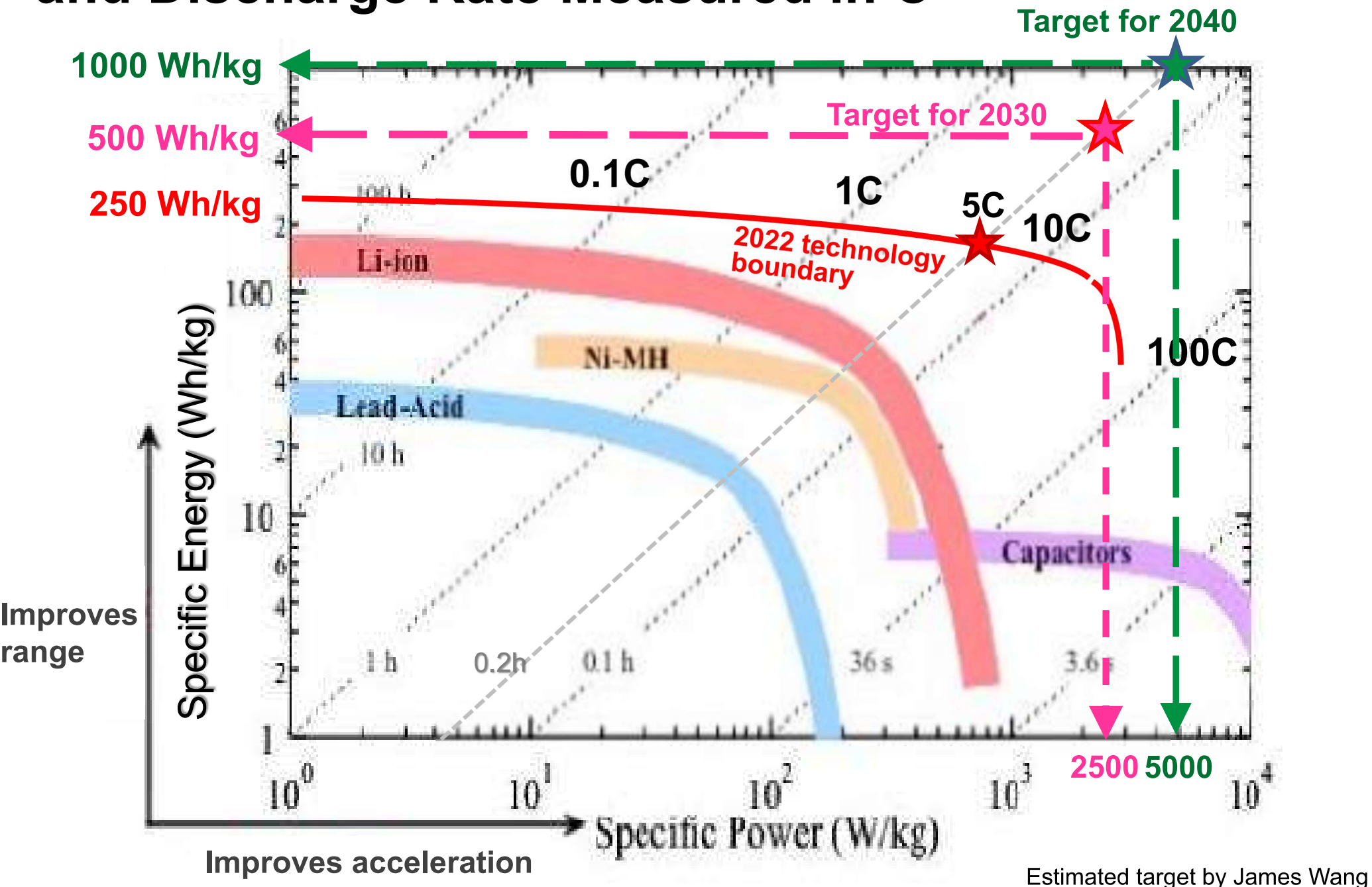


Comparing Specific Power

Specific Power (Watts/kg)



Battery Targets for Specific Energy, Specific Power and Discharge Rate Measured in C



Hydrogen Power

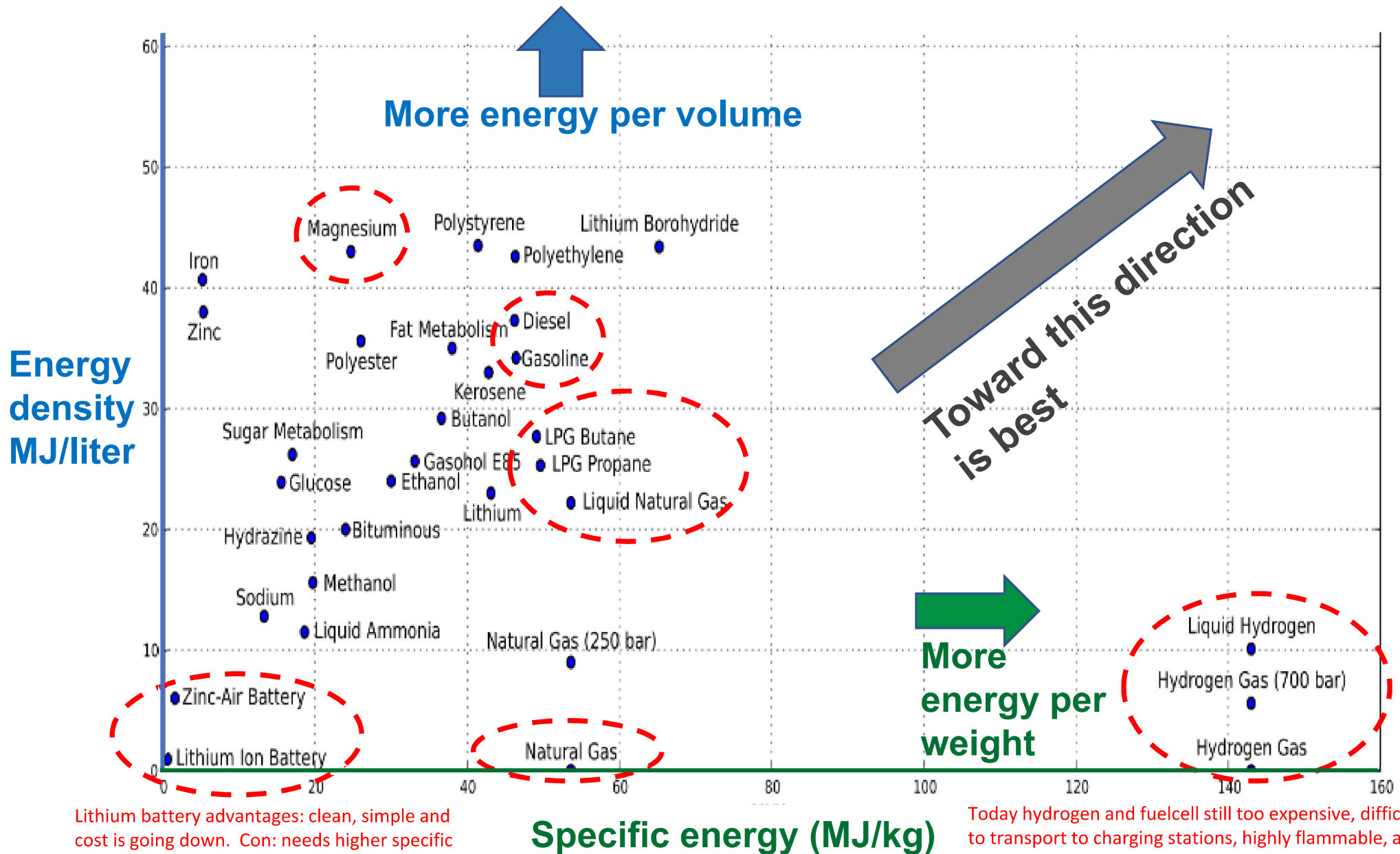
Hydrogen

Hydrogen is invisible, odorless, non-toxic, non-corrosive and non-hazardous. Nor does it ignite by itself, but when mixed with air it is an ignitable gas over a wide range of concentrations (from 4% to 75% by volume). The hazard potential of hydrogen is comparable to that of natural gas. Hydrogen must be produced, stored, transported and used carefully.

Without oxygen, hydrogen is non-explosive. Storing hydrogen in tank is therefore not dangerous in itself. Safety valves ensure that the hydrogen is blown off in a controlled manner at overpressure and volatilizes. However, escaping hydrogen can be ignited and flared by an ignition source without causing an explosion.

Safety precautions are designed accordingly, and handling is regulated by a comprehensive set of standards. In Europe, there exists special hydrogen pipelines totaling over 1,500 km in length.

Want High Specific Energy & High Energy Density



Lithium battery advantages: clean, simple and cost is going down. Con: needs higher specific energy, recyclability, and to be less volatile.

Today hydrogen and fuelcell still too expensive, difficult to transport to charging stations, highly flammable, and does not have the "power density" required for flight.



HYDROGEN

STATS

DENSITY

~71 g/L

TEMPERATURE

-260 °C

CO₂ EMISSION

0 kg/L

SPECIFIC ENERGY

40,000 Wh/kg

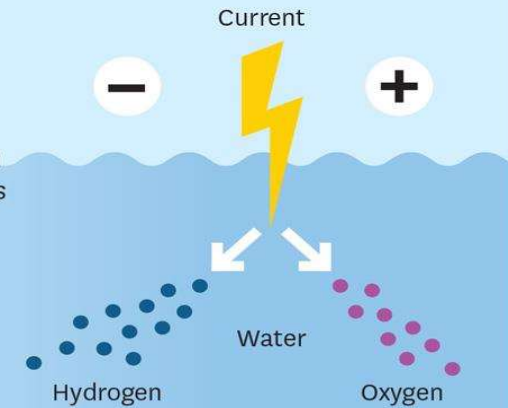
How to Produce Hydrogen



Electricity can be used to collect hydrogen from water. Scientists are looking for smarter ways to make this happen.

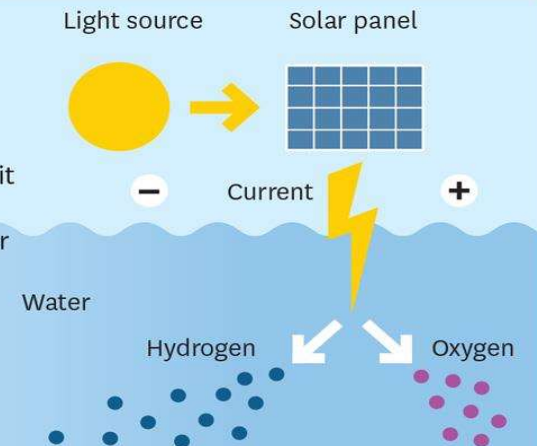
Electrolysis

An electrical current passed through water can split water into its components—hydrogen and oxygen. Researchers worldwide are studying catalysts to make the process more efficient and cheaper.



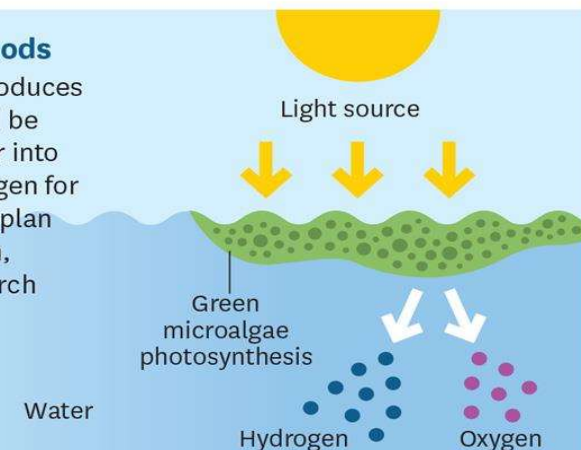
Photoelectrolysis

Some scientists are studying how to use sunlight to fuel reactions that can split water into hydrogen and oxygen. And other methods don't use electricity as an intermediary at all.

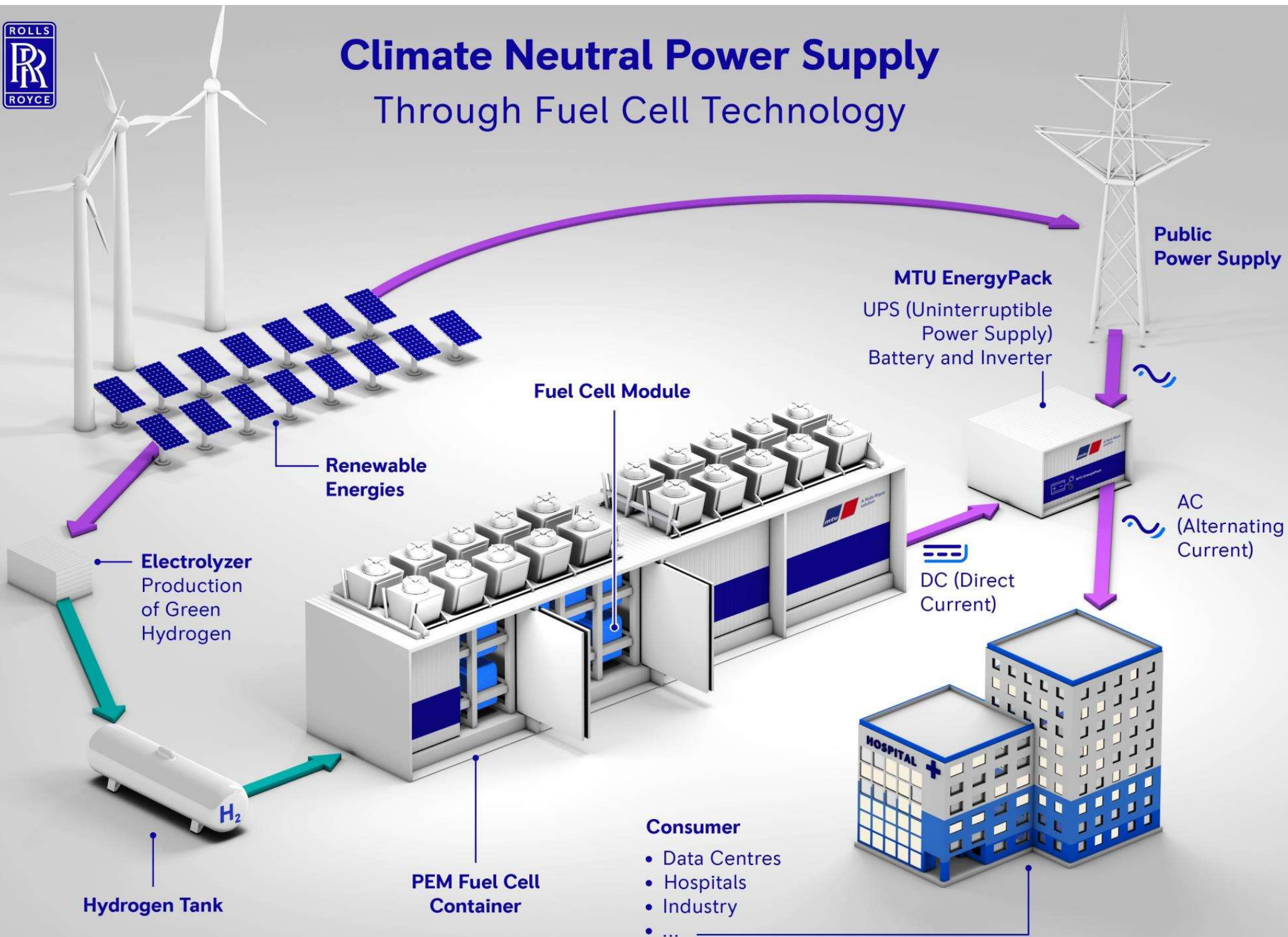


Biological Methods

Algae naturally produces hydrogen. It could be used to split water into hydrogen and oxygen for human use. Don't plan on it anytime soon, though: The research is preliminary.



Climate Neutral Power Supply Through Fuel Cell Technology



Hydrogen versus Liquid Fossil Fuel

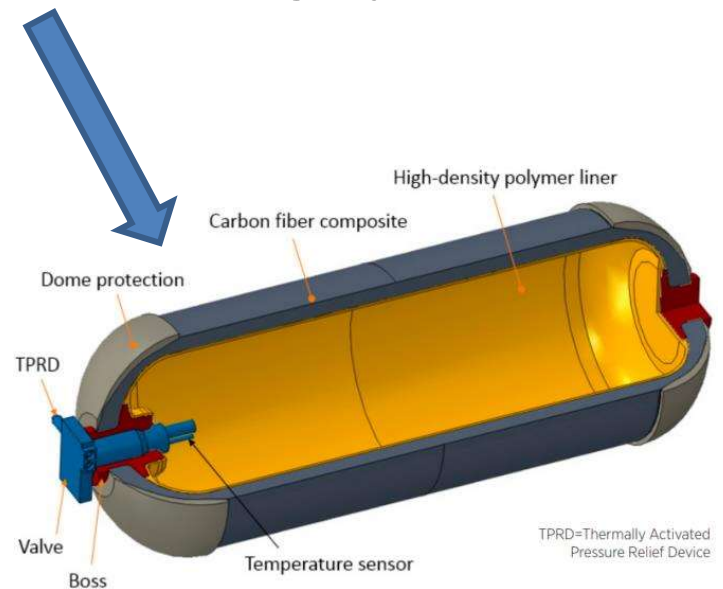
Hydrogen gas has 3 times the specific energy (Wh/kg)

Compressed Hydrogen gas takes 6 times the volume (m^3)

To get the equivalent amount of energy, the tank volume for a hydrogen aircraft needs to be twice the volume.

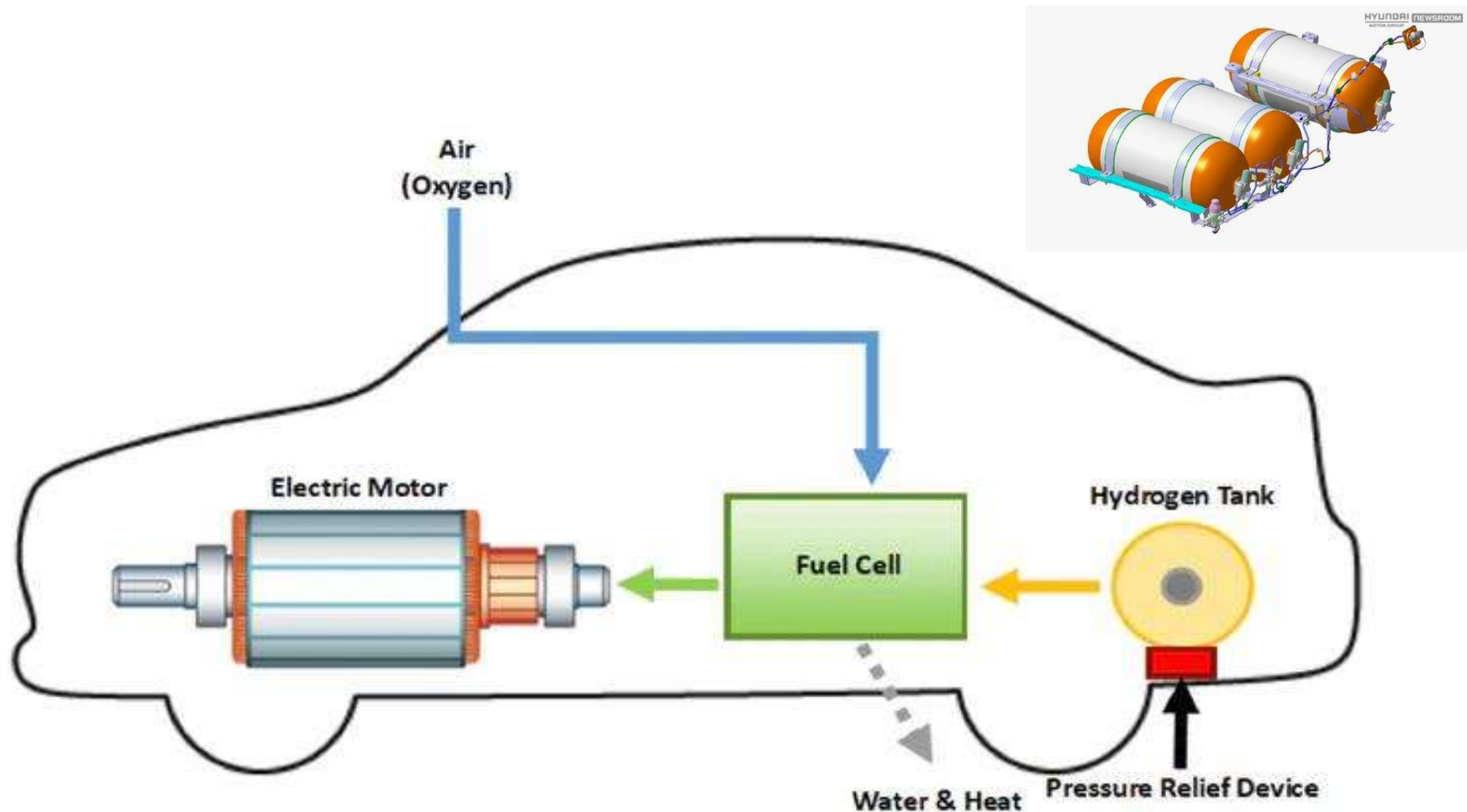
Compressed hydrogen must be stored in a strong cylindrical pressure vessel.

Aircraft wet wing tanks are not suitable for hydrogen



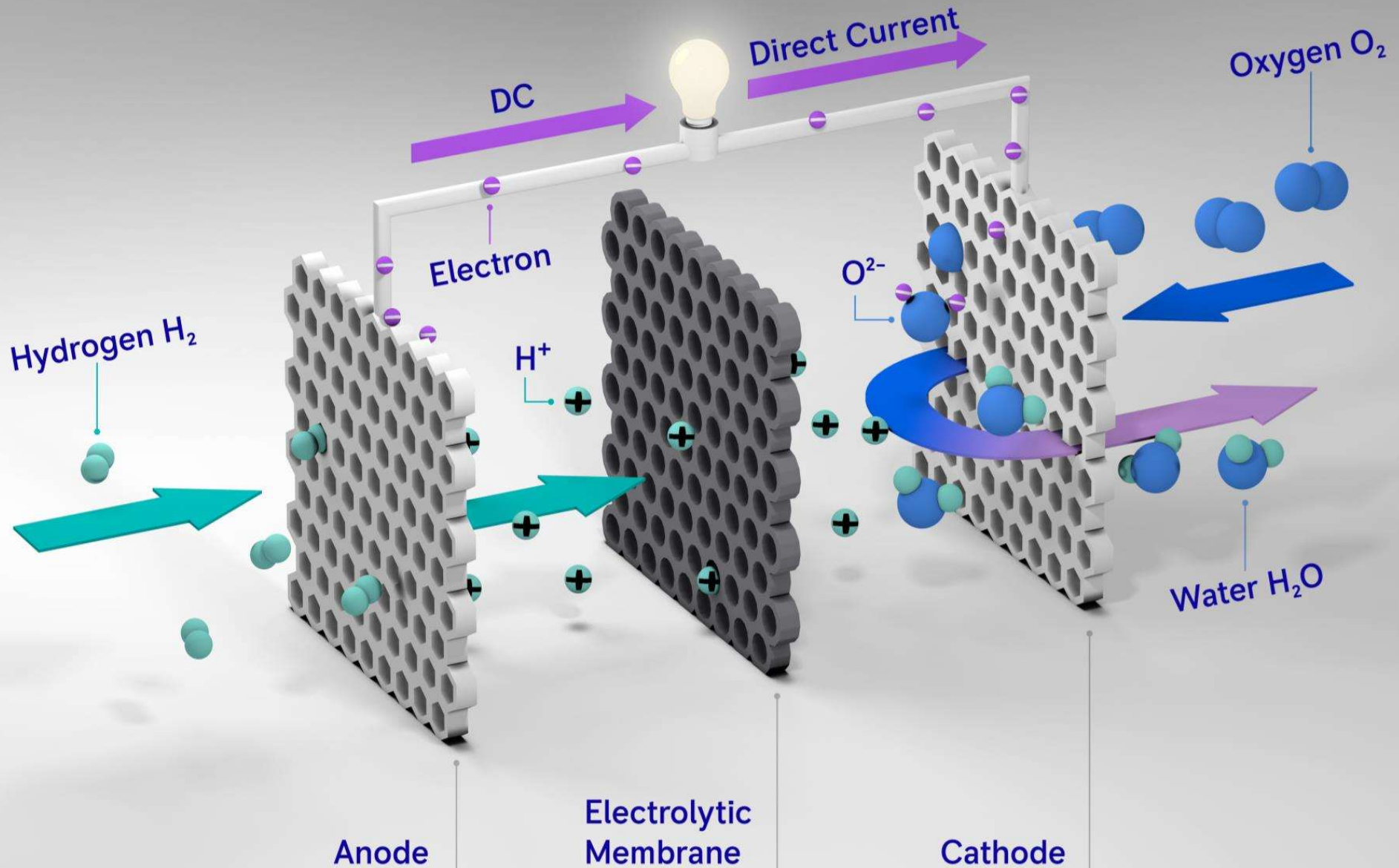
Hydrogen Fuel Cell as Substitute for Battery

(Here one does not burn hydrogen like a fuel into an engine)



In California hydrogen cost around \$16 per kg

Functional Principle for PEM Fuel Cell



Three Challenges of Hydrogen Fuel Cells

01 | MARKET LOGISTICS
\$16.51/kg is too expensive.

02 | CELL EFFICIENCY
Currently the best fuel cell can
only convert about 35%.

03 | PLATINUM CATALYST
About 50g of Pt is needed in
Fuel Cells.

Hydrogen Powered Fuel Cell Cars

5 criteria that determine whether hydrogen cars may succeed or not: Price, convenience, performance, environment, competition.

Currently, only 2 hydrogen cars on the market now, Toyota Mirai (\$50k) and Hyundai Nexo (\$59k). Honda Clarity (\$71k) was discontinued at end of 2021 due to high price and poor sale.



Currently hydrogen is \$16/kg in California

Each car can hold 5-6 kg of H₂ and good for 400 miles.

At Dec 2021, only 86 hydrogen refuel stations in USA (60 in CA)

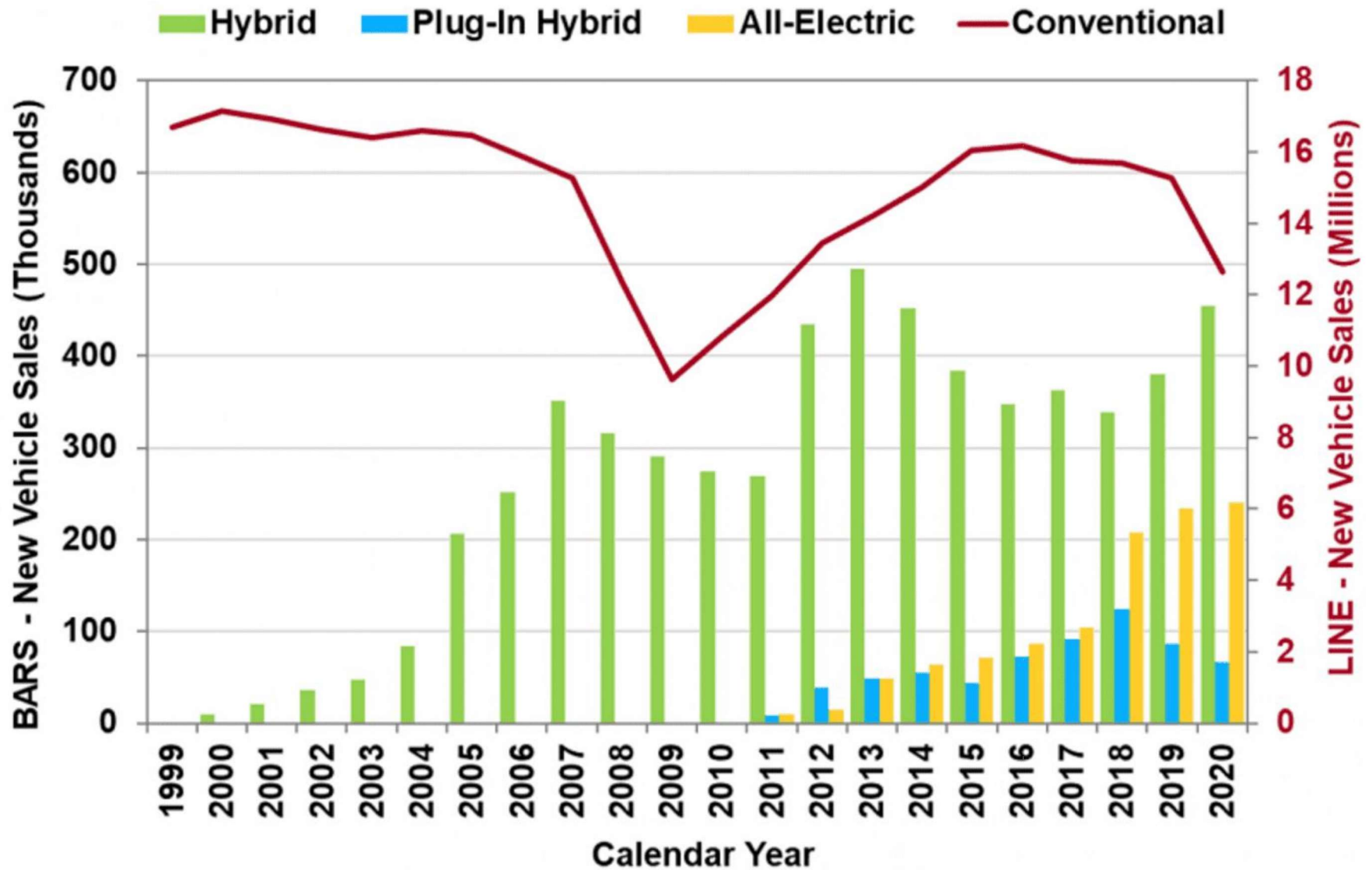
Hydrogen Fuel Cell Vehicle Sales in US, Cumulatively



INSIDE EVs



New US Vehicle Sales by Technology Type 1999-2020

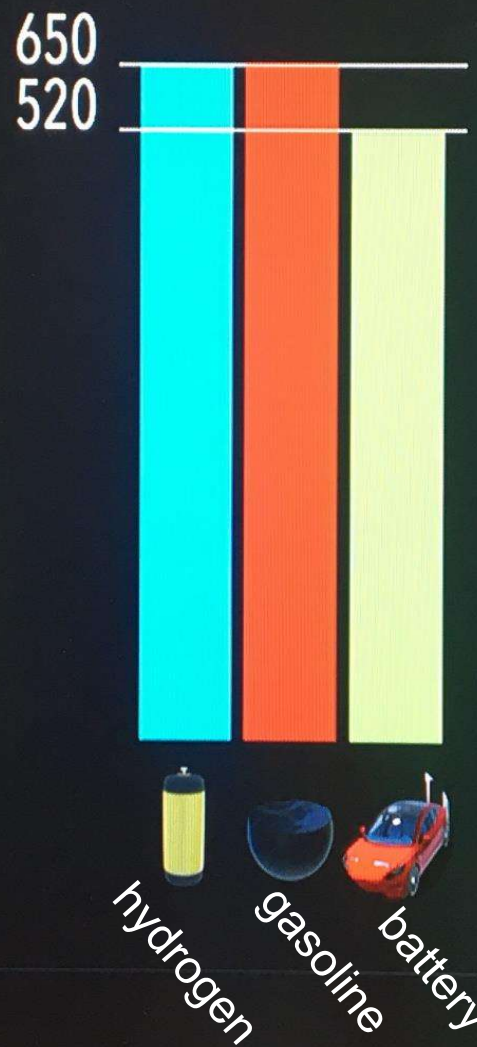


FUEL COMPARISON AS OF 2020

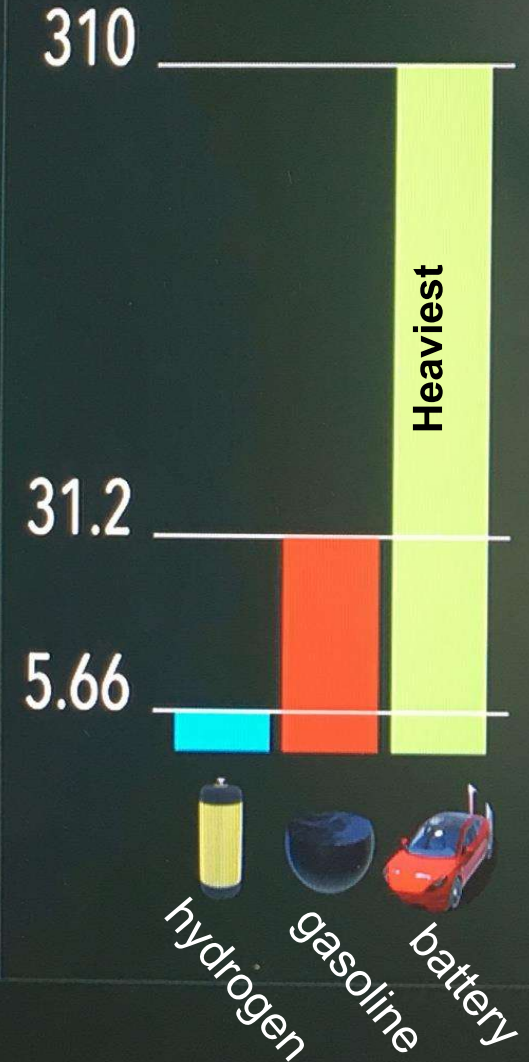
Cost to drive



RANGE Km

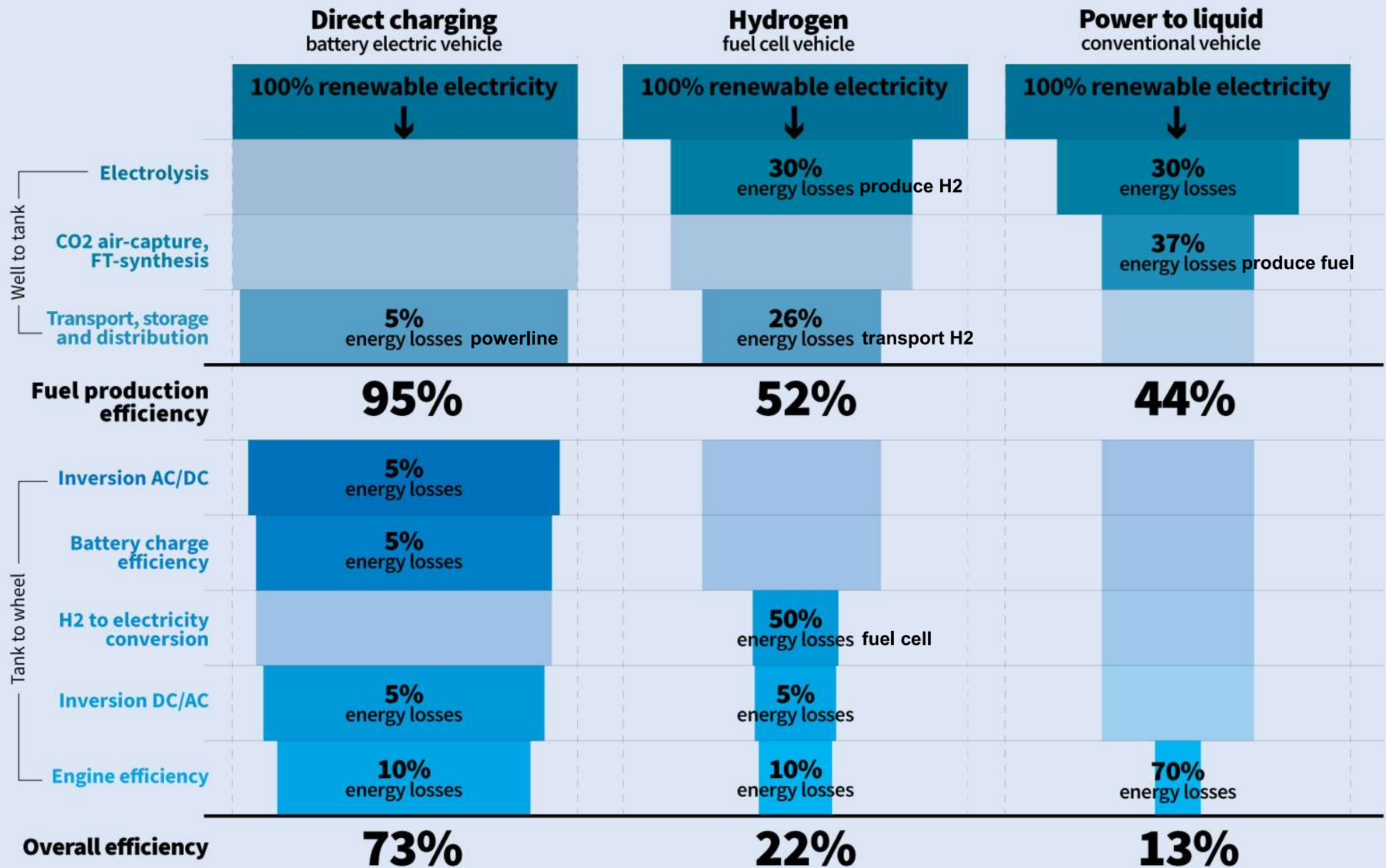


WEIGHT KG

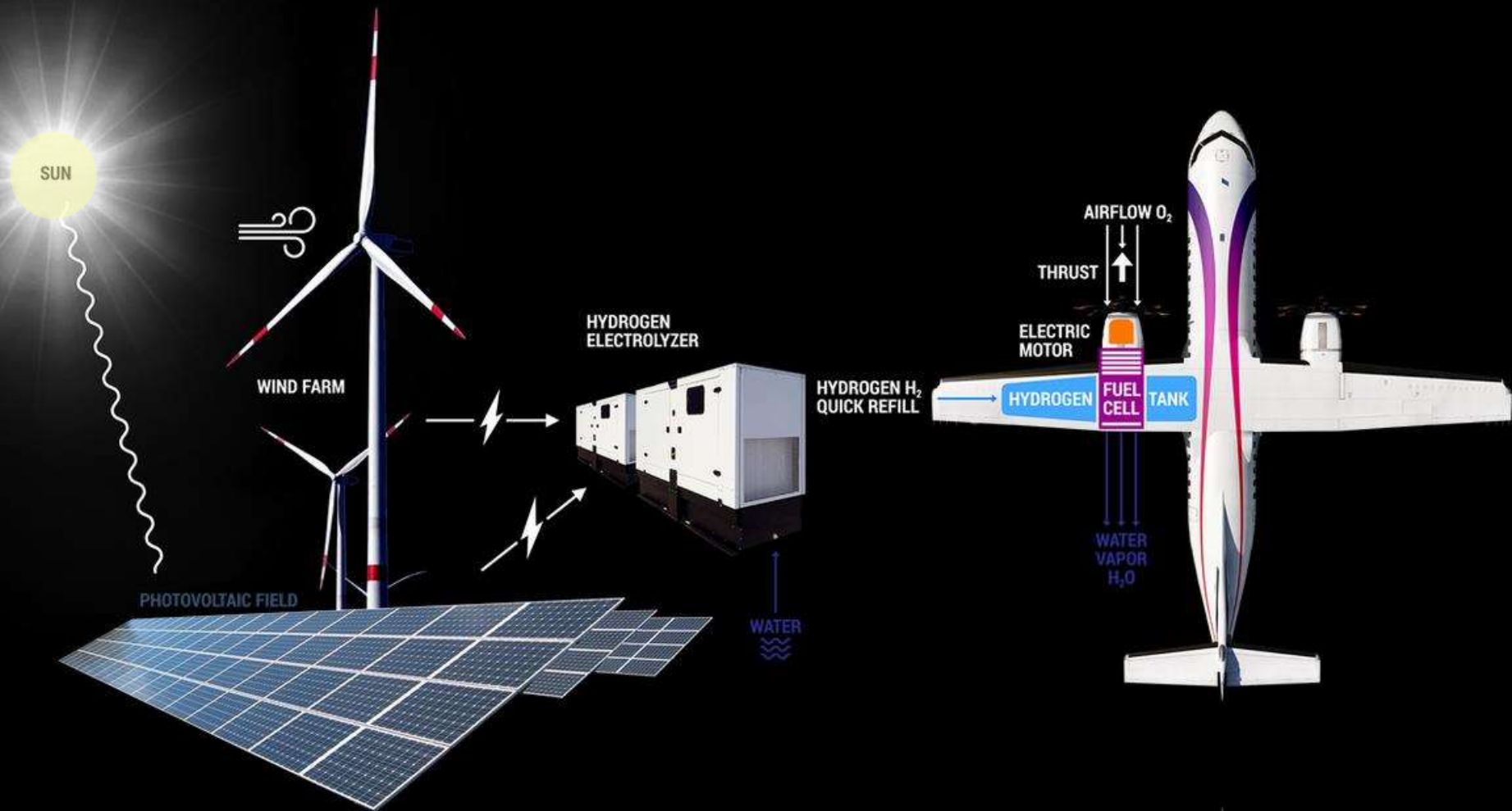


Source: from Subject Zero Laboratories

Comparing Well-to-Wheel Efficiency



Well-to-Prop Cost for Fuel Cell Electric Aircraft



Hydrogen Maybe Suited to Larger Aircraft

Airbus ZEROe Concept



Blended-Wing Body (BWB)
The exceptionally wide interior opens up multiple options for hydrogen storage and distribution. Here, the liquid hydrogen storage tanks are stored underneath the wings. Two hybrid hydrogen turbofan engines provide thrust.

Turboprop
Two hybrid hydrogen turboprop engines, which drive the six bladed propellers, provide thrust.



Introducing Airbus ZEROe

Maybe entering service by 2035

Turboprop



<100
Passengers



Hydrogen
Hybrid Turboprop
Engines (x 2)



1,000+nm
Range



Liquid Hydrogen
Storage & Distribution
System

Blended-Wing Body



<200
Passengers



Hydrogen
Hybrid Turbofan
Engines (x 2)



2,000+nm
Range



Liquid Hydrogen
Storage & Distribution
System

Turbofan



Hydrogen
Hybrid Turbofan
Engines (x 2)



Liquid Hydrogen
Storage & Distribution
System

AIRBUS

Source: announcement by Airbus on September 2020

Use hydrogen as fuel or in fuel cells may have much higher Specific Energy than lithium batteries, but

- fuel cells' specific power is lower
- the more electric power supplied from fuel cells, the more heat generated
- in cold weather temperature, have to warm up the fuel cell stacks first
- expensive to manufacture due the high cost of catalysts (platinum)
- fuel cells technology still being refine
- difficult to economically manufacture hydrogen at local charging stations
- lack of infrastructure to support the distribution of hydrogen to charging stations. Extremely difficult to get hydrogen to roof top vertiports

Use hydrogen as fuel or in fuel cells may have much higher Specific Energy than lithium batteries, but

- can lose hydrogen in storage just due to “boiloff”**
- NASA requires 30 meters safety zone for fueling hydrogen**
- Helen Leadbetter of UK ATI says takes 175 minutes to fill the hydrogen tank for a regional aircraft**
- not practical to do produce hydrogen at local airport or vertiport because it takes megawatts to do electrolysis**
- purity of hydrogen is also an issue, hard to get aerospace grade H₂**
- hydrogen fire can be difficult to see in day light**
- Double the aircraft hydrogen tank size can double the range**

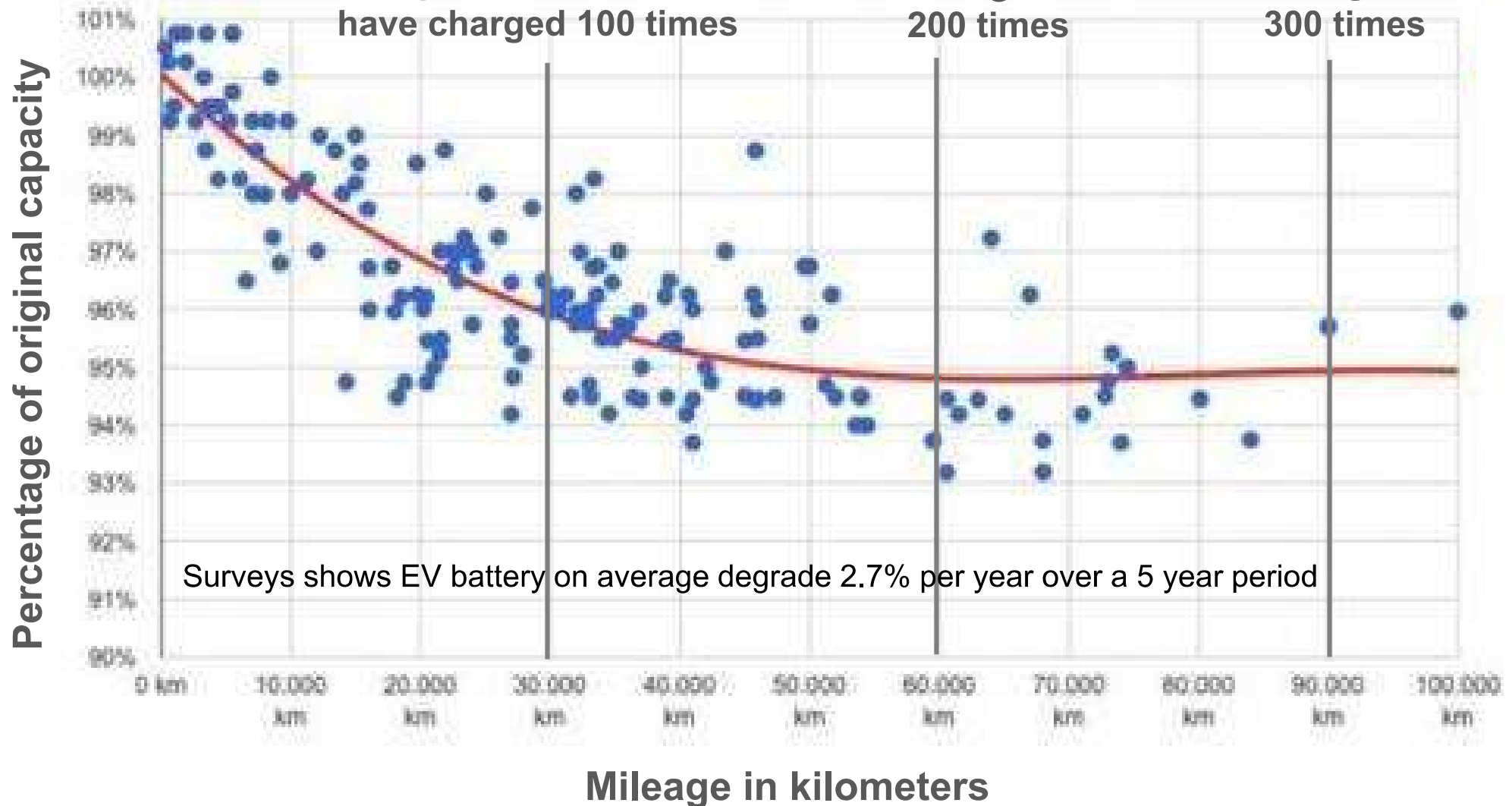
Battery Life

Lithium Battery Capacity Degrades Over Time

If range is 300 km from a full charge, then 30,000 km means have charged 100 times

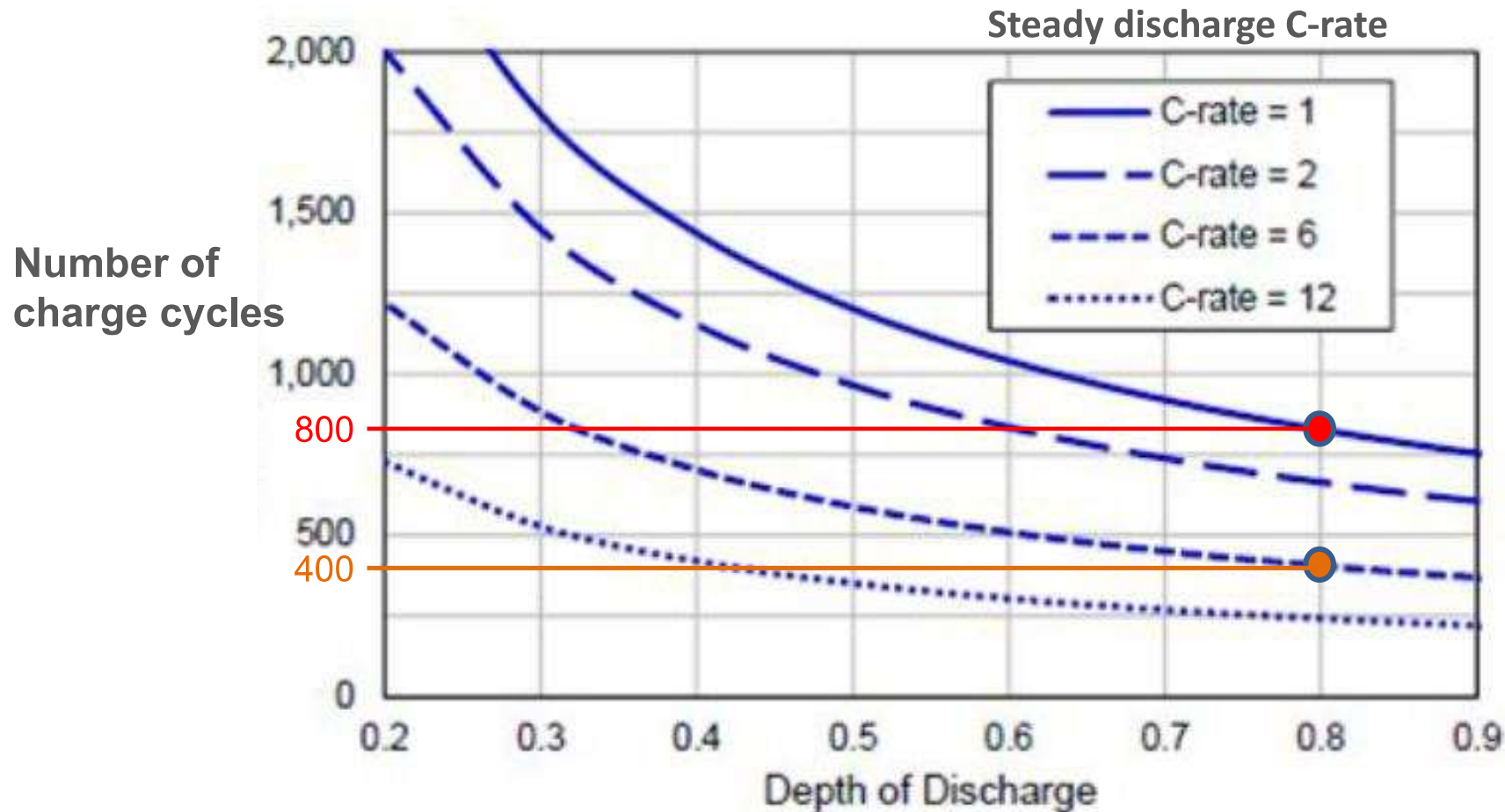
Charged 200 times

Charged 300 times



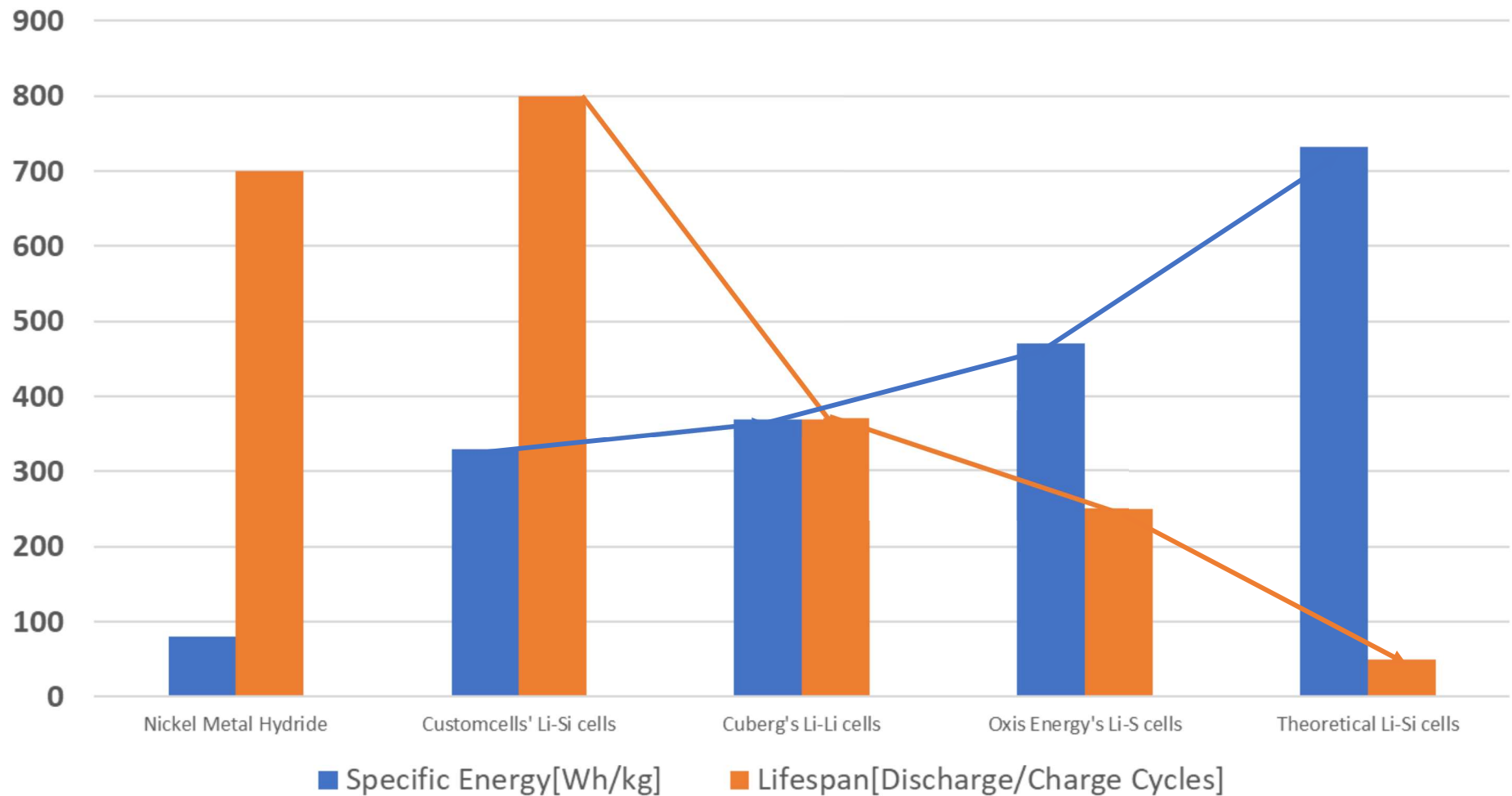
Note, it is very bad for lithium batteries to run them completely empty and then charge. Should not run them beyond 80% depth of discharge.

Effect of Discharge Rate on Charge Cycles



- 1.Scott, R.C., Vegh., J.M., "Progress Toward a New Conceptual Assessment Tool for Aircraft Cost," 76th Annual Vertical Flight Society Forum, 2020.
- 2.Liu, Z., Tan, C., Leng, F., "A Reliability-Based Design Concept for Lithium-Ion Battery Pack in Electric Vehicles," Reliability Engineering & System Safety, vol. 134, pp. 169-177, 2015.
- 3.Singh, P., Chen, C., Tan, C. & Huang S., "Semi-Empirical Capacity Fading Model for SoH Estimation of Li-Ion Batteries," Applied Sciences, vol. 9, 2019.
- 4.Zhou, C., Qian, K., Allan, M., Zhou, W. "Modeling of the Cost of EV Battery Wear Due to V2G Application in Power Systems," IEEE Transactions on Energy Conversion, vol. 26, no. 4, pp. 1041-1050, Dec. 2011.
5. Vegh., J. M., "VFS Short Course on Introduction to Practical Cost Estimating Methods for VTOL" June 2021

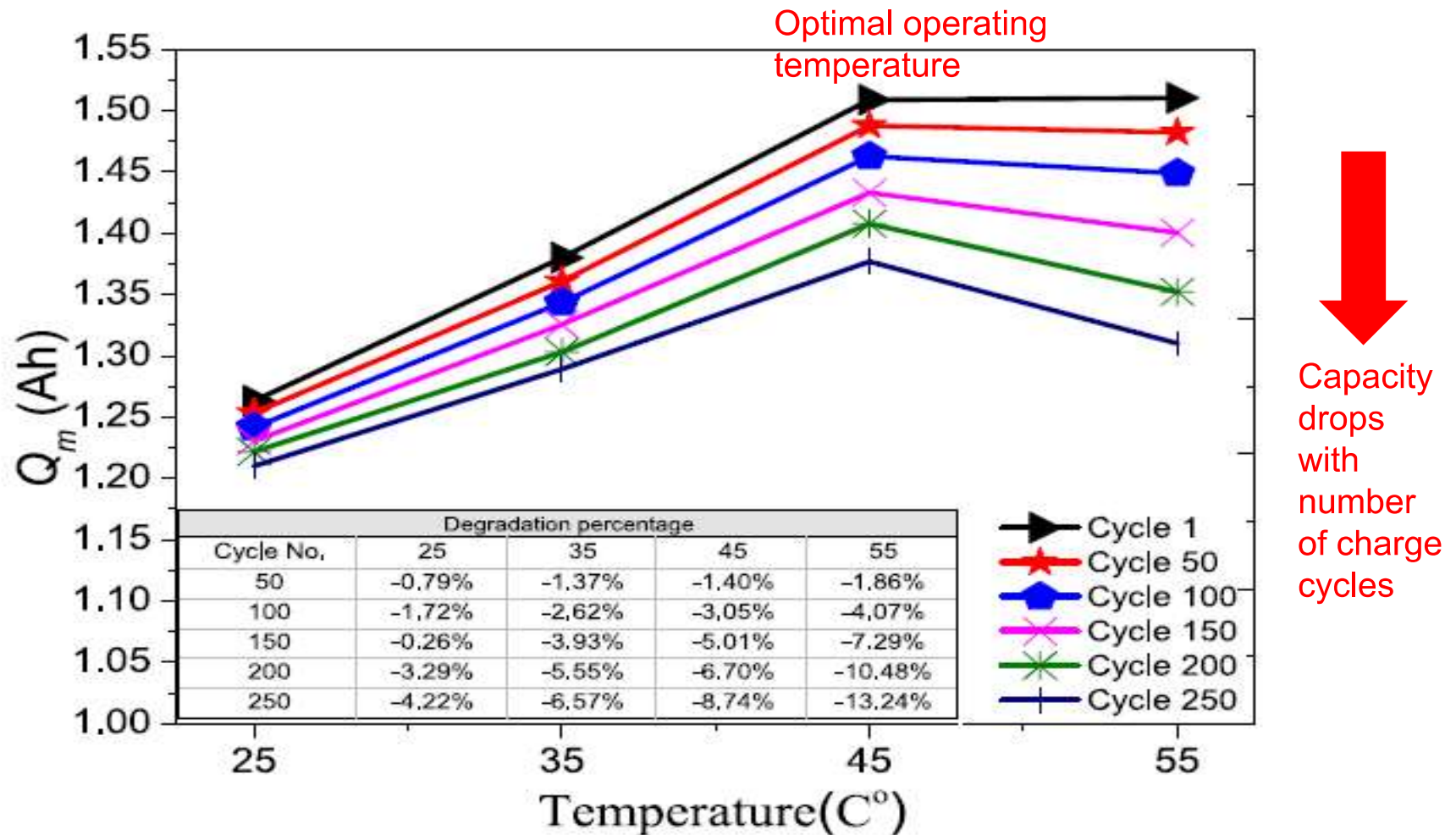
Higher Specific Energy → Fewer Charge Cycles



Today's lithium cells may last hundreds of full cycle charges if they are treated gently.

For now, do not count on them to last over 400 charges for eVTOL usage.

Maximum Charge Storage Capacity as a Function of Cell Operating Temperature

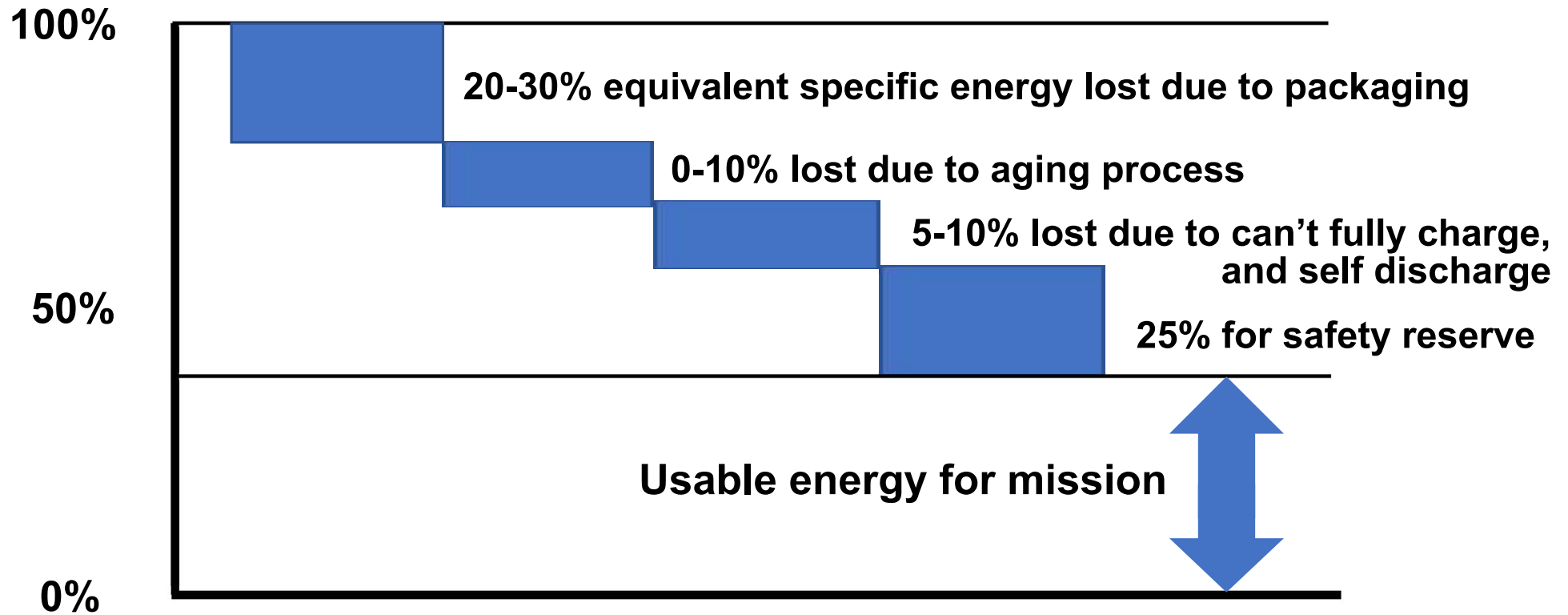


Q_m is the initial maximum charge stored in lithium-ion cell, it's measured in amp-hours. Above shows at higher operating temperature, the cell will lose more capacity with charge cycles.

Source: Leng, F., Tan, C. & Pecht, M. Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature. Sci Rep 5, 12967 (2015). <https://doi.org/10.1038/srep12967>

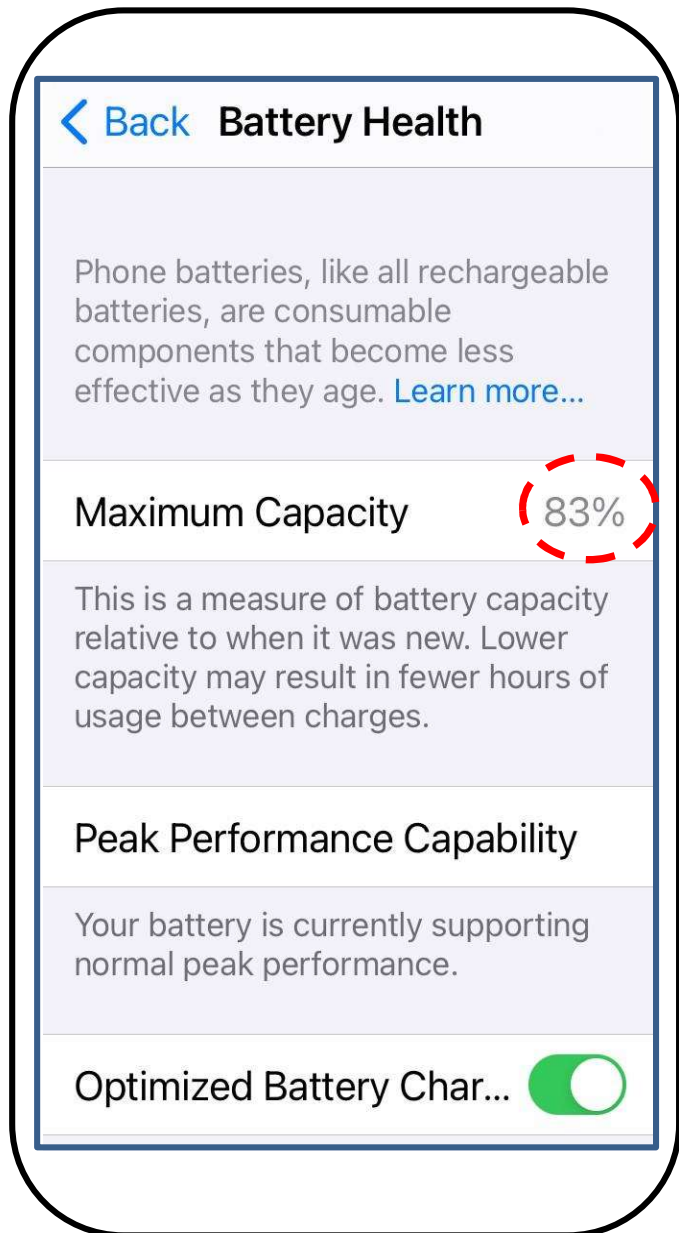
Real Usable Capacity From a Lithium Cell

Cell's usable energy



When a company goes for an aircraft endurance or speed record, they use good batteries !

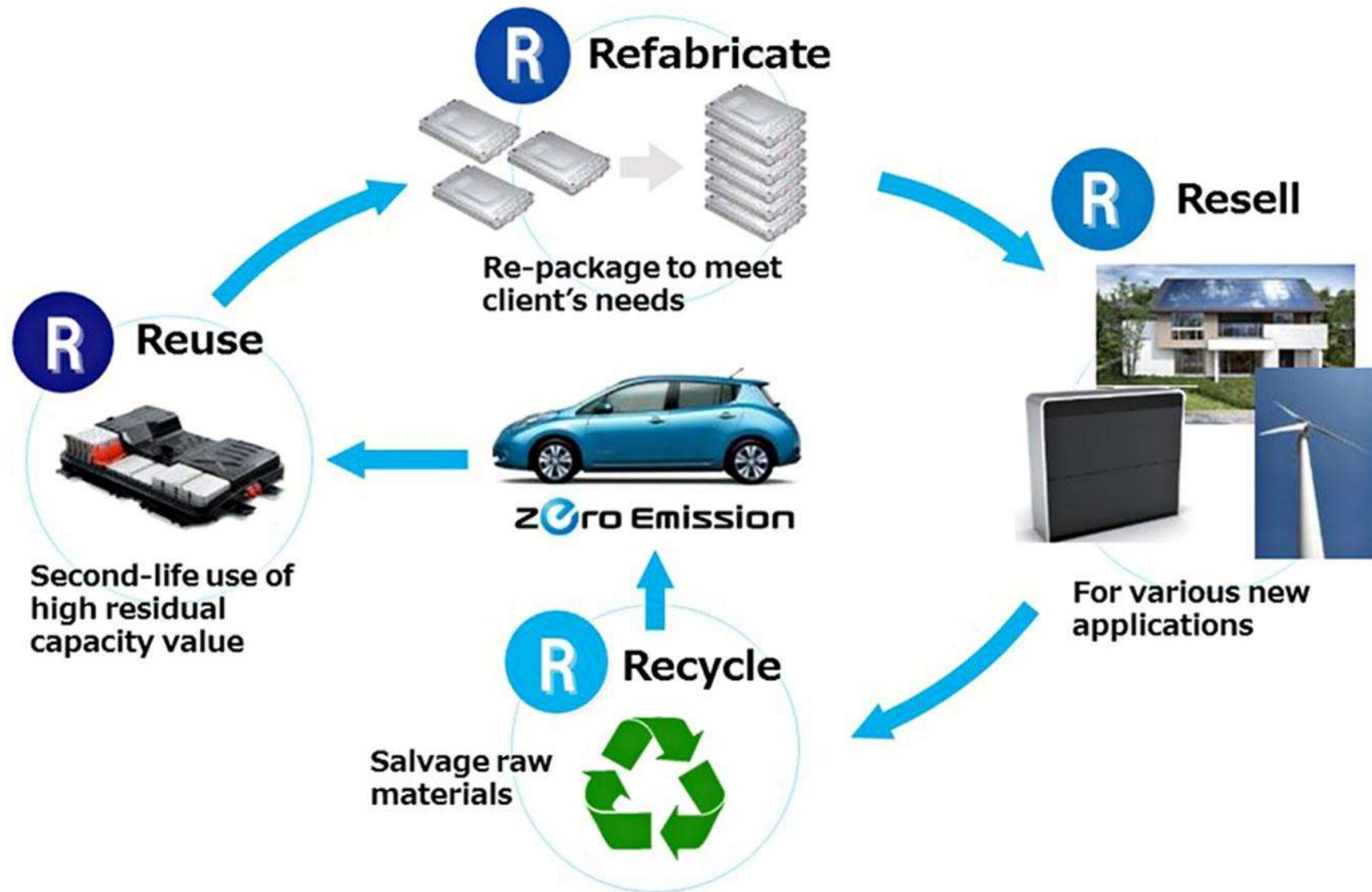
When to Retire the Battery?



- As battery ages, its internal impedance goes up, hence, the ability to deliver peak power goes down, that can become dangerous,
- its maximum capacity will drop.
- In iPhones you can see the battery health. When it gets to 83%, the iPhone just does not last a day of use.
- For EV, the car is still drivable when battery health goes down to 75%
- For eVTOLs, should replace the battery when the health reaches 90%.

What to do with Retired Batteries?

Scope of 4R Business

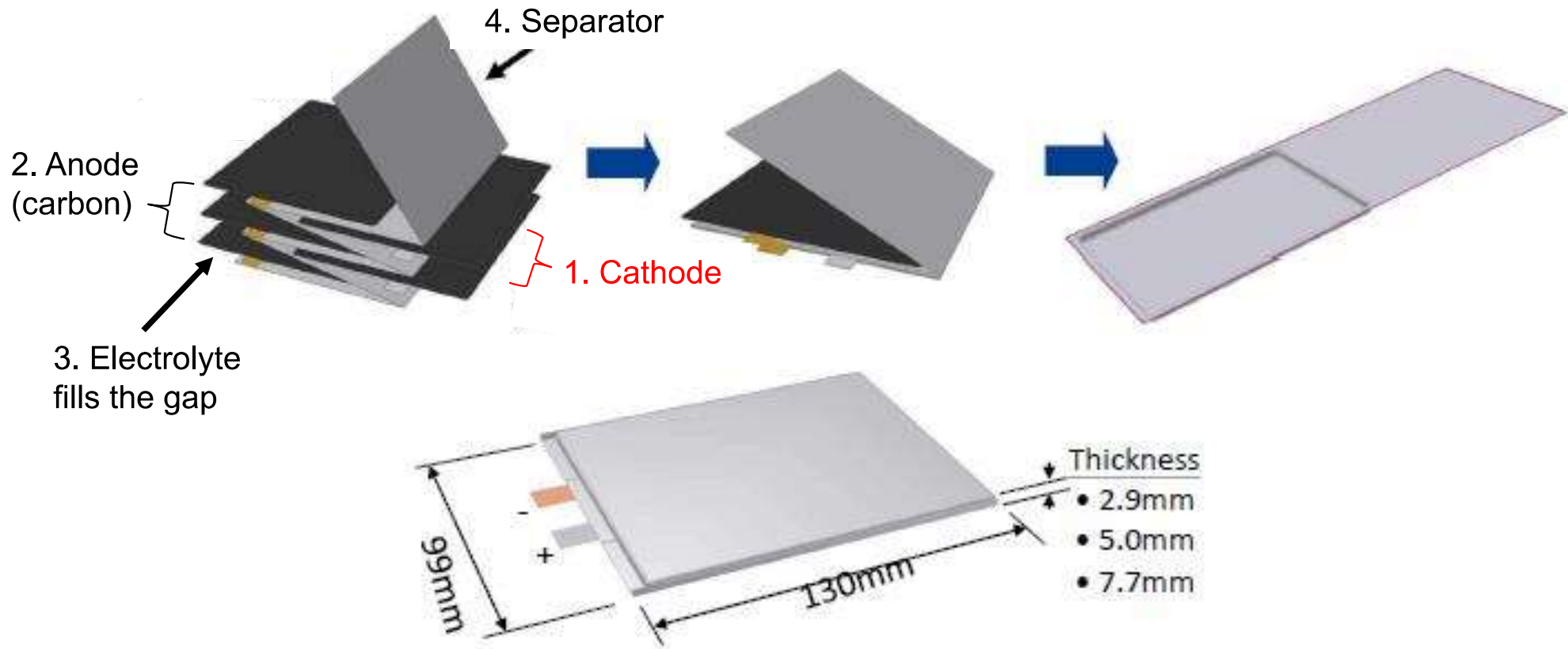


Beta Technologies Uses Second Life Batteries for Vertiport



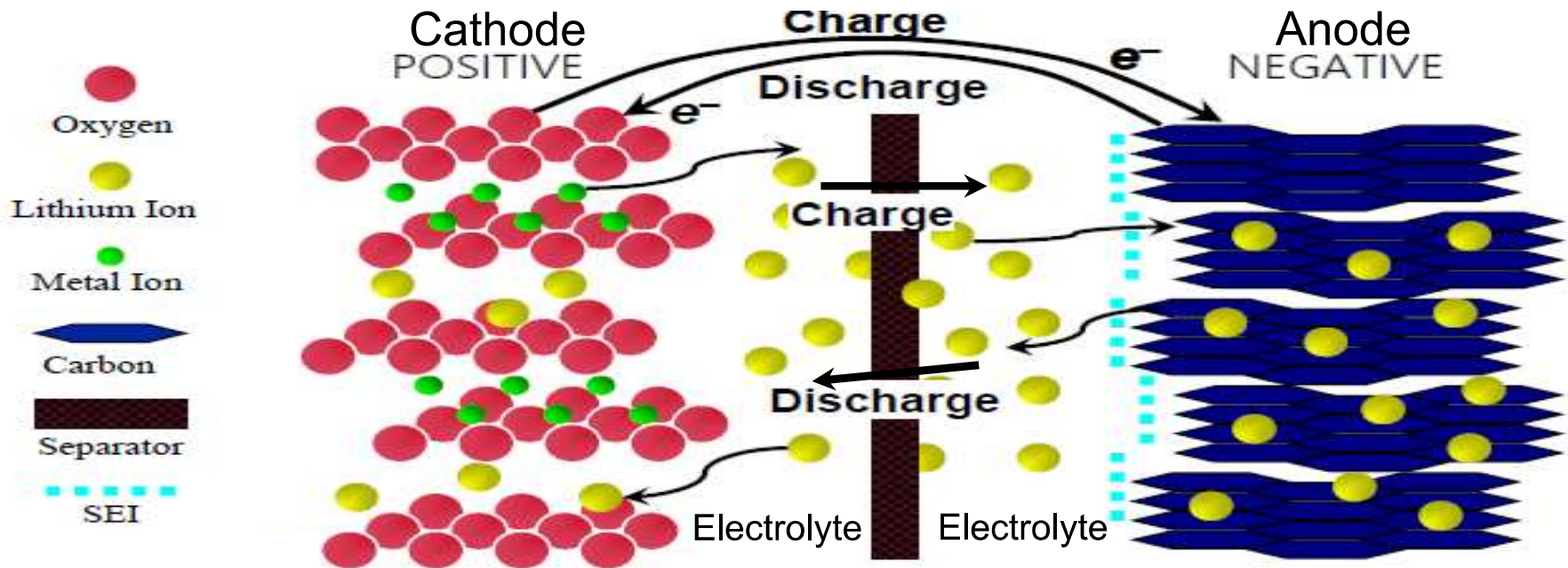
Battery Construction and Safety

Four Major Components of a Lithium Cell



1. Lithium oxide is used for the cathode as the active material.
2. When charged, lithium ions are moved to and stored in the anode.
3. The electrolyte is composed of salts, solvents and additives. Electrolyte has high ionic conductivity, is mainly used so that lithium ions can move back and forth easily.
4. Separator functions as a physical barrier keeping cathode and anode apart. It prevents the direct flow of electrons and it lets only ions pass through the microscopic hole. Separators are made from polyethylene (PE) and polypropylene (PP)

Internal Dynamics of a Lithium Cell

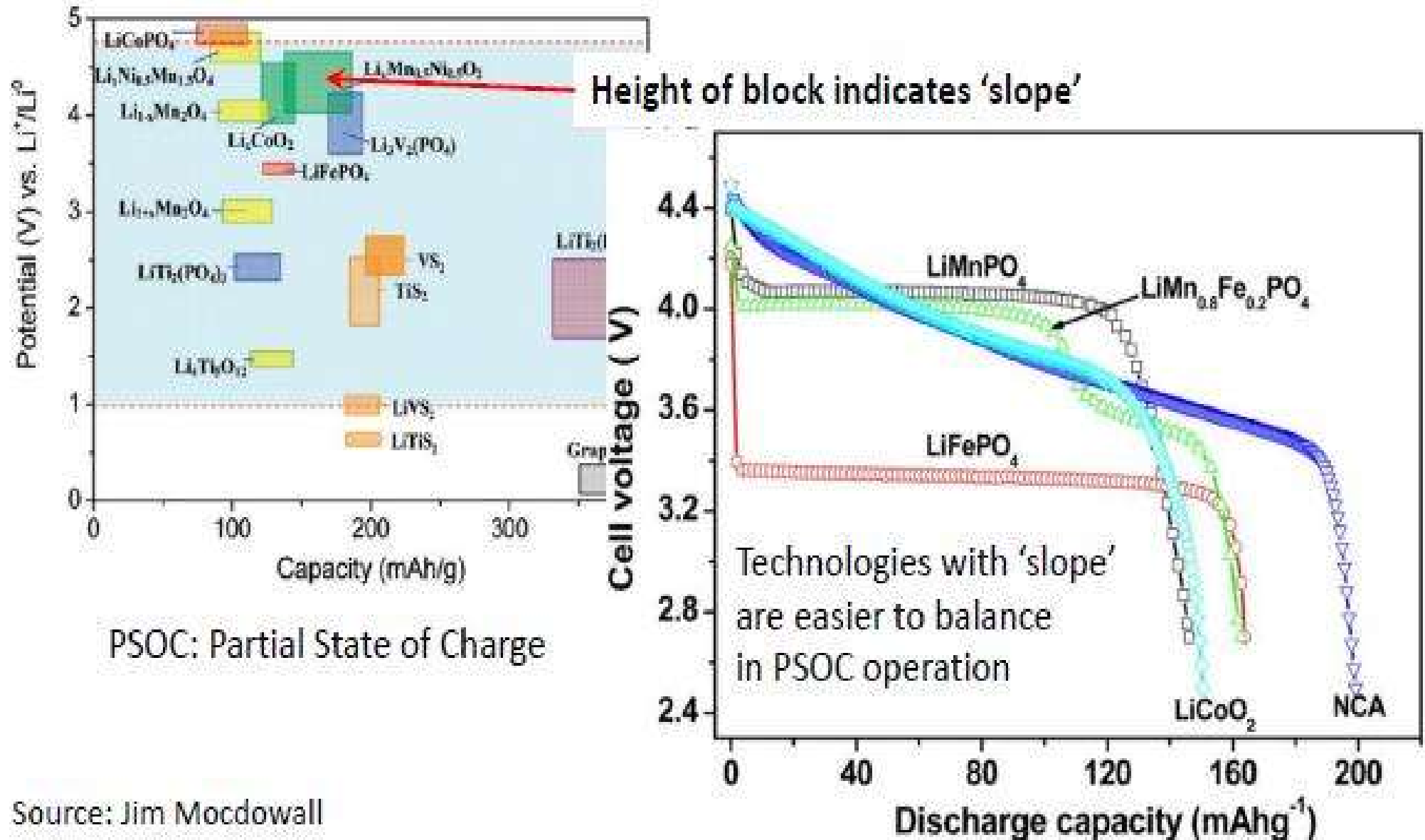


- A Lithium-ion battery generates electricity through chemical reactions of lithium.
- Lithium oxide (lithium + oxygen) is used for the cathode as the active material.
- When charged, lithium ions are moved to and stored in the anode.
- During discharge the lithium ions flow back to the cathode through the electrolyte and the negatively charged electrons e^- flow through the wire.
- The electrolyte is composed of salts, solvents and additives. Electrolyte has high ionic conductivity, is mainly used so that lithium ions can move back and forth easily.
- Separator functions as a physical barrier keeping cathode and anode apart. It prevents the direct flow of electrons and it lets only ions pass through the microscopic hole.
- Cathode and anode determine the basic performance of a battery, electrolyte and separator determine the safety of a battery.

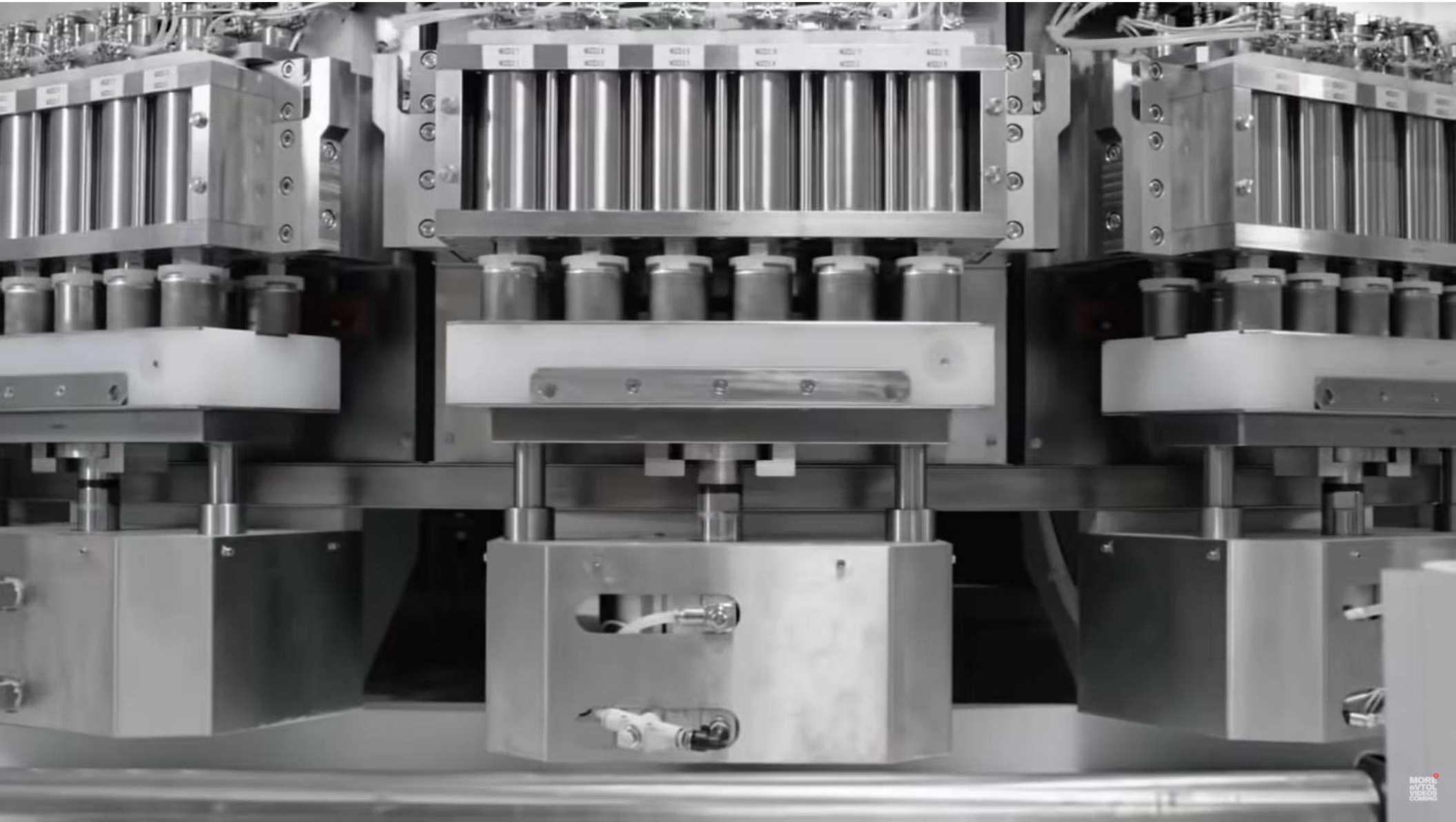
Sources: Jim Mccodwall and Samsung how lithium cell works:

<https://www.samsungsdi.com/column/technology/detail/55272.html?pageIndex=1&idx=55272&brdCode=001&listType=list&searchKeyword=>

Starting Voltage and Discharge Rate



Cylindrical Lithium Cell Manufacturing



Cylindrical Lithium Cell Manufacturing

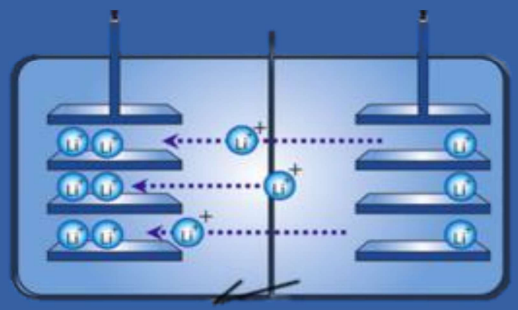
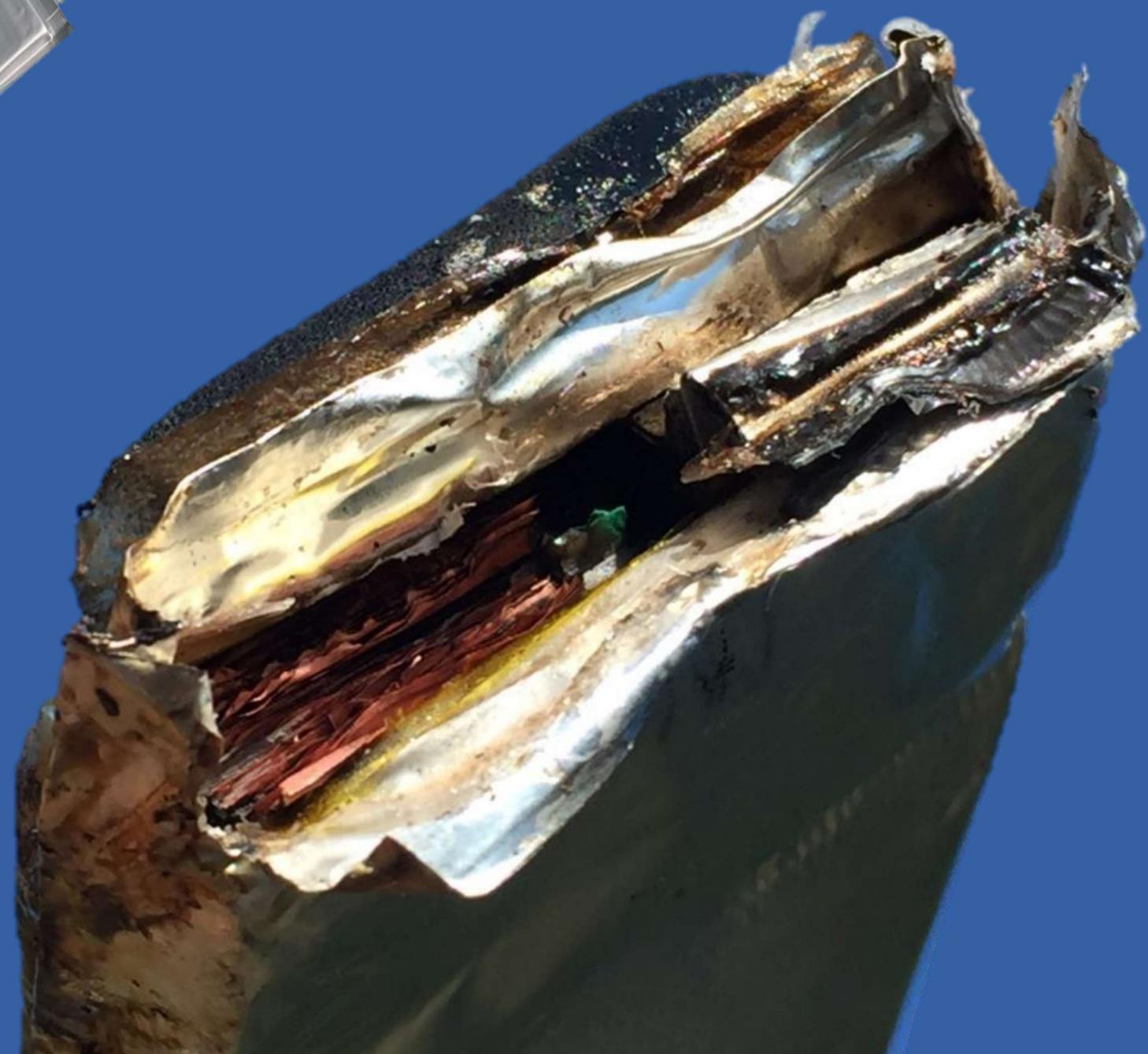


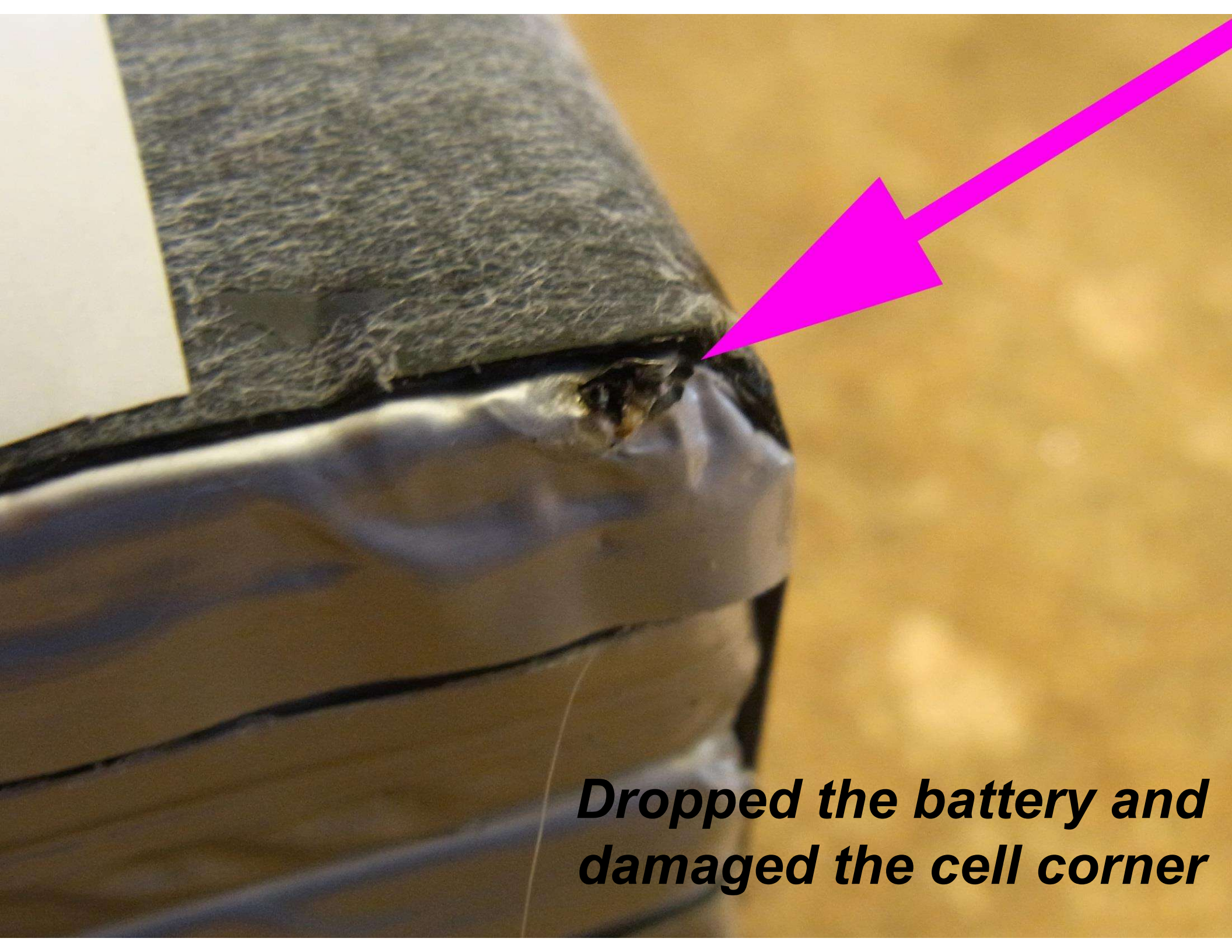


**Example of a
good 5S pack**



**Example of a
damaged 6S pack**



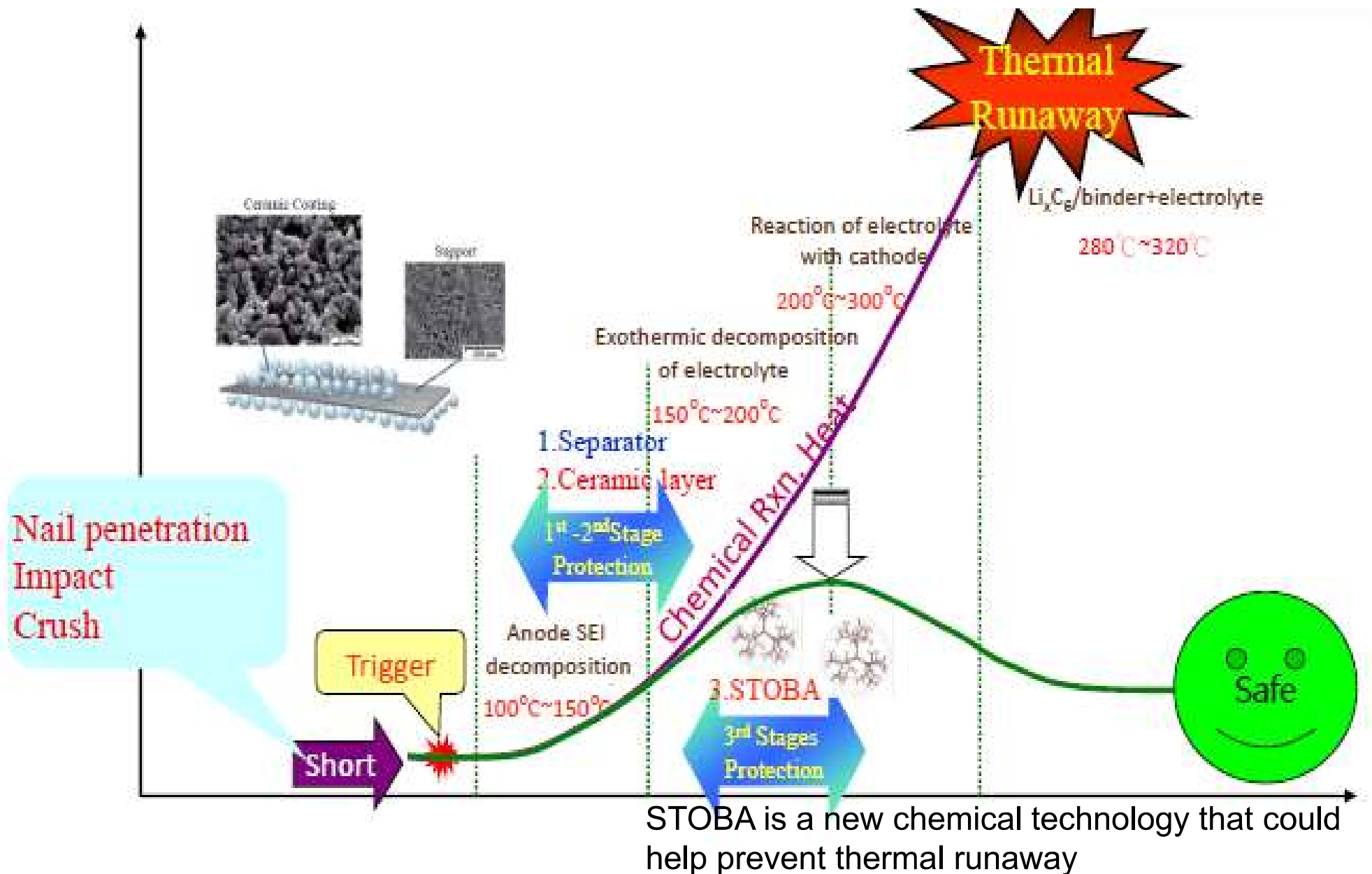


***Dropped the battery and
damaged the cell corner***



Torn Open and Charred Cell

Thermo Runaway is When the Internal Temperature of a Lithium Cell $> 150^{\circ}\text{C}$





Example of a damaged pack due to sustained high current drain. Internal heat caused a single cell burst but did not reach thermo runaway to cause a fire.

Lithium Fires Are Almost Impossible to Stop



A Crash Can Cause Battery to Ignite

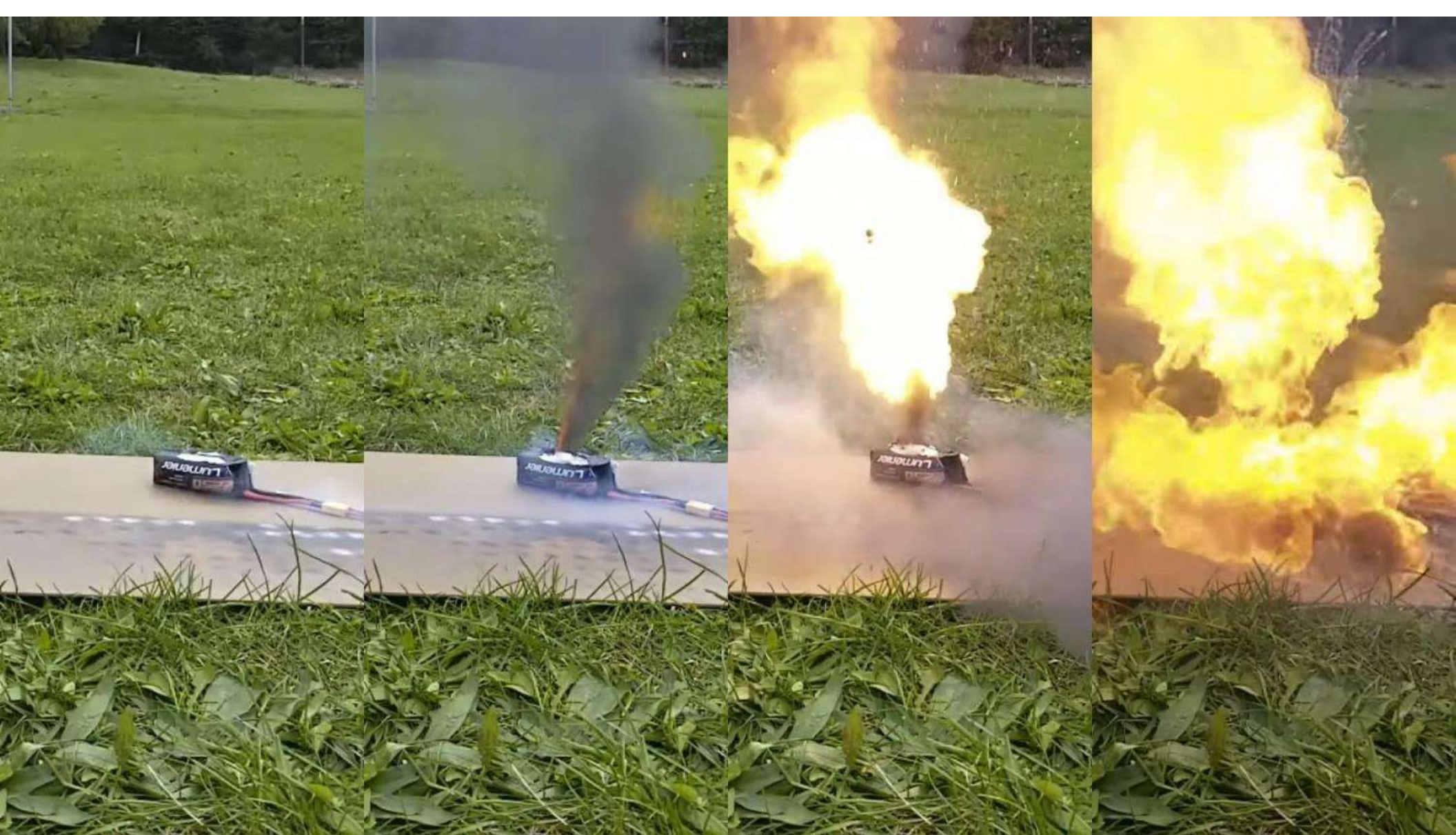


Fire Can Happen During Charging



Spontaneous Fire Destroyed Buses in 20 Min





There are manufacturers making lithium pouch for fire containment, but they are too heavy for flight. They are useful for charging and putting out fire.

Fire Protection Bags and Covers



Common Tests for Lithium Batteries

- Heating
- Cold temperature
- Impact
- Crush
- Short circuit
- Nail penetration
- Corner cut
- Abnormal charging and discharging
- Extremely high current draw
- Deep discharge

JW Rule of Thumb for Using Lithium Battery

- 1. Higher C capable cells are heavier.**
- 2. If you need to discharge at 5C then buy 10C cells.**
- 3. Not all manufacturers are equal !!**
- 4. Discharging at higher C reduces cell life.**
- 5. Do not discharge to below 20% of capacity.**
- 6. Charging at higher C reduces battery life. <2C is best now**
- 7. Best store the cells at around only 50% fully charged.**
- 8. Always balance the cells while charging.**
- 9. Cell capacity and voltage will degrade with use.**
- 10. Do not physically damage the cell.**
- 11. Do not use the cells if they are damaged or impaired.**
- 12. Always prepare a way to put out battery fire in emergency.**

Battery for Electric Cars

Battery Pack in Nissan Electric Car

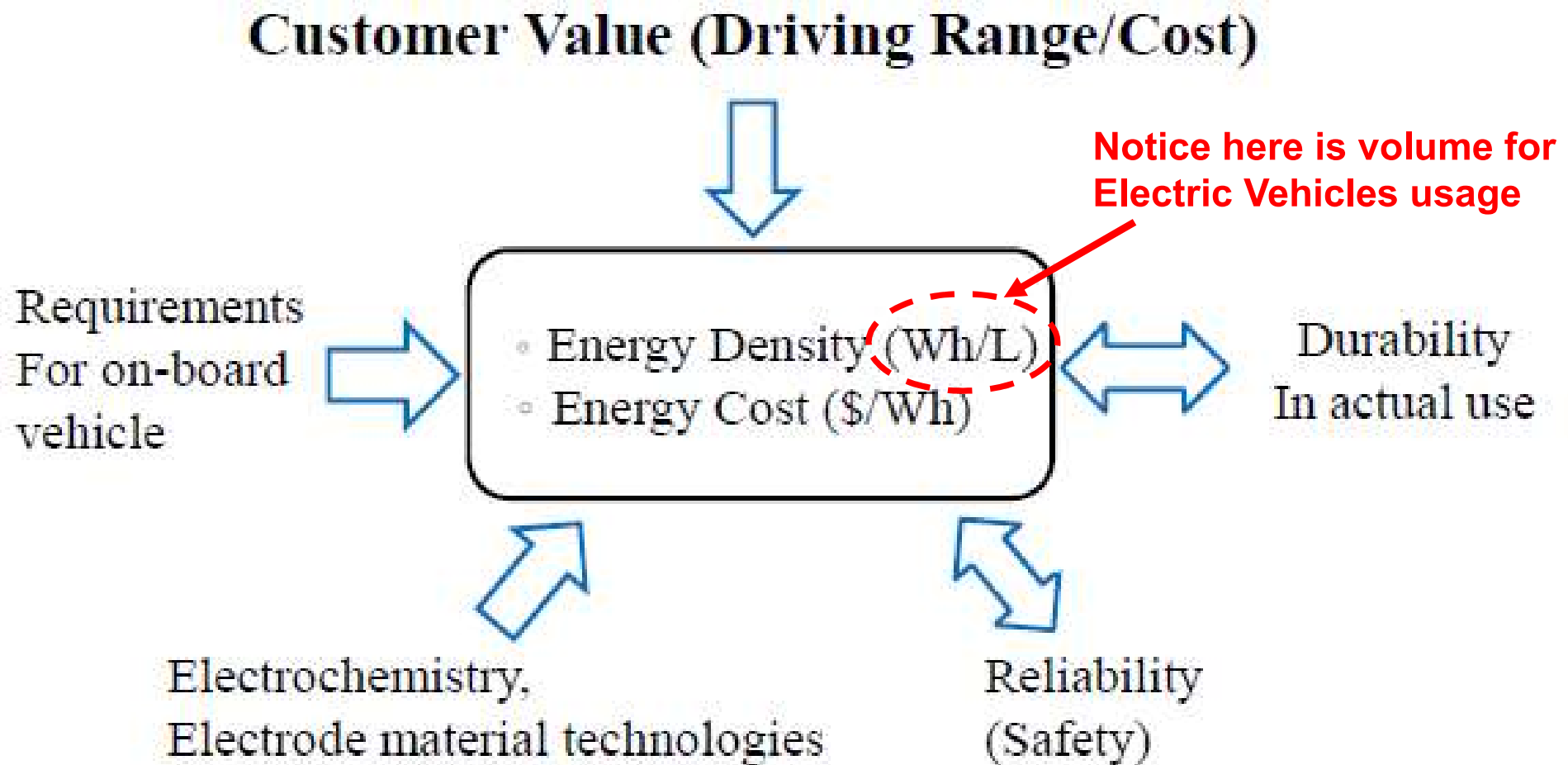


Nissan 3.Zero e+ features a 62kWh battery (with 288 cells), capable of delivering 217ps and 340Nm of torque, and resulting in a claimed driving range of 239 miles (385km) from a single charge. 97 mph top speed.

Requirements for Hybrid-Electric Vehicle Use

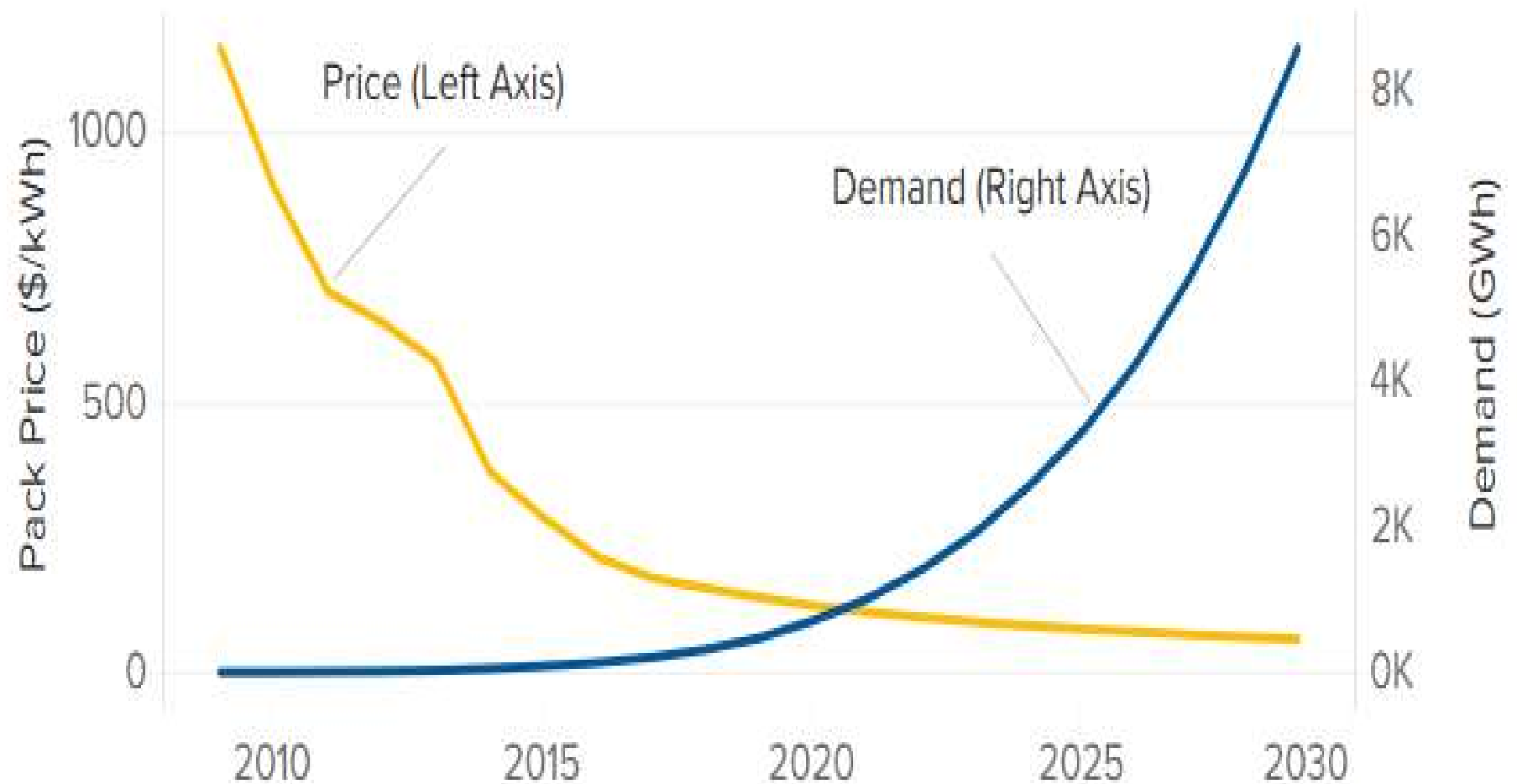
- Long service life – 10~15 years
- Wide temperature range performance -30°C to 60 °C
 - High temperature degradation
 - Low temperature degradation
- Higher power and energy density Large current
 - ⇒ input and out put power at low temperature
- Higher reliability
- Lower cost
- Recycle (reuse)

Requirements for Hybrid-Electric EV Use



Nissan's EV Battery Requirements to AESC

Li-ion Battery Market for EVs



SOURCE: Rocky Mountain Institute/BloombergNEF. Data is projected starting with 2020.

Battery Affects Purchasing Price and Operating Cost

Battery makes up 1/3 the price of electric car, and 50% of the operating cost for eVTOL aircraft.



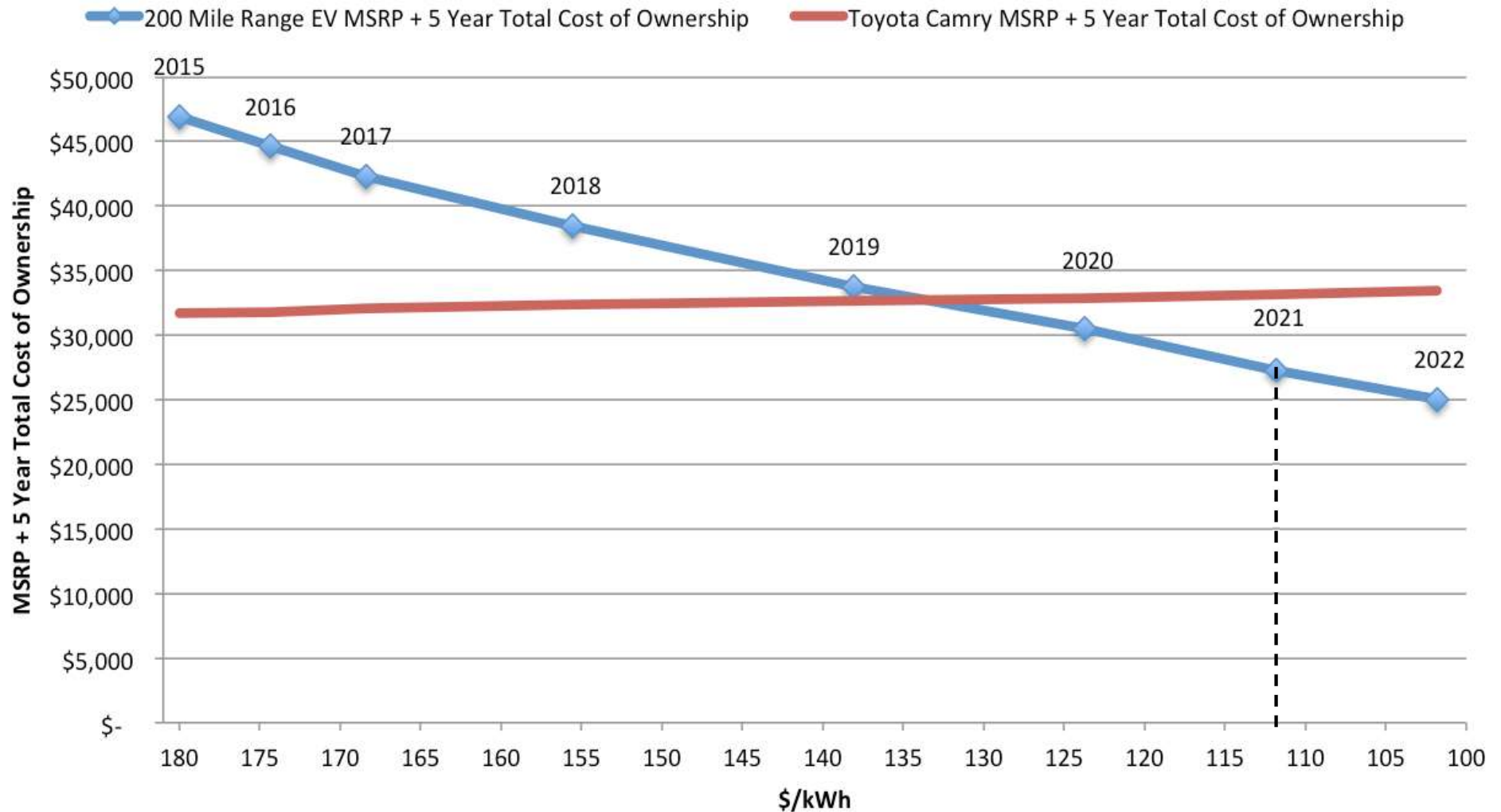
Source: BloombergNEF

Note, lithium cell price has been dropping because it has become a commodity, and 73% are made in China.

**However, expect lithium
battery price to be more
expensive for aviation use**

Today it's Cheaper to Own Electric Vehicle

Projected Price Parity Point for 200-Mile Range EV Inclusive of Five Year Total Cost of Ownership



ELECTRIC VS GASOLINE

SPECIFIC ENERGY WH/KG

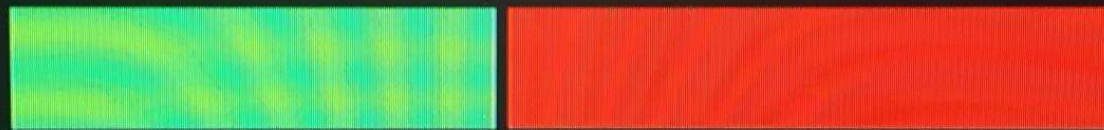
250



2,480

RANGE

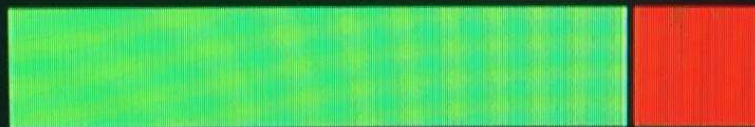
520 km



650 km

EFFICIENCY

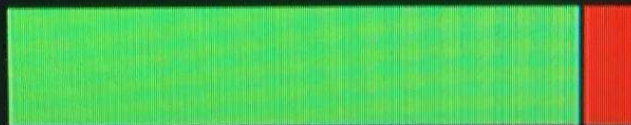
95 %



20 %

WEIGHT

310 Kg



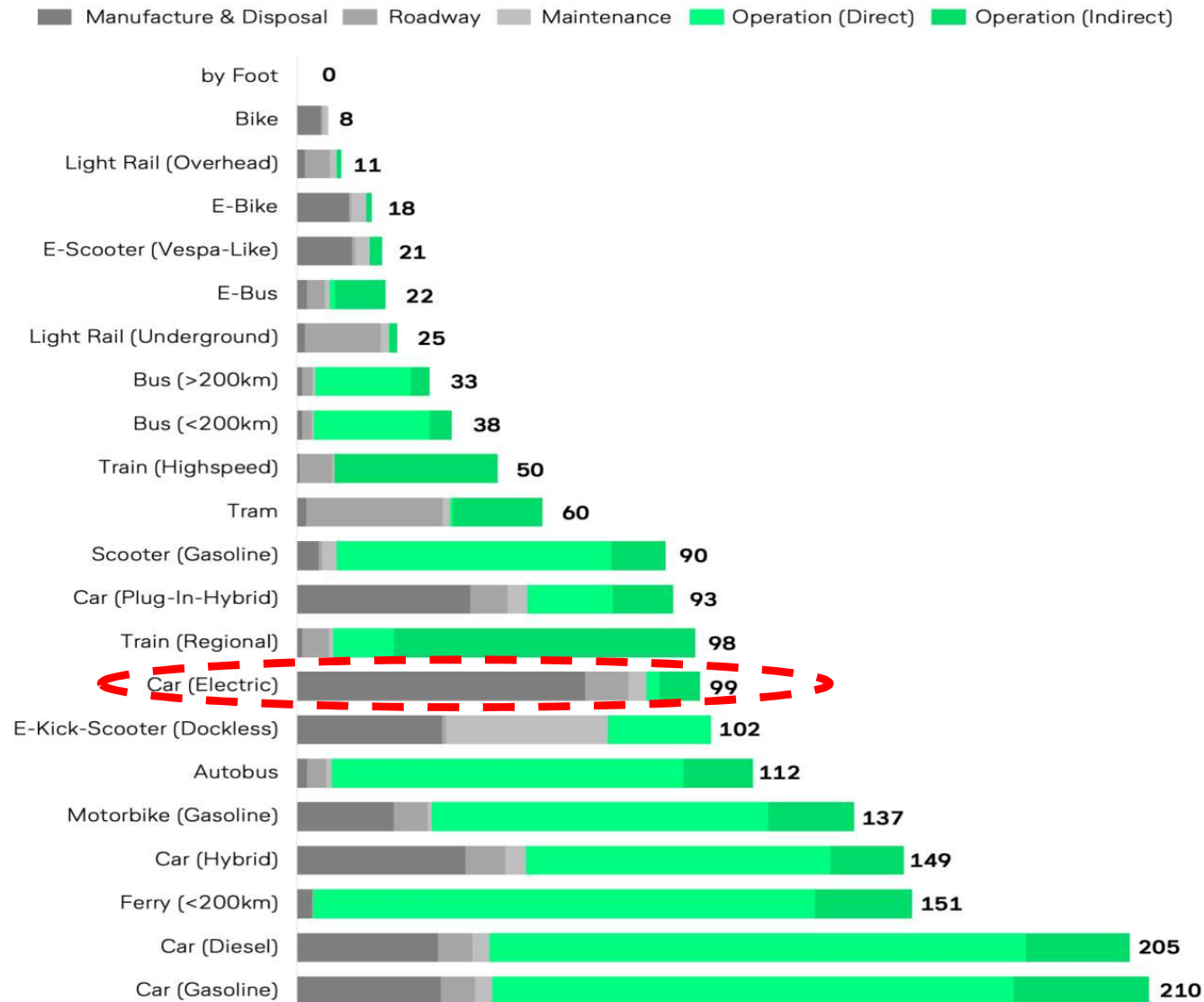
31.2 Kg

Ranking Urban Transportation Modes

TNMT

Ranking urban transport modes

Average carbon emissions by transport type (in gram per pkm)



Sources: Lufthansa Innovation Hub Analysis, TNMT.com, press and various research studies — see extra Airtable

Source: Lufthansa Hub Report 2021
https://tnmt.com/wp-content/uploads/2021/04/CO2-by-transport-type-visual_LIH.png

Electric Flight for Urban Air Mobility

Infrastructure Required at a Vertiport

SCHEDULING
MANAGEMENT

PASSENGER
FACILITIES AND
SECURITY

AIR TRAFFIC
CONTROL AND
TECHNICAL
OPERATIONS

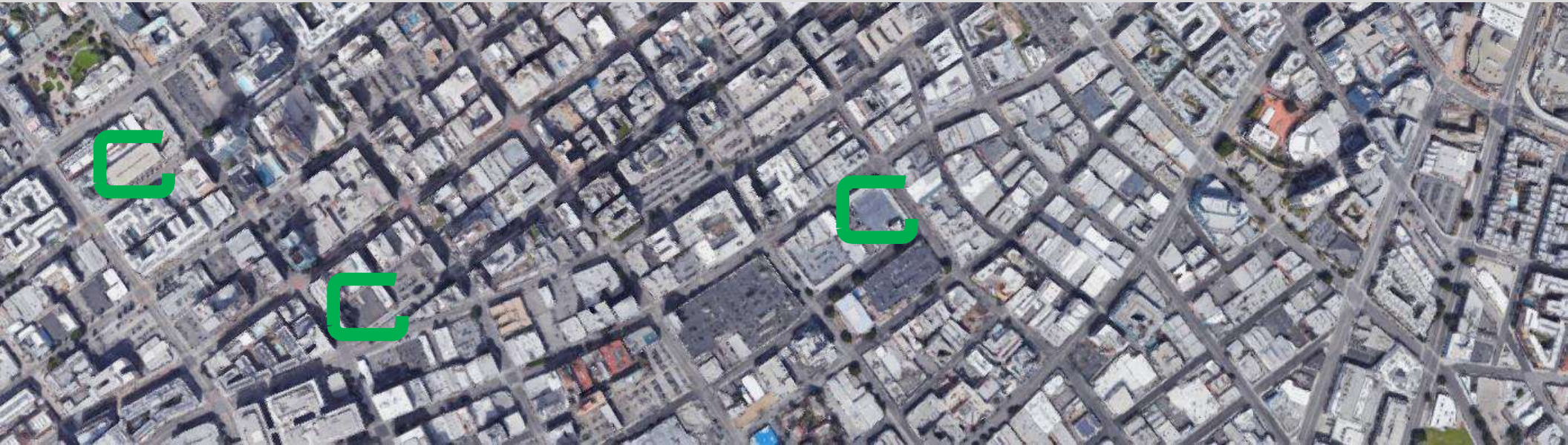
MAINTENANCE
FIRE SAFETY
PILOT WELFARE

RECHARGING /
BATTERY SWAPPING

GATES WITH
NAVIGATIONAL AIDS

TOUCHDOWN AND
LIFT-OFF AREA

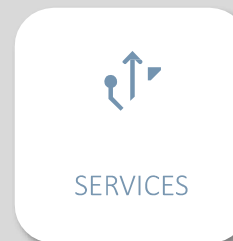
Vertiport Requirements



There are several location and site considerations in the development of a vertiport. Skyports undertake extensive site analysis and work with the landlord to assess each site for suitability



- Available footprint
- Loading capacity
- Approach and departure paths
- Multi-modal connectivity
- Weather conditions



- Power grid access and capacity
- Passenger access



- Planning permission
- Aviation regulation approval
- Emergency services approval

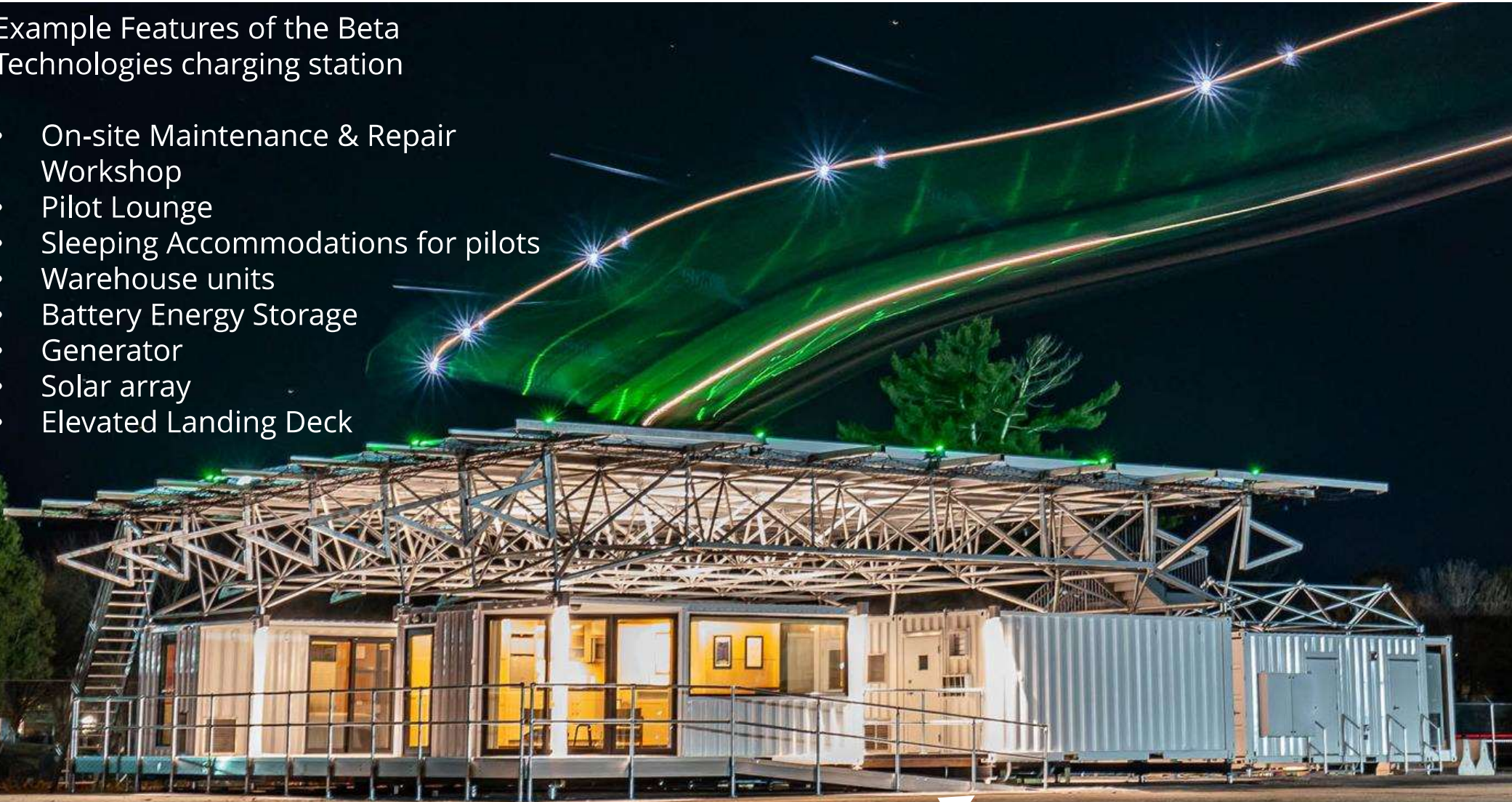


- Route & network analysis
- Passenger throughput & cash flow analysis

Vertiport and Charging Deck for Single eVTOL

Example Features of the Beta Technologies charging station

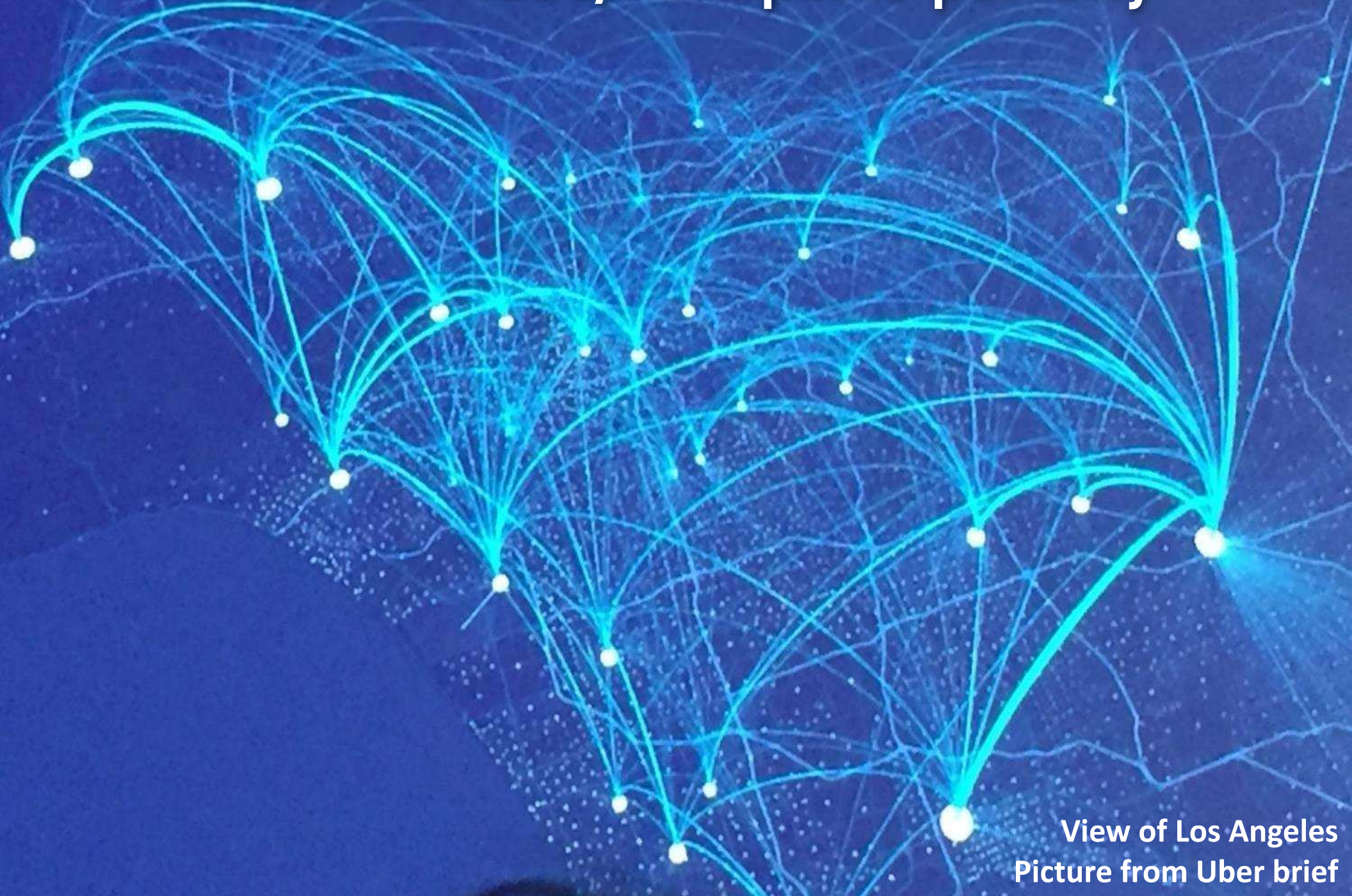
- On-site Maintenance & Repair Workshop
- Pilot Lounge
- Sleeping Accommodations for pilots
- Warehouse units
- Battery Energy Storage
- Generator
- Solar array
- Elevated Landing Deck



Spent eVTOL lithium battery can have a second life as buffer for charging stations

Source: Beta Web Site

20 to 30 Hubs/Vertiports per City



View of Los Angeles
Picture from Uber brief

Example of a Mega Vertiport



1,000 LANDINGS / HR

+ **1,000** TAKEOFFS / HR

x **5** PASSENGERS / eVTOL

= **10,000** PASSENGERS / HR

ON \leq **3** ACRES

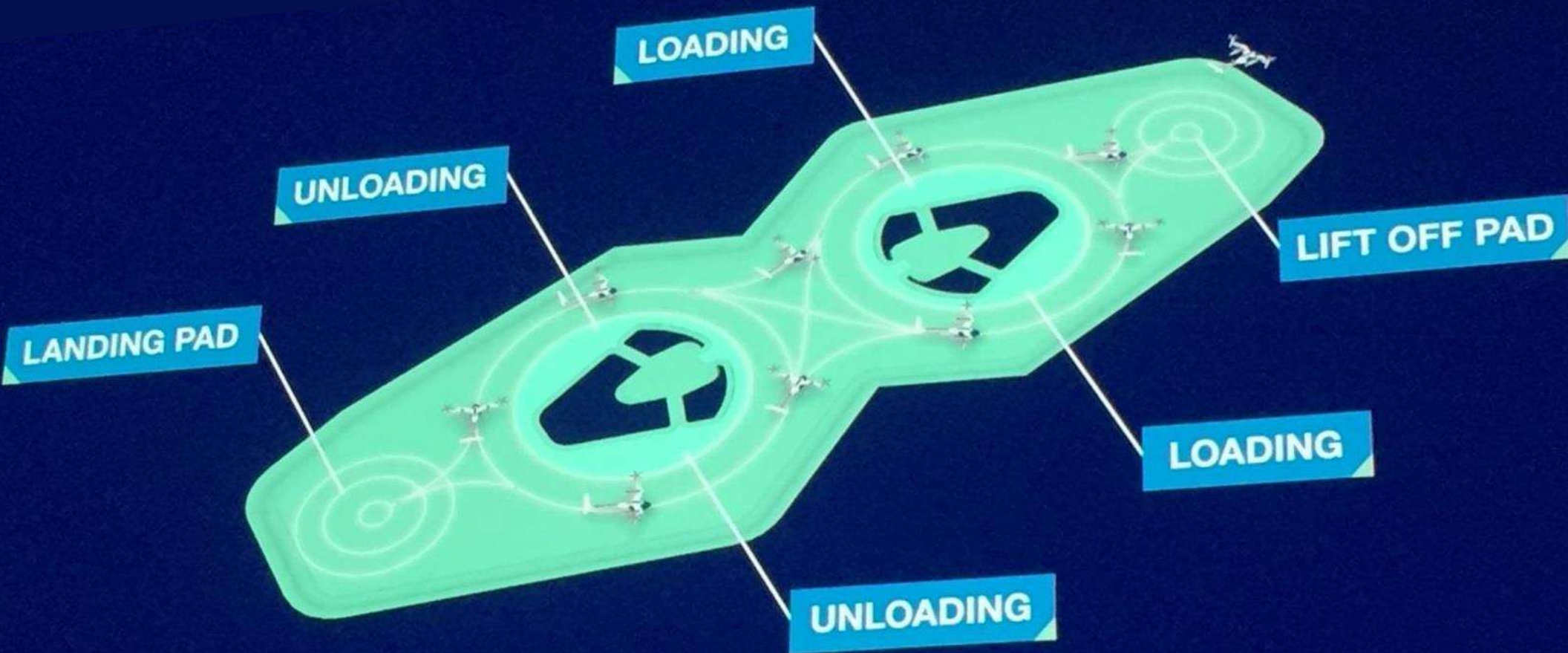
PICKARD CHILTON

Source: proposal by Uber



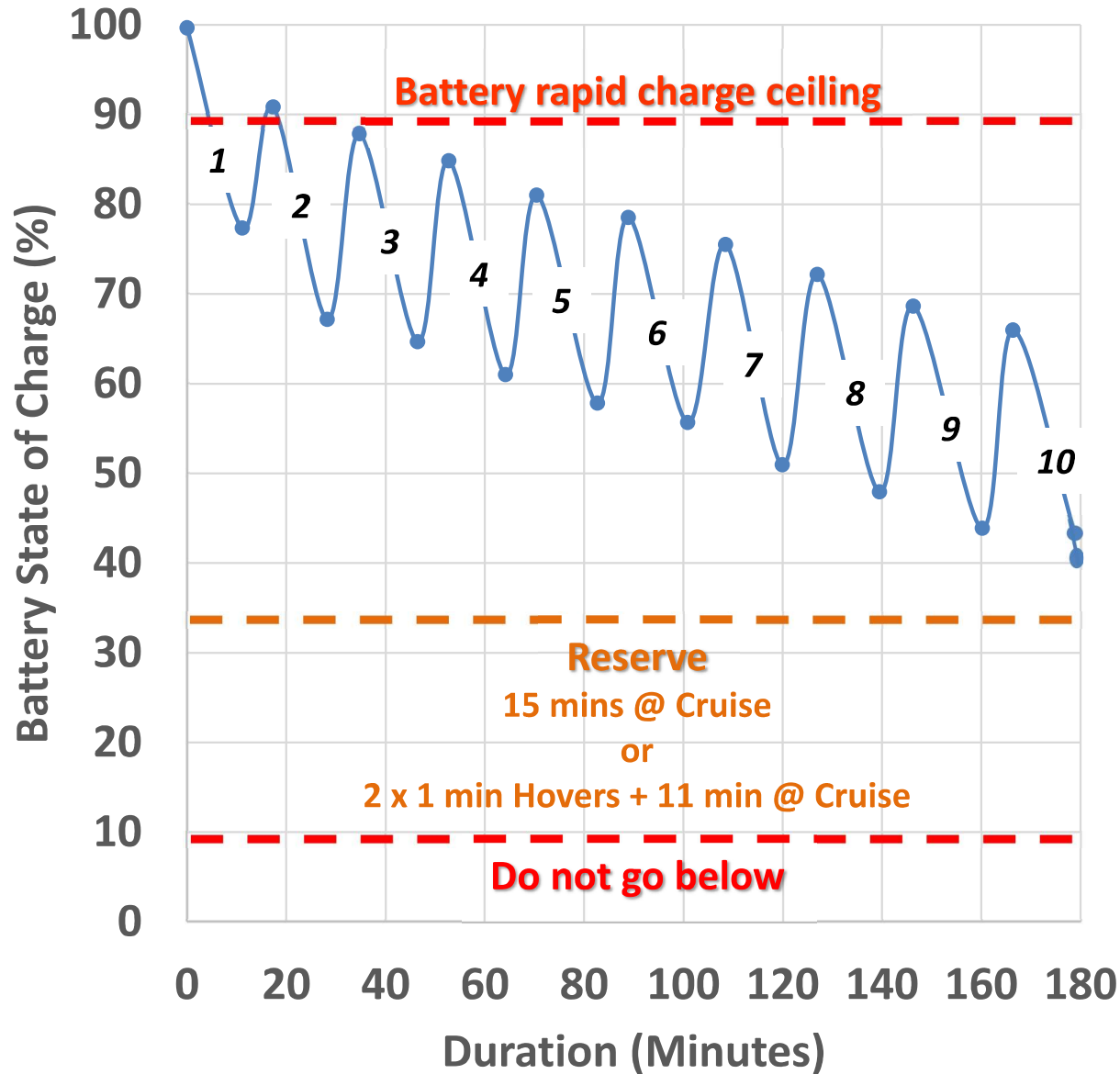
(Concept by Corgan)

6 Minutes between unloading and loading passengers
This also permits a quick charge to top off battery



(Vertiport Concept by Corgan)

Ten Missions in 3-Hour Continuous Operation



Action	Time
Takeoff	1 min
Cruise	10 min
Landing	1 min
Position/Plug	½ min
Ground Charge	6 min
Unplug/Position	½ min

Average mission 19 minutes
Ten x 25 mile missions

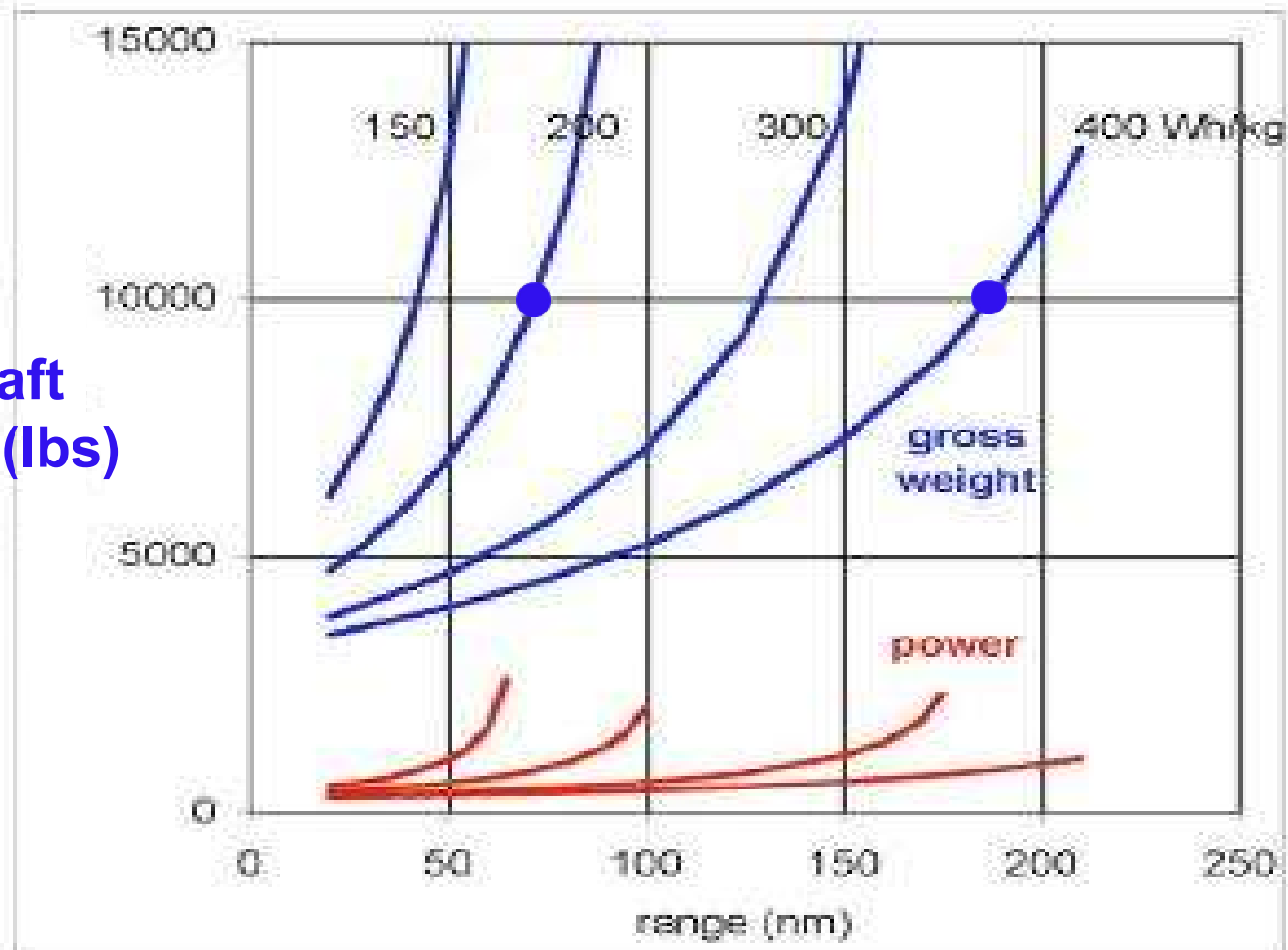
Feasibility of Concept



Electric, side-by-side, 6 passengers

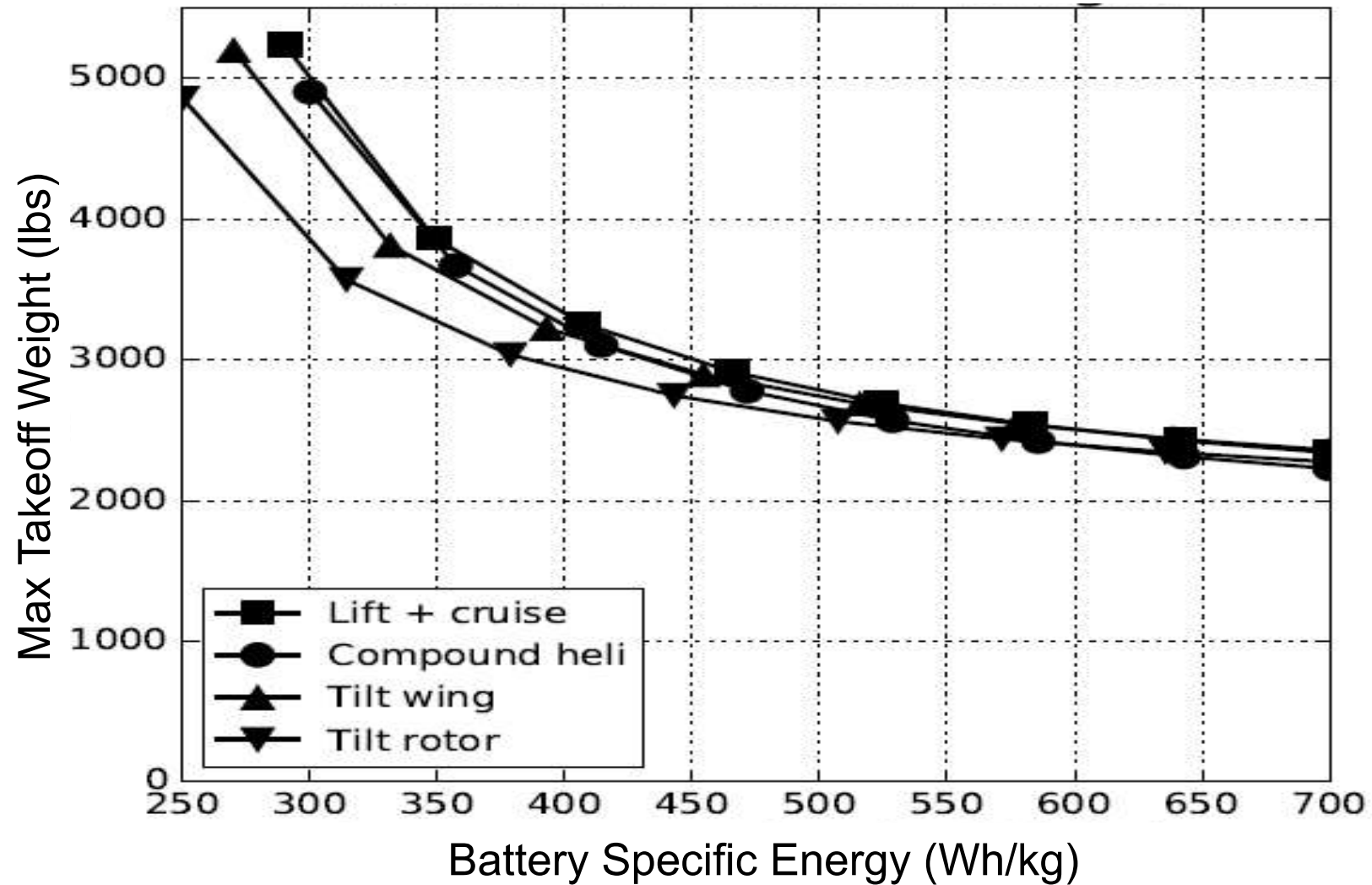


Aircraft
weight (lbs)



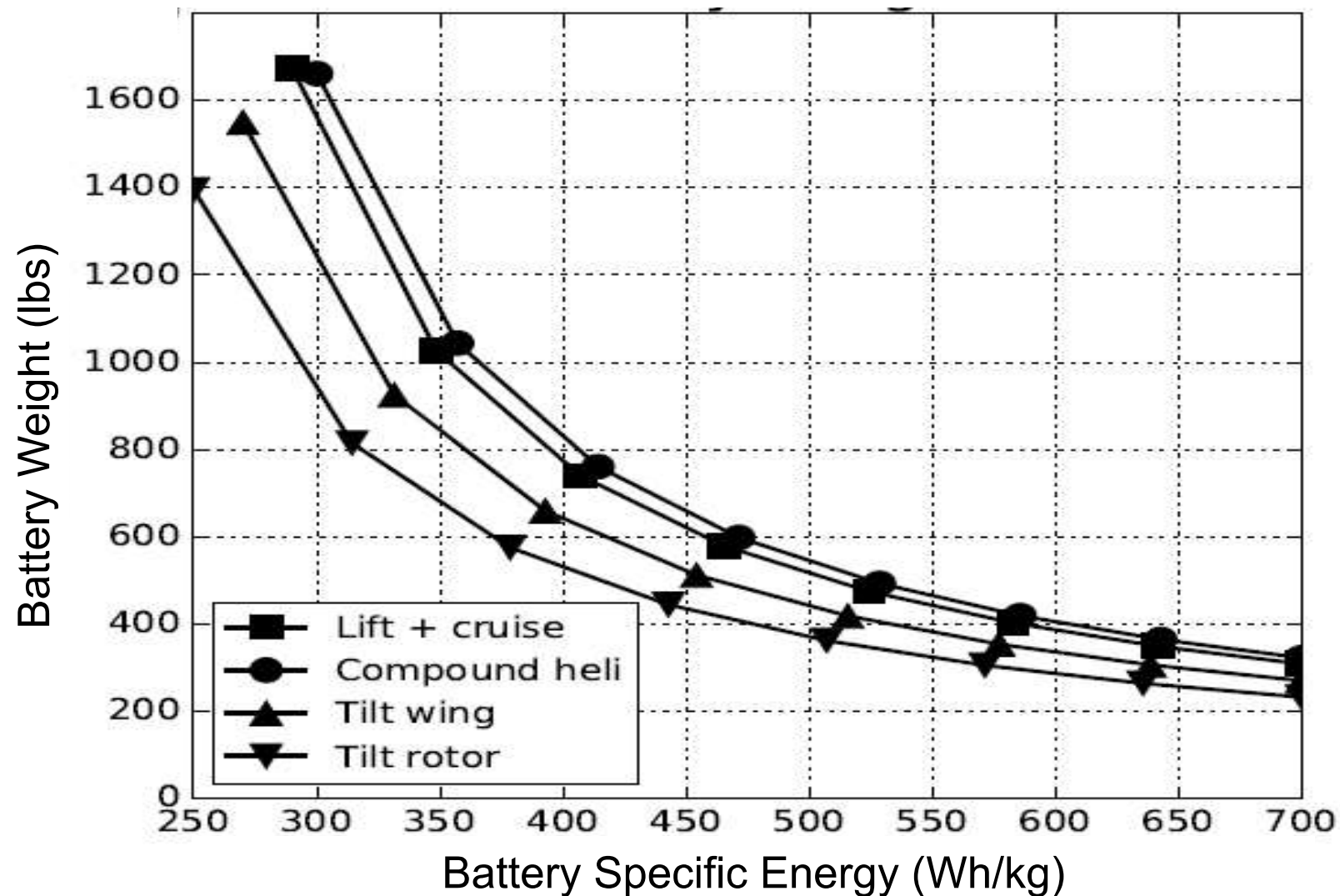
Effect of Specific Energy on eVTOL Weight

For a prescribed range, increasing specific energy helps reduce aircraft weight

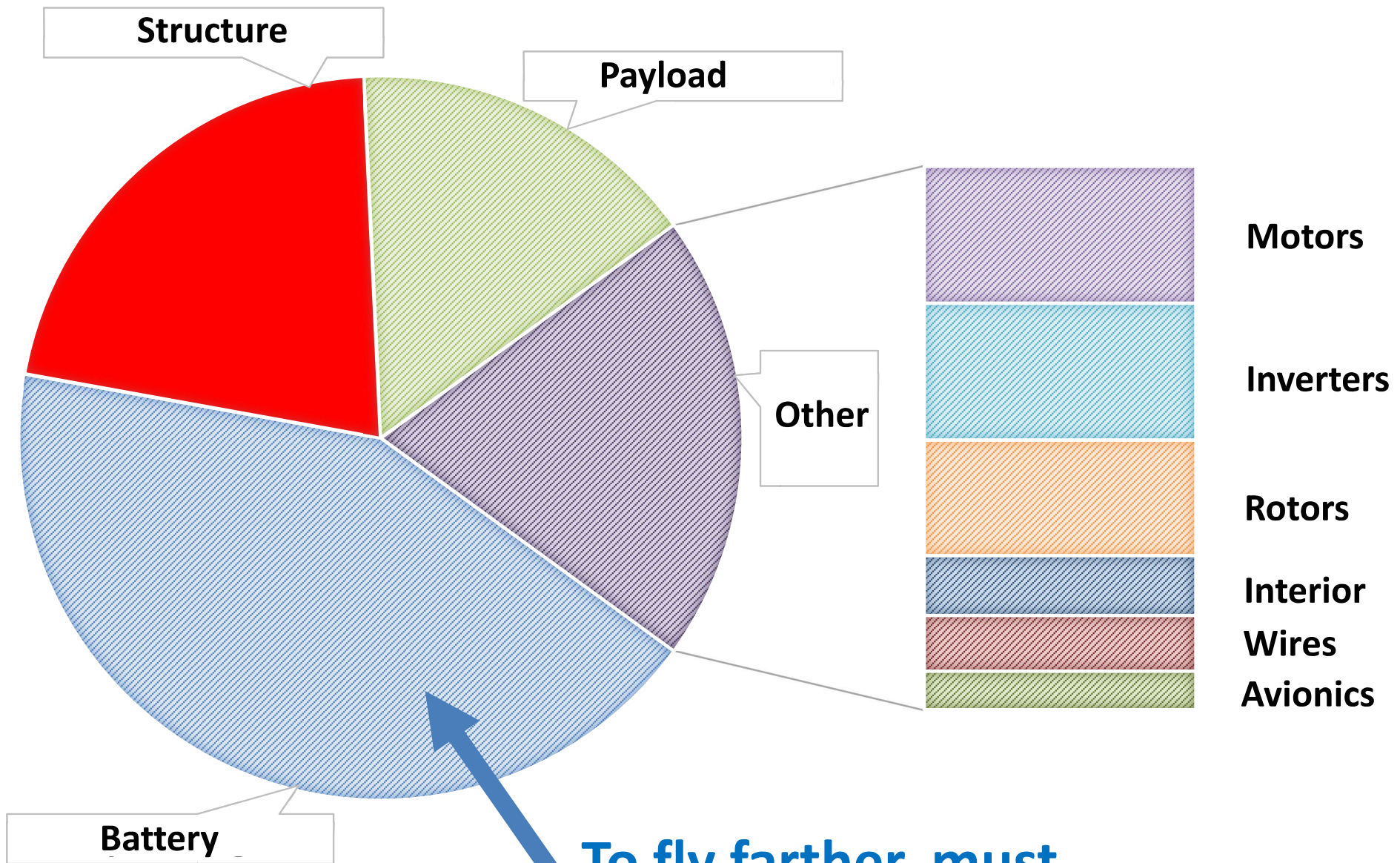


Effect of Specific Energy on eVTOL Weight

For a prescribed range, increasing specific energy helps reduce battery weight

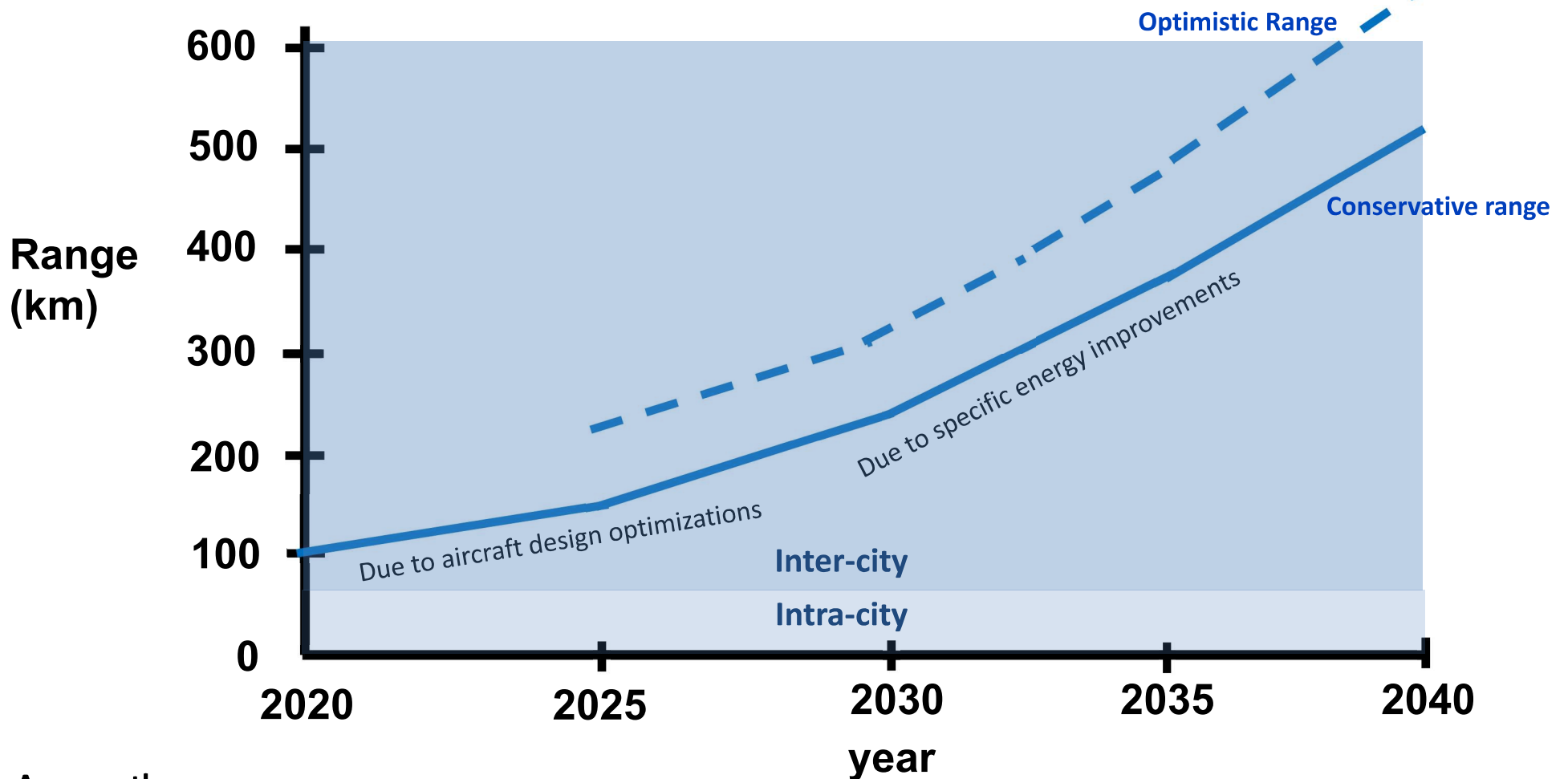


Weight Breakdown for an eVTOL Aircraft



**To fly farther, must
increase the specific energy of the battery !**

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

2. Battery and Energy Source

by Dr. James Wang

SNUevtolclass@gmail.com

For students to use in the 2022 eVTOL Design Short Course at SNU,
please do not reproduce or distribute