

Transformational Energy Storage for Planes, Trains and Ships

Dr. Halle Cheeseman, ARPA-E Program Director

May 10, 2023

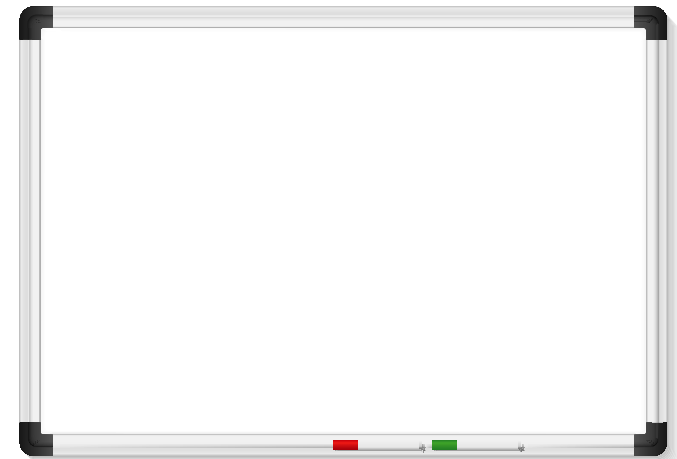
Transformational Energy Storage for Planes, Trains & Ships

ARPA-E Mission: Energy Efficiency, Energy Independence & Lower Emissions.
- Energy Resilience & Nuclear Waste Management.

- Focused Program: Frame a Problem, Identify Metrics, Solicit Solutions
- OFF Roadmap – Transformational, High Risk & Further Out

Purpose of a Workshop:

- ✓ To hear from Industry Experts
- ✓ To build a community
- ✓ To define the White Space
- ✓ To discuss possible program metrics
- ✓ Scope is Non-hydrocarbon.



ARPA-E Programs are bold and ambitious – EVs4ALL, \$42MM

i) Very Fast Charging for the 37% of Americans who will not have access to home charging



ii) Improved low temperature performance for the Americans who live in Northern States



Cut low temperature battery performance losses in half



Small Vehicles
>200Wh/kg
5 minute charging



Large Vehicles
>400Wh/kg
15 minute Charging

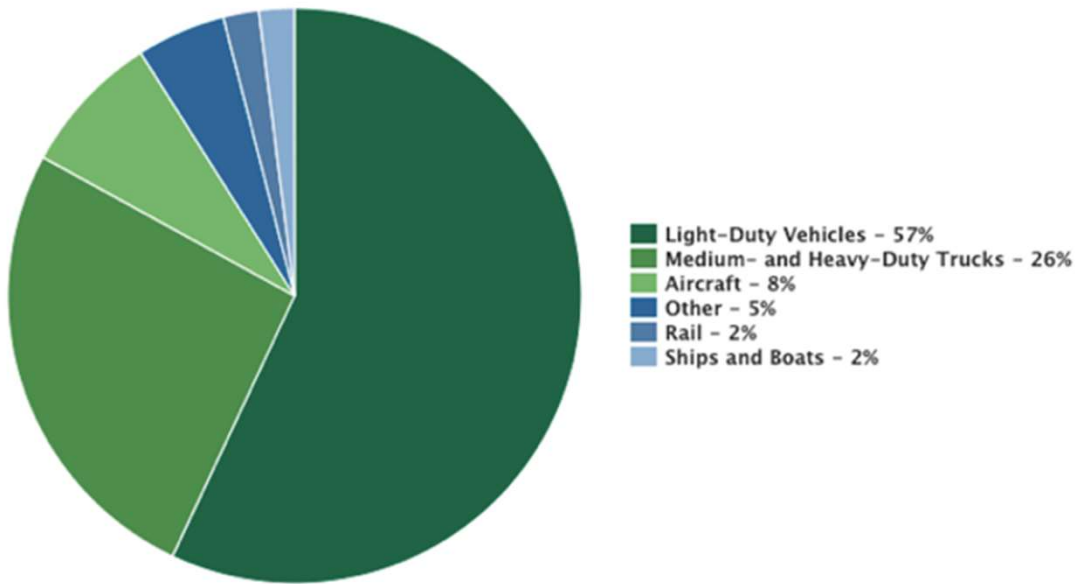
iii) Better Affordability for New Vehicles with Abundant Materials & **Range Retention** for Used Vehicles.

- <\$75/kWh versus SOA \$120/kWh
- Cut battery degradation losses in half

Battery 1K starts with the Vision of Eliminating GHGs

Planes, Trains & Ships account for 200 million tons of CO₂ emissions in the US & 1.8 billion tons globally (Annual).

2020 U.S. Transportation Sector GHG Emissions by Source

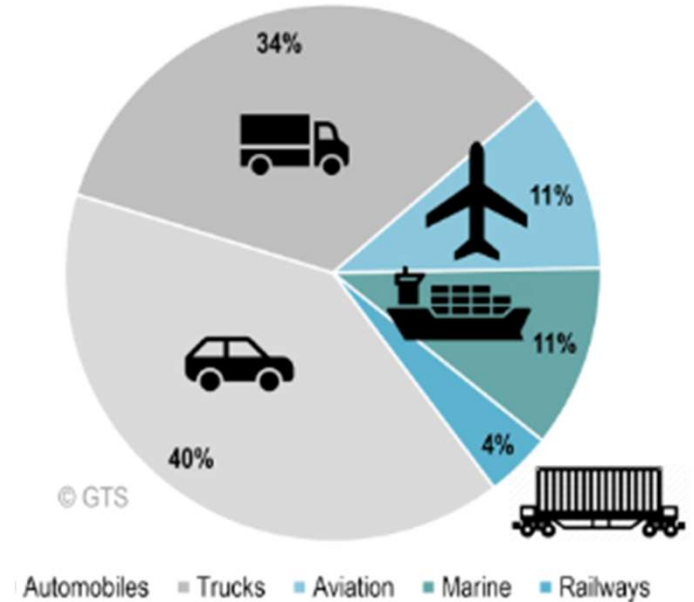


Transportation accounts for 27% US Emissions (Ref: EPA)



Global emissions properly consider shipping

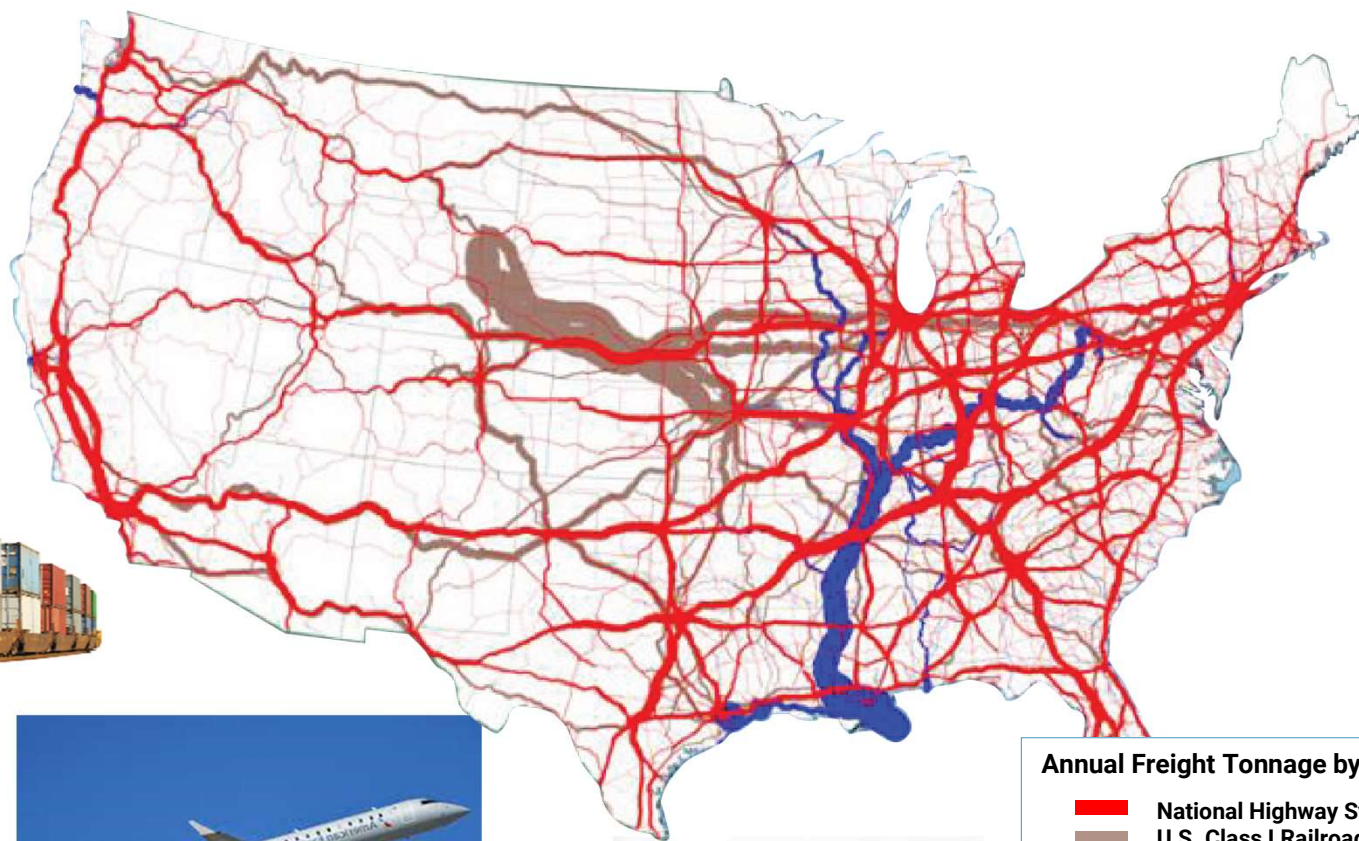
CO₂ Emissions by the Transport Sector






© GTS
Automobiles Trucks Aviation Marine Railways

Geography of Transport Systems 2014

Heavy Usage, Fast Refuel, Longevity & Robustness



Annual Freight Tonnage by Mode

-  National Highway System
-  U.S. Class I Railroad
-  Inland Waterways

Volume Scale (Tons/Year)



Why is Electric interesting?

Truly Zero Emissions (w/zero carbon based electricity)

Reduce Noise Pollution

- Take-off plane noise is particularly egregious

Energy infrastructure already in-place globally (Electricity)*

- Although charging **will** be challenging for larger applications

Potentially more Energy Efficient & Economical

- Electricity cheaper than fuels and have more price stability (1/3rd OPEX cost), Less maintenance?

Could enable new business platforms & Operations

- smaller airports, reduce hub and spoke, higher altitude(less friction)
- Autonomous, smaller trains (Potential for platooning)
- Autonomous coastal ships & freighters

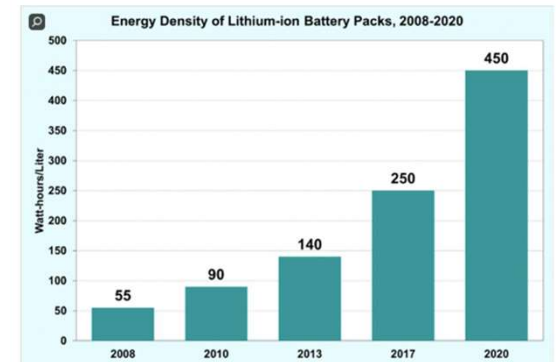


We are targeting Fossil Fuel Free Electrification of **Planes, Trains and Ships**

- ✓ They are Workhorses operating >16 hours per day and >20 years
- ✓ Idleness = lost revenue
- ✓ They each need a Transformational Energy Storage Solution(s)

Since May 2022 we have learnt:

- Battery 1K should be ESS 1K
- 1K is net & EOL
- 1K could be Wh/Kg or Wh/L
- 1K could be 1000 miles
- 1K could be 1000 weeks Life
- 1K could be 1000 seconds Refuel
- 5K could be 5kW/Kg for a power option

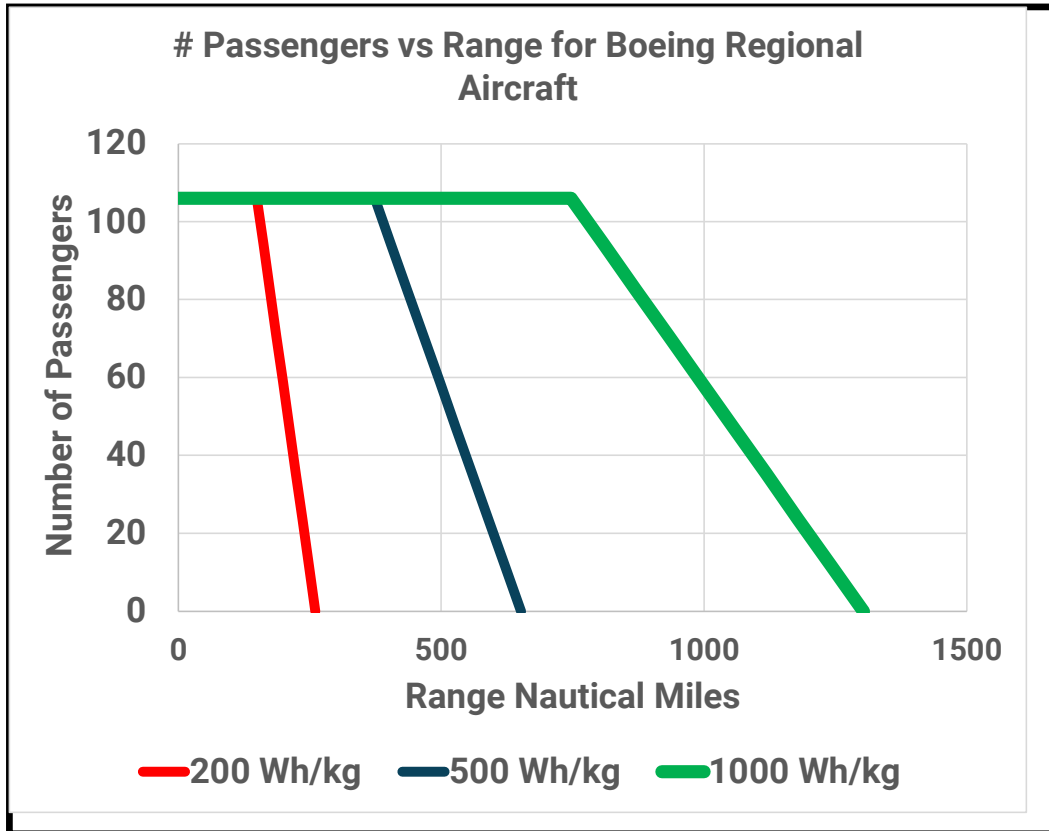


Muralidharan et al, Adv. Energy Mats, January 2022

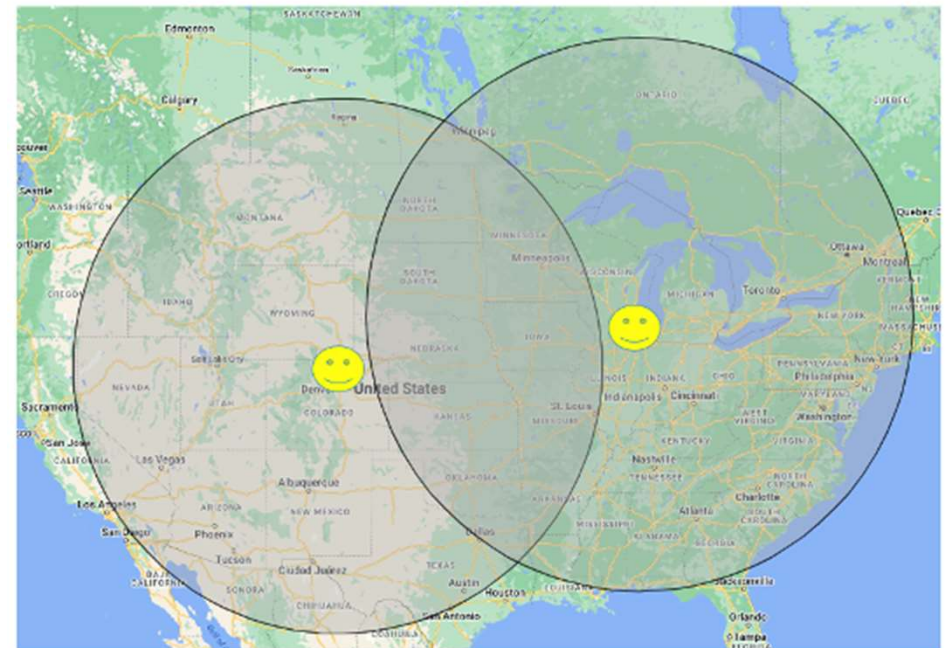
E.G. 1000Wh/L for the battery
= 40MWh for a 40ft container
2/3 full



1,000 Wh/Kg makes regional jet electrification possible



700 NM radius circles centered on Denver & Chicago



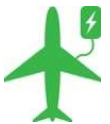
Assumptions: eta 83.7%, L/D = 25, Reserve = 19%



Lots of Electric/Hybrid activity in Planes – and challenges to solve

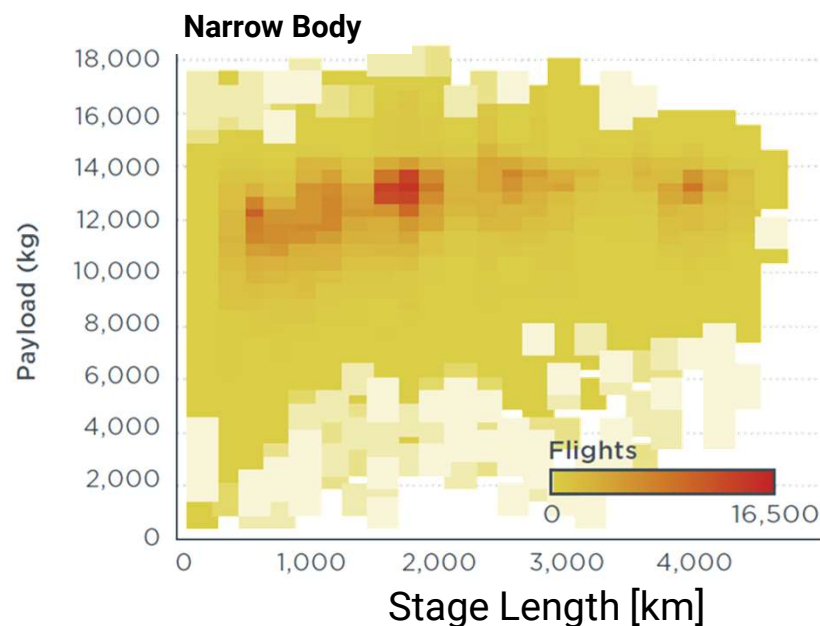
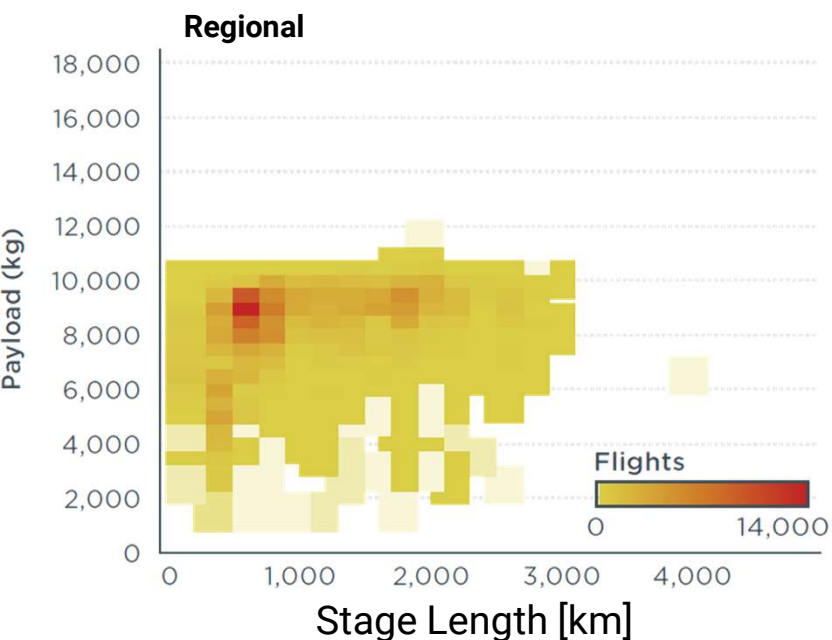


- **Aviation is not just about Wh/Kg**
 - Capacity Retention – cycles & years
 - EOL = 1K not BOL
 - 1K = Battery, BMS, Thermal management etc
 - Quick Recharge/refuel Times
 - Total Cost of Ownership (TCO)
 - LCA & the Circular Economy
 - Power for take-off (@ low SOC)
 - Energy for Reserve
 - Landing weight not less than take-off weight
 - **AND UNCOMPROMISING SAFETY**



Typical operations by aircraft type – Regional & Single Aisle

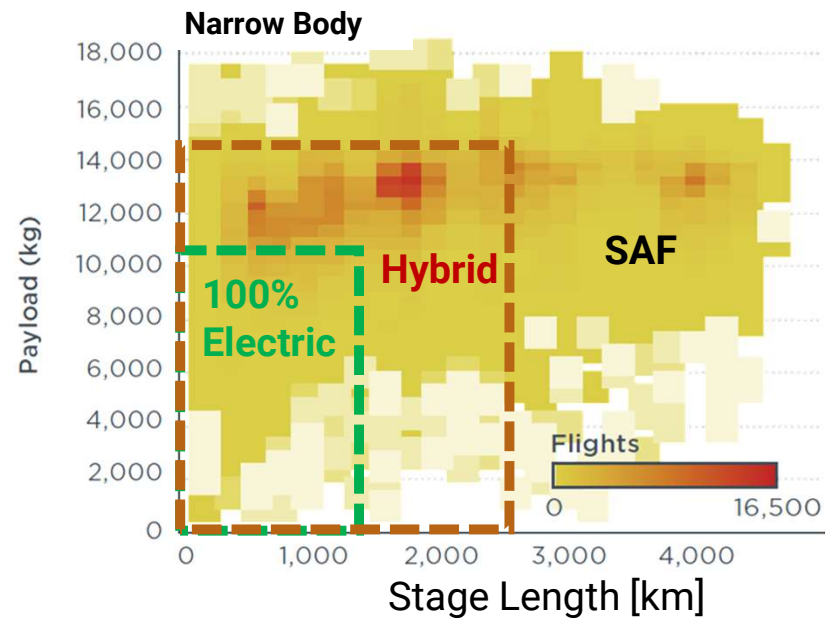
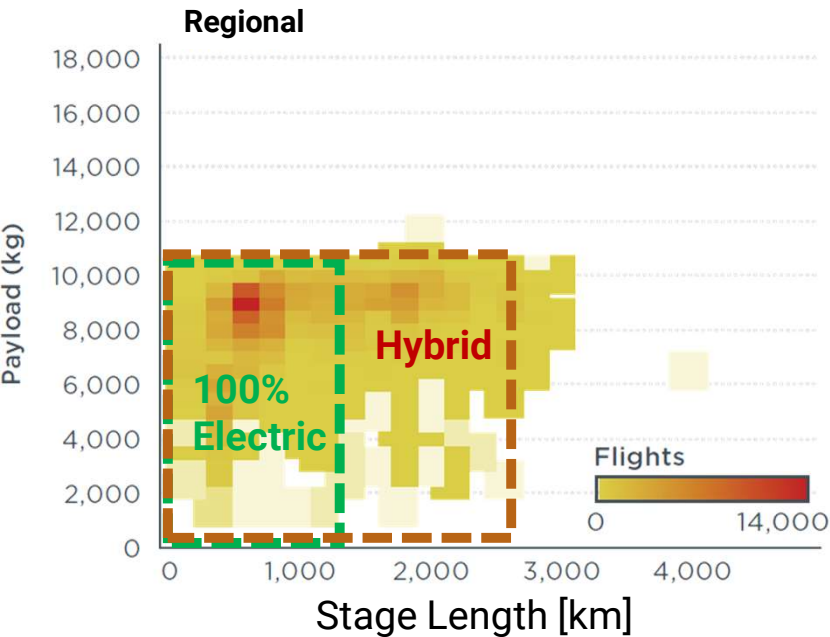
U.S. Domestic and international (to and from the United States)





A Vision of the possibilities....

U.S. Domestic and international (to and from the United States)



Electric = Battery 1K; Hybrid = Battery(1/2K & 5kW/Kg) + H₂ (2kWh/Kg) - Fuel Cell; SAF = Synthetic Fuel



Railroads: An industry already working the Problem



AMTRAK eTicket

PRESENT THIS DOCUMENT FOR BOARDING

RESERVATION NUMBER 527F8C

RES# 527F8C-17APR23

NHV



WAS

One-Way

New Haven, CT
Union Station

Washington, DC
Union Station

APRIL 30, 2023

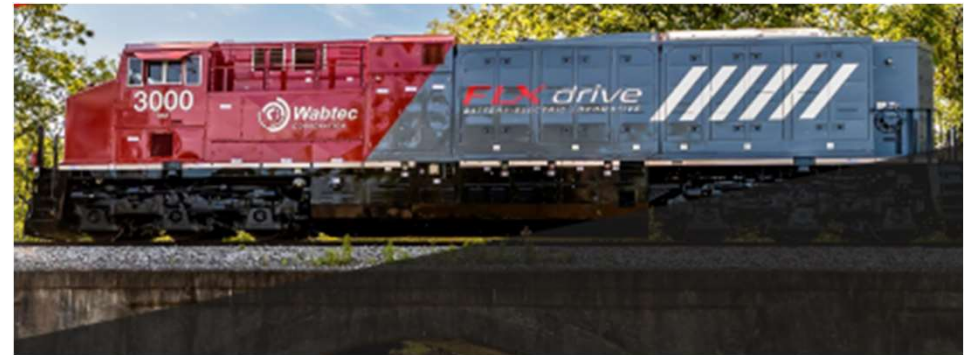
“Congratulations on reducing your carbon footprint. This train will produce 83% less greenhouse gas emissions than if you drive (saving 188.52lbs of CO₂e) and 72% less than if you fly (saving 48.8lbs of CO₂e)”

• Congratulations on reducing your carbon footprint. This train trip will produce 83% less greenhouse gas emissions than if you drive (saving 188.52 lbs of CO₂e) and 72% less than if you fly (saving 48.80 lbs of CO₂e).



CHANGING WHAT'S POSSIBLE

Wabtec FLXDrive: Locomotive #3000



FLX SPECS

| | FLXdrive 2.0 |
|----------------------------|--------------|
| No. of axles | 6 |
| Wheel Arrangement | CoCo |
| Number of cabs | 1 |
| Max Battery Capacity (MWh) | 8.5 |
| Traction power (MW) | 3.2 |
| STE (kV) | 890 |
| Weight (tons) | 196 |

OH Supply



Credit: Wabtec

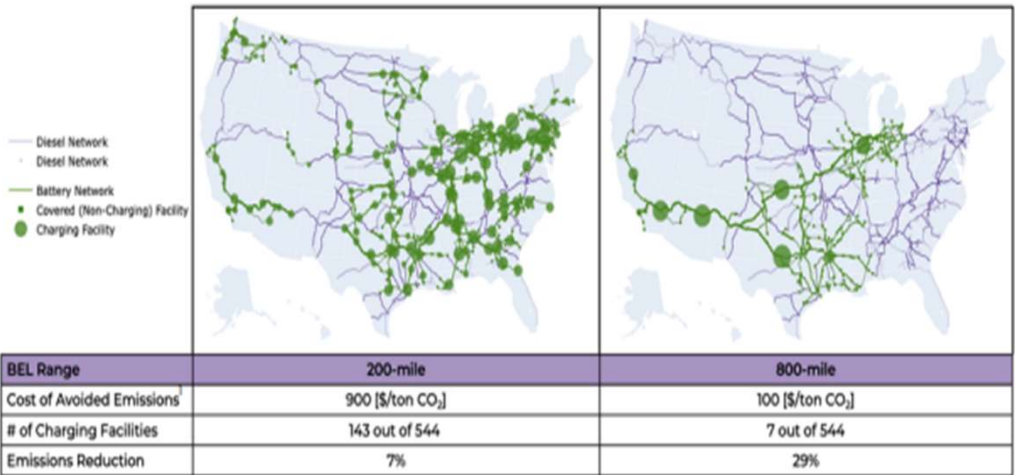


BEL (Battery Electric Locomotive) – Range & Charge/Refuel Time are everything!

Cross Country US Freight



From Kansas to Los Angeles – 1,740 miles, 75 wagons total



| | MWh size | # Battery wagons |
|----------------------------|----------|------------------|
| SOA Battery no charging | 280MWh | 45 |
| SOA Battery 3 fast refuels | 48MWh | 8 |
| Battery 1K no charging | <200MWh | <6 |
| Battery 1K 3 fast refuels | <48MWh | <2 |

Optimization results of an aggregated transcontinental U.S. rail network where 20% shipments are served by BELs.



Ref. NUFRIEND Insights-Range

Taken & adapted from Zenith et al, SAGE Journal: Vol 234, Issue 7, August 2019





Electric Ferry Plans are starting to get interesting

"100 nautical miles is a rather smallish ocean"

Andreas Thaler Comment

The world's largest electric ferry can take you and your closest 2000 friends across the ocean

 Peter Johnson | Jan 17 2023 - 3:17 pm PT |  46 Comments



- Incat Tasmania; Operator Buquebus
- Delivery planned in 2025
- 148 meter long
- 2 electric motors (5-9.6MW)
- 2,100 passengers and 226 vehicles
- 25 knots max
- Max range 100nm
- Travel between Argentina & Uruguay
- 500 tons of equipment & tanks replaced with 400 tons of batteries
- Aluminum vessel not steel



Battery 1K could be a good solution for short haul container ships

Yara Birkeland - Specifications

- Autonomous Battery Driven Container Vessel
 - 80 meters x 15 meters; dead weight 3,120MT
- Replaces 100 Diesel Trucks/day
- Capacity: 120 TEUs
- Propulsion System: 2 x 900kW Azipull pods
- 6.7MWh Battery Pack (Leclanche)
 - 20 strings x 51 modules x 32 cells = 32,640
 - 8,000 cycles to 80% initial capacity
- One way maximum expected mission: 30NM
- Maximum speed 13 knots (ECO 7knots)

Yara Birkeland All-Electric container ship– maiden voyage 11/2021

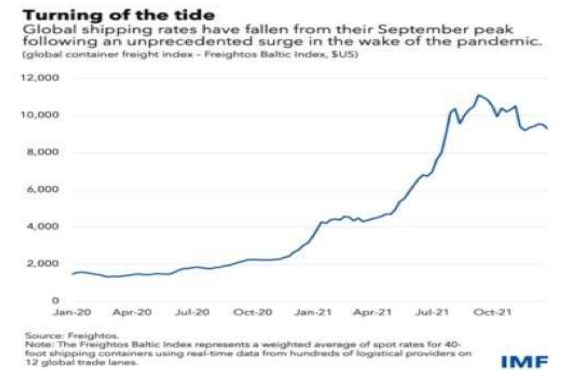


Credit: Maritime Executive



Shipping has significant differences to Rail and Aviation

- Ships are a very diverse category
- Biggest Emissions opportunity - Ocean container ships
 - Total Energy Required a showstopper for all electric?
- While cost may be paramount price is more **"Elastic"**
 - The Bottom Line: What is important to you!



- Turnaround time is longer than planes or trains: **0.3 days Japan; 1 day New York***
- Volumetric Energy Density may be more important than gravimetric
 - E.g#. 1,000TEU vessel, 10,000 KM Range. 470Wh/L = 35% volume, 1200Wh/L = 12%
- Legislation and/or other value added innovation may drive the change needed.
- Fuel Cells and/or Hybrids for sure will have a part to play

There is no shortage of applications enabled or helped by Battery 1K

Full Battery Electric



Regional Jet missions



Cross Country Freight



Coastal Shipping

Enabler for Hybrid



Wide body jets



Ocean Cargo ships



Fuel Cells

Critical Range Extender



Small planes



Ferries



Specialty

Some merit



Urban Taxis



Harbor Shipping



Long distance Freight

Battery 1K How? Unthink what a Battery is?



Actives + Non-Active => electrodes => Cells + Pack hardware => Battery Pack => Big Box

.....And/Or Think Backwards

Fossil Fuels versus Battery Materials....an intriguing comparison

Jet Fuel
12kWh/Kg



0 Kg

Lithium
11.1kWh/Kg



Li₂O = 5.2kWh/Kg.

Aluminum
8.4kWh/Kg



Al₂O₃ = 4.3kWh/Kg

Magnesium
6.1kWh/Kg



MgO = 2.8kWh/Kg

Zinc
1.35kWh/Kg



ZnO = 1.1kWh/Kg

**1kWh/Kg vs
Theoretical**

19%

23%

36%

91%

How do we package these metals to deliver 1000Wh/Kg



7 Strategies for Transformational Electrochemical Energy Storage

Mechanically..... or Externally Rechargeable

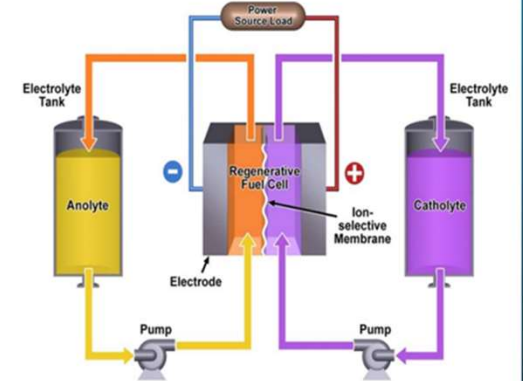


Credit: Electric Fuel – Zinc Air System Power Sources Symposium

(Swappable) Energy Box



Separate Power/Energy

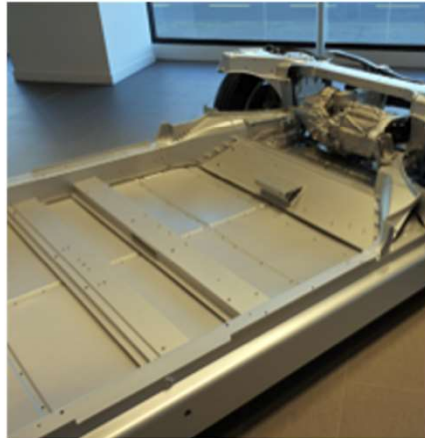


Credit: DOE/PNNL

External Catholytes



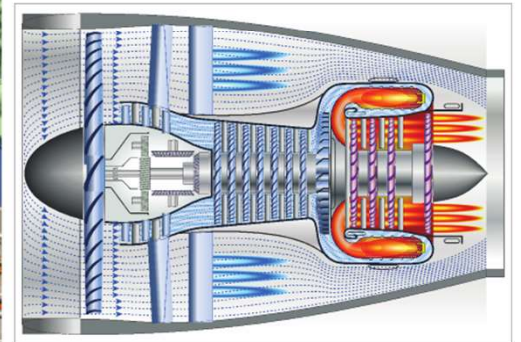
Gantrify



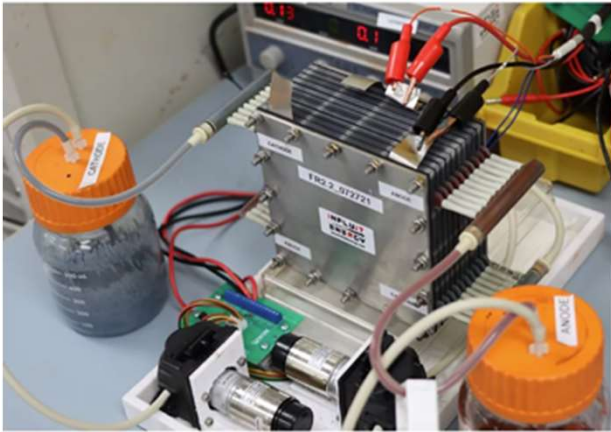
Revisit the Past



Run at High Temperatures



Unleashing the potential- Examples of think differently



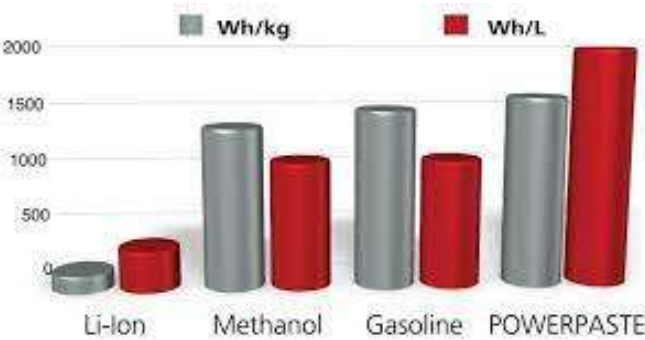
Electro-active pumpable slurries (Credit: Influid Energy)



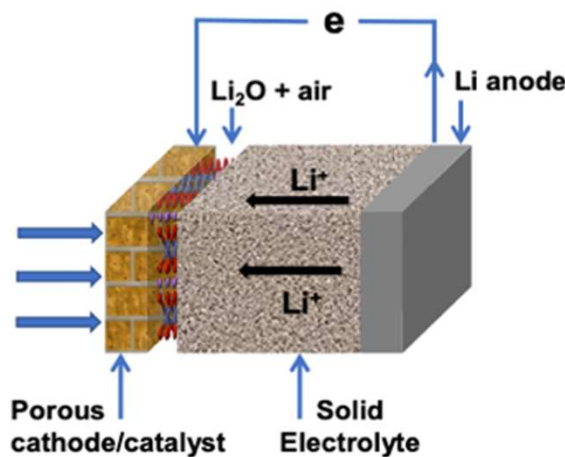
Aluminum Mechanically Recharged (Credit: L3 Harris)



Molten/High temperature liquid batteries: (Credit: Ambri)



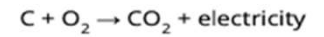
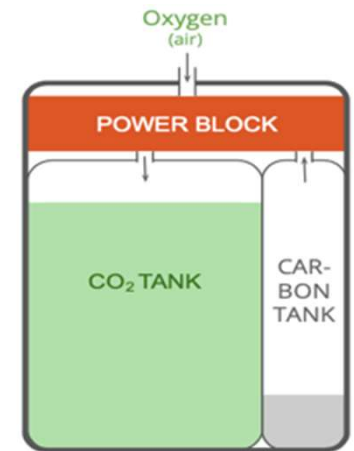
Hydrogen entrapment e.g. via hydrides (Credit: Fraunhofer Inst)



Solid State Batteries (Credit: Mohammad Asadi- Illinois Institute of Technology)



Revisit Primaries



Carbon Dioxide Battery (Credit: NOON Energy)

ESS-1 Solutions have many considerations, For Example

Uncompromised Safety

- ✓ **Range Retention**
- ✓ ✓ **Energy Density**
- ✓ ✓ ✓ **Fast Turn Around Time**
- ✓ ✓ ✓ ✓ Pumpable, electroactive materials
- ✓ ✓ ✓ ✓ Mechanically Rechargeable
- ✓ ✓ ✓ ✓ Swappable Batteries (Energy Box)
- ✓ ✓ ✓ ✓ Fuel Cells/Battery-FC Hybrids
- ✓ ✓ ✓ ✓ On-board charging
- ✓ ✓ ✓ ✓ Separation of Reserve vs Operation

ESS-1 Solutions have many considerations, For Example

Uncompromised Safety

- ✓ Early Characterization
- ✓ Shut-down/safety-catch mechanisms
- ✓ Non flammable/non toxic solvents
- ✓ No thermal runaway reactions
- ✓ Internal Hard Short Proof
- ✓ Prevention & Mitigation strategies
- ✓ Extensive Proving in Trucks

Energy Density

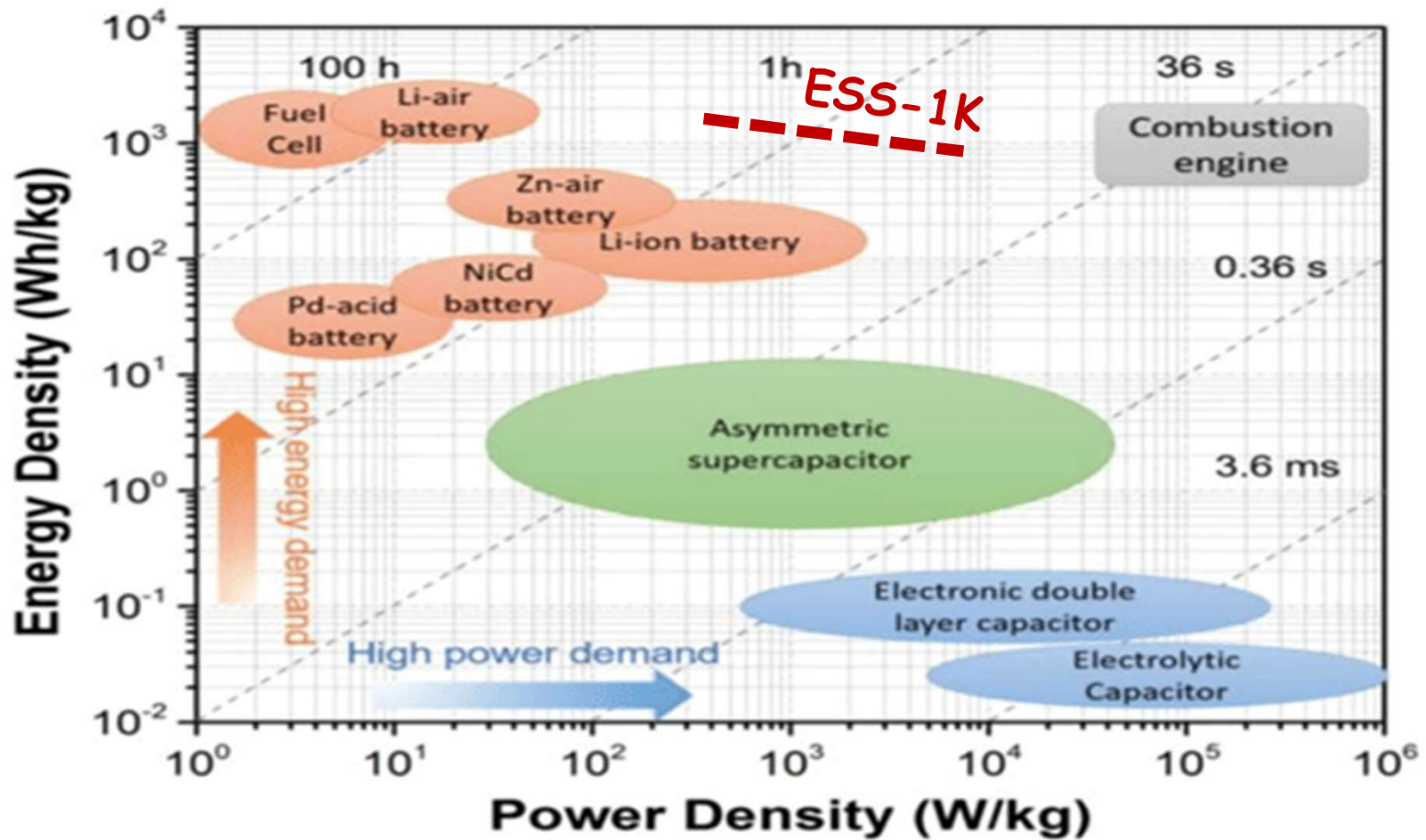
- ✓ Light Weight Anode Materials
- ✓ External catholytes
- ✓ Combine Electrochemical Function w/mechanical structure
- ✓ Bipolar enabled designs
- ✓ Binderless designs

Range Retention

- ✓ Low expansion/compression
- ✓ High Faradaic Efficiency
- ✓ Low/fixed/Impedance designs/architectures/interfaces/connects
- ✓ Low Activation Energy Kinetics
- ✓ No dendrites/shape change
- ✓ Iso-thermal designs

Fast Turn Around Time

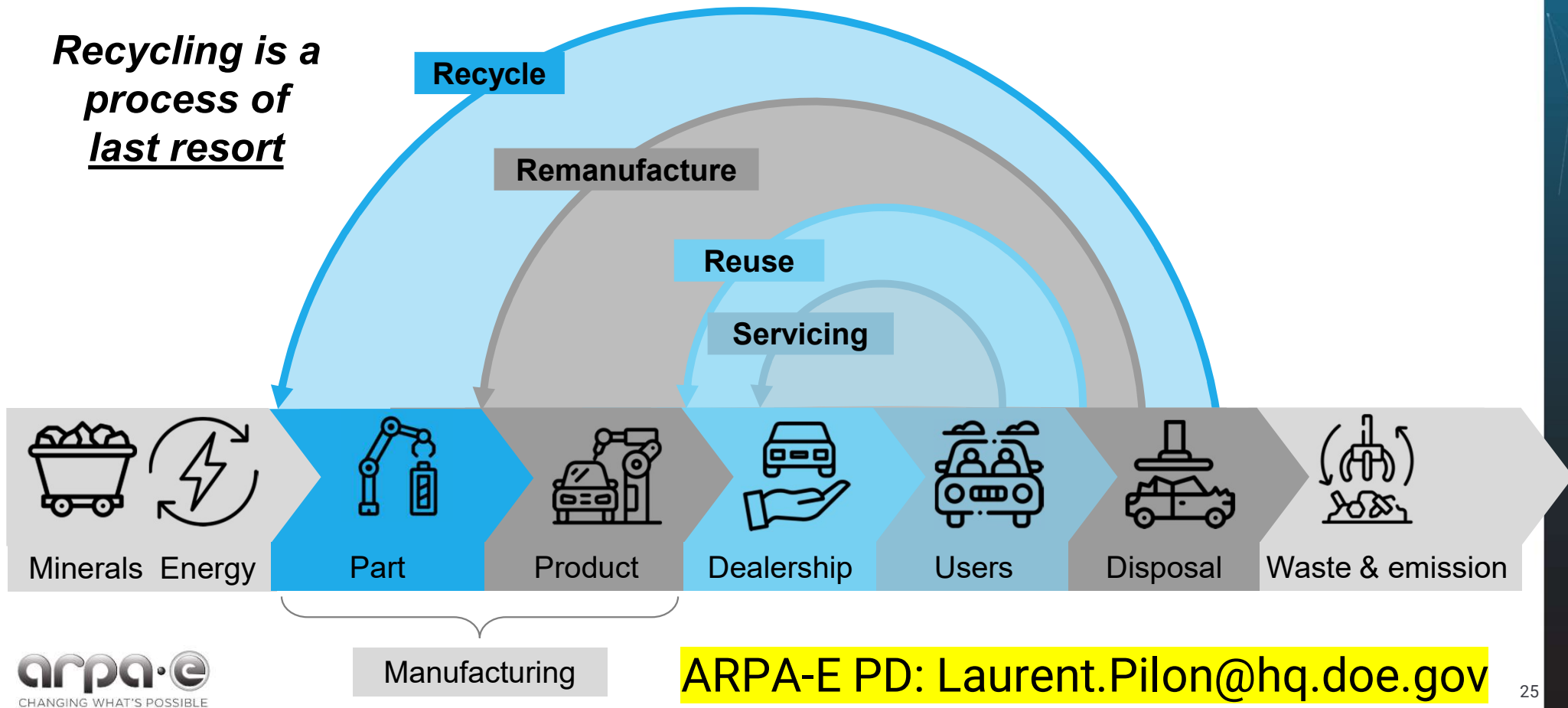
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Ragone Reference: Shao et al, Design & mechanisms of Asymmetric Supercapacitors, Chem Rev. (2018)

Circularity is more than recycling... it helps recover manufacturing value!

Recycling is a process of last resort



Energy Storage 1K: The culmination of much work into a bold program

KICK-OFF: What if?



40+ Organizations: Applications/solutions

PART II: How might we?



NASA-VTO Aviation Workshop 4/25/23

ESS – 1K Workshop May 10th & 11th in DC

- ✓ Speakers – Aviation, Railroads, Maritime
- ✓ Panels – Aviation, Railroads, Maritime
- ✓ Technology Innovation Blast x 20
- ✓ Breakout Groups
 - Applications-Solutions alignment
 - Prioritizing metrics

Possible Program

