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WATER EMERGENCY TRANSPORTATION AUTHORITY

Presentations for December 8, 2022 Board of Directors Meeting

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Item 5a(i): Regional Transit Network Management

Progress Update

1. **Refine Project Focus**
   - Review previous work product
   - Define 6 areas
   - Align on outputs

2. **Establish Operating Model Concept**
   - Outline and describe operating model elements
   - Develop data request and categorize returns
   - Develop template and undertake initial analysis and evaluation

3. **Assess Current State**
   - Evaluate current state of process, roles, governance, etc. for 6 areas
   - Document findings and convert into usable format for gap analysis and recommendations

We are here

4. **Define Operating Model**
   - Highlight specific areas where operating model shifts could be beneficial in the future state
   - Identify interdependencies and risks across the areas that require further consideration or mitigation

5. **Preferred RNM Framework/ Next Steps**
   - Reconcile findings across 6 areas and incorporate remaining functional areas
   - Recommend preferred RNM Framework and provide a set of actionable next steps

The final steps of the process will define a future-state RNM framework and ***who*** might fit into specific roles

Regionalization for each Functional Area is based on the Regionalization Considerations & Categories:

Will "*regionalizing*" this accountability / responsibility…

C Improve the Customer Experience

Such as:
- Reduce travel times
- Improve equity
- Simplify the user interface
- Enhance accessibility

and / or

E Unlock Efficiencies

Such as:
- Enable sharing of costs
- Generate economies of scale
- Reduce time spent on coordination activities
- Reduce duplicative efforts / activities

and

F Be Feasible

Such as:
- Is not cost prohibitive
- Within achievable legal / regulatory limitations
- Agency has path to authority, where required
- Is operationally possible

Preliminary Regional Role for Functional Area Activities

Fare Integration Policy

- Set the **regional vision** for fare integration **(C/F)**
- Establish regional fare integration **policies** (e.g., Tier 3/4) **(C/E/F)**
- Establish policy implementation plans, including the **identification of funding** **(E/F)**

Wayfinding & Mapping

- Set the **regional vision** for wayfinding **(C/F)**
- Establish regional wayfinding **policies** (e.g., design standards, compliance requirements) **(C/E/F)**
- Establish policy implementation plans, including the **identification of funding** **(E/F)**
- Deliver centralized procurement, where relevant **(E/F)**

Accessibility

- Align on current-state findings and confirm what a regional vision for accessibility (fixed route and paratransit) entails **(C/F)**
- Establish regional **policies**, definitions, and metrics for accessibility (e.g., eligibility requirements) **(C/E/F)**
- Establish policy implementation plans, including the **identification of funding** **(E/F)**

Bus Transit Priority

- Set the **regional vision** for BTP **(C/F)**
- For BTP Corridors: Define corridors, establish standard data / reports; identify needs / initiatives; serve as the central coordination point for state, county, and city stakeholders **(C/E/F)**
- For Non-BTP Corridors: Recommend potential initiatives; serve as the central coordination point for state, county, and city stakeholders **(C/E/F)**
- Establish policy implementation plans, including the identification of funding **(E/F)**

Rail Network Mgmt.

- Set the **vision** for the regional rail network **(C/F)**
- Translate regional vision into regional implementation plan (project prioritization, sequencing, integration points, project funding, delivery approach, etc.) **(C/E/F)**

Connected Network Planning

- Identify regional transit gaps to create CNP **(C/F)**
- Establish and create data tools for regional planning **(E/F)**
- Identify funding priorities and establish service standards **(C/E/F)**
- Align CNP gaps and recommendations with county planning guidelines and future updates to Plan Bay Area 2050 **(C/F)**

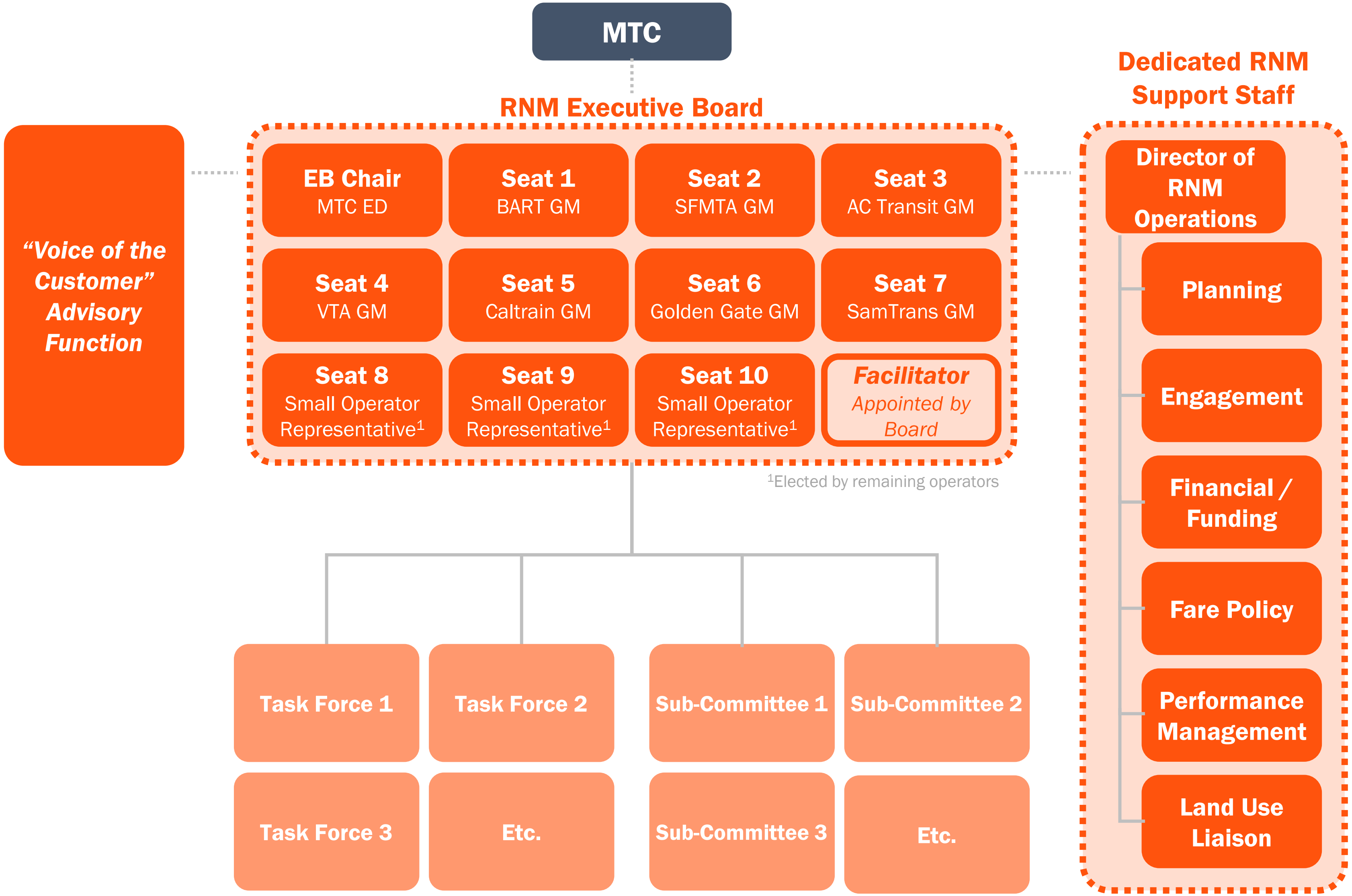
Legend: **C** = Improve the Customer Experience **E** = Unlock Efficiencies **F** = Be Feasible

Key Takeaways

1) **Regional Role:** Regional entity will set the vision, make select funding decisions, develop the regional policies, create implementation plans, and implement regional programs (as needed) by coordinating stakeholders
2) **Operator Role:** Operators will be highly involved in regional decision making, provide local stakeholder perspectives / needs, and implement regional policies
3) **RNM Framework:** RNM Framework will need to be designed to facilitate the effective and efficient interplay of these two roles (see slide 14 for key operating model needs)

Note: Additional detail on Functional Area shifts are under ongoing assessments and will be provided at a later date

Preliminary Short / Near-Term RNM Structure



✓ Customer Focused:

- Enables highly inclusive decision making to bring a broad range of perspectives
- Dedicated "Voice of the Customer" element to keep the customer at the forefront of decision making

✓ Structured for Scale:

- Task Forces and Sub-Committees can be added or subtracted as additional Functional Areas are added or regional priorities shift
- Team of Dedicated Support Staff can grow over time to provide needed capacity to Operators
- Joint teams, with potential opportunities for seconded staff, enable high quality proposals to reach the Executive Board, driving effective use of GM time

✓ Balances Short-Term Momentum with Long-Term Transformation:

- Allows RNM to be stood up quickly to begin working on priority items, but also allows continuous evolution
- Seeks to drive cost and time effectiveness
- Feasible within current legislative constraints

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Item 12: Onboard Passenger Survey Report

ONBOARD PASSENGER SURVEY RESULTS

December 8, 2022

San Francisco Bay Ferry
A SERVICE OF WETA

PASSENGER SURVEY PURPOSE & BACKGROUND

- Learn about our current passengers and analyze ridership segments/trends
- Assess passenger satisfaction and areas for improvement
- Inform future policies, passenger experience improvements and marketing efforts to increase ridership

PROCESS, REPORT & OUTREACH

- Statistically valid sample captured on all transbay regular routes, weekdays and weekends
- CDM Smith led overall project, NDS did onboard collection
  - WETA has worked with both firms in previous surveys
- Full summary report included in packet and posted to WETA website
- Planning press release/media outreach, social media posts and newsletter story

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MOST NOTABLE FINDINGS

1. Highest ever passenger satisfaction at 99%

    Overall satisfaction is exceptionally strong on all routes but comments point to areas to focus on

2. More than 40% of passengers began riding post-2020

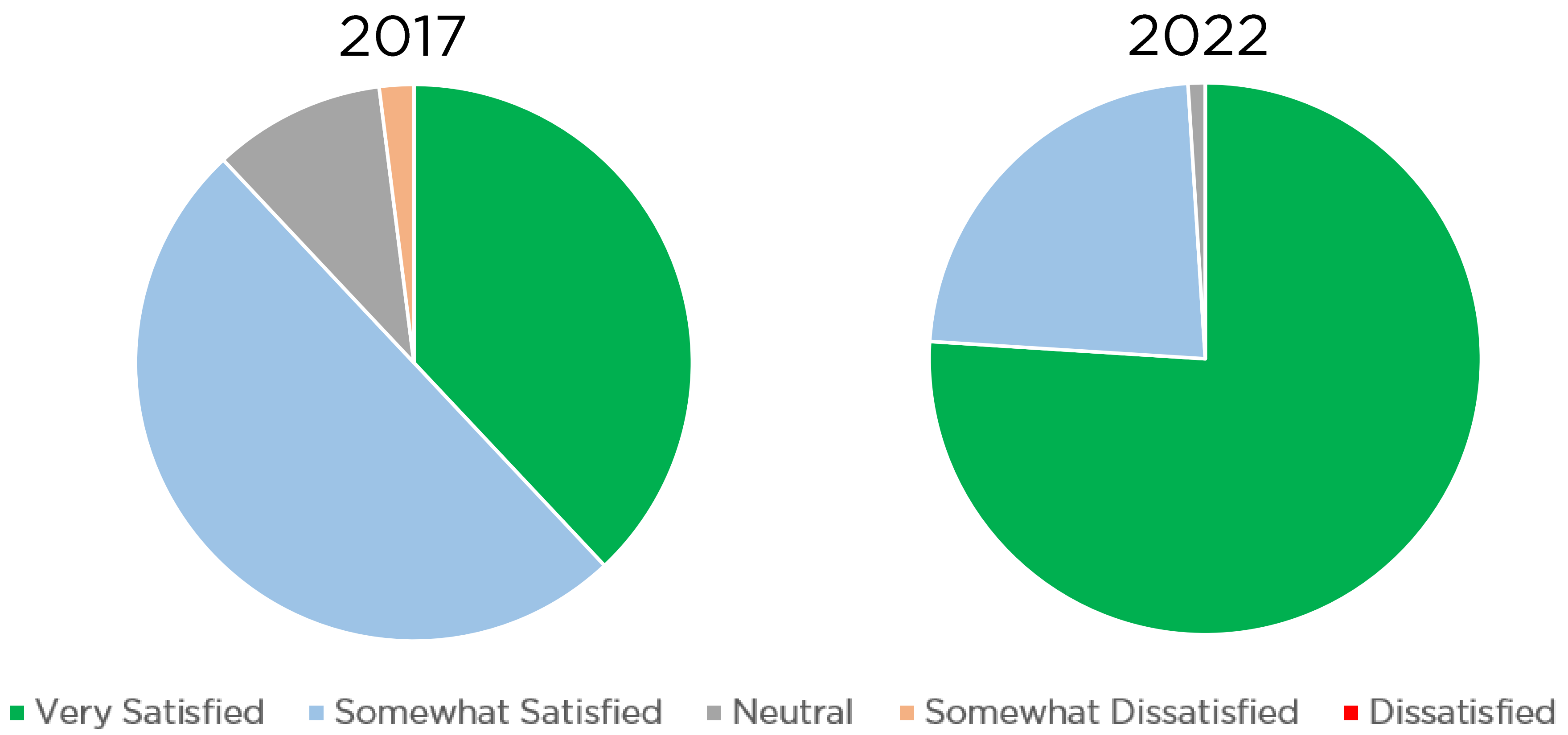
    Indication of success of Pandemic Recovery Program and marketing efforts in replacing lost ridership and building new service relevant to wider swath of travelers

3. The passenger base is younger and more diverse, but continues to skew toward those with higher incomes.

PASSENGER SATISFACTION

- San Francisco Bay Ferry has always performed well in this measure, but 99% satisfaction is an all-time high
- Major change from prior surveys: shifts from "neutral" to "satisfied" and from "satisfied" to "very satisfied"
  - "Dissatisfaction" has never been above 2%
  - In 2017, 10% chose "neutral" – that's 1% in the 2022 survey
  - In 2017, 38% chose "very satisfied" – that's 76% in 2022
- Brand affinity strong as 98% satisfaction as well

PASSENGER SATISFACTION



NEW RIDERSHIP GROWTH

- We asked whether respondents rode the ferry prior to 2020 to gauge to scope of our holdover ridership vs. new riders
- 42% of passengers became ferry riders post-2020
- Share of new riders is highest on South S.F., Richmond and Harbor Bay
- Vallejo has the greatest share of pre-2020 riders (66%)
  - This route had the highest ridership through peak COVID and maintains the highest weekday ridership now

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DEMOGRAPHIC CHANGES

- Survey necessarily undercounts minors due to mechanics of collecting sample
  - Will consider questions to address in future surveys
- Share of passengers age 18-34 increased from 29% in 2017 to 38% in 2022
- Riders identifying as Caucasian/White fell below 50% for the first time, with significant increases in Asian/Pacific Islander and multiracial categories

DEMOGRAPHIC CHANGES

- Limited change in overall passengers' income distribution
- More income diversity among non-commuters/weekend than commuters/weekday riders
  - Given strong weekend ridership recovery, this indicates salience and impact of fare decreases
- Vallejo route shows significantly *larger* shares under $100,000 household income (44%) vs. system (30%)
  - Vallejo has has lower share over $200,000 (25%) vs. system (30%)

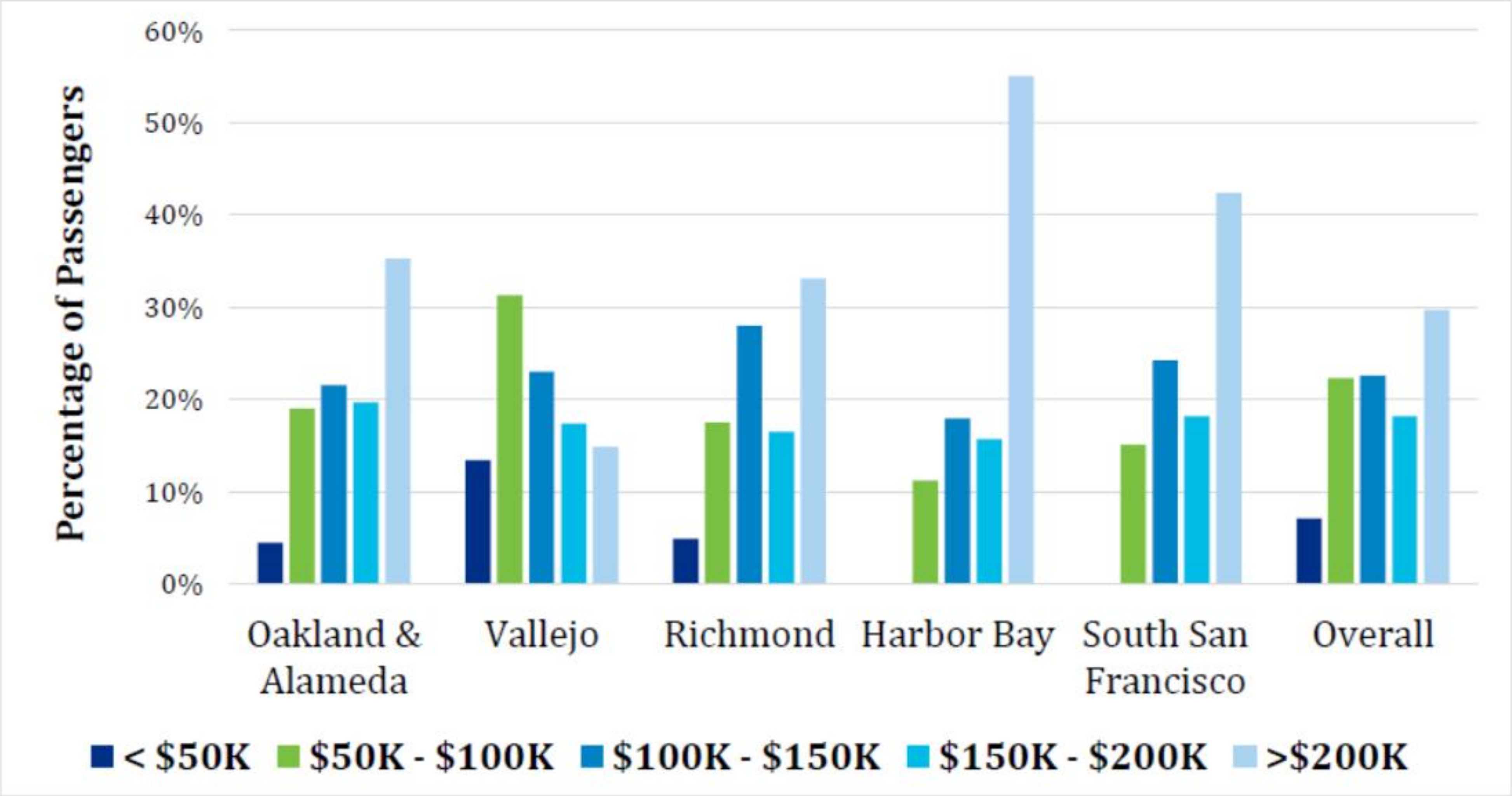
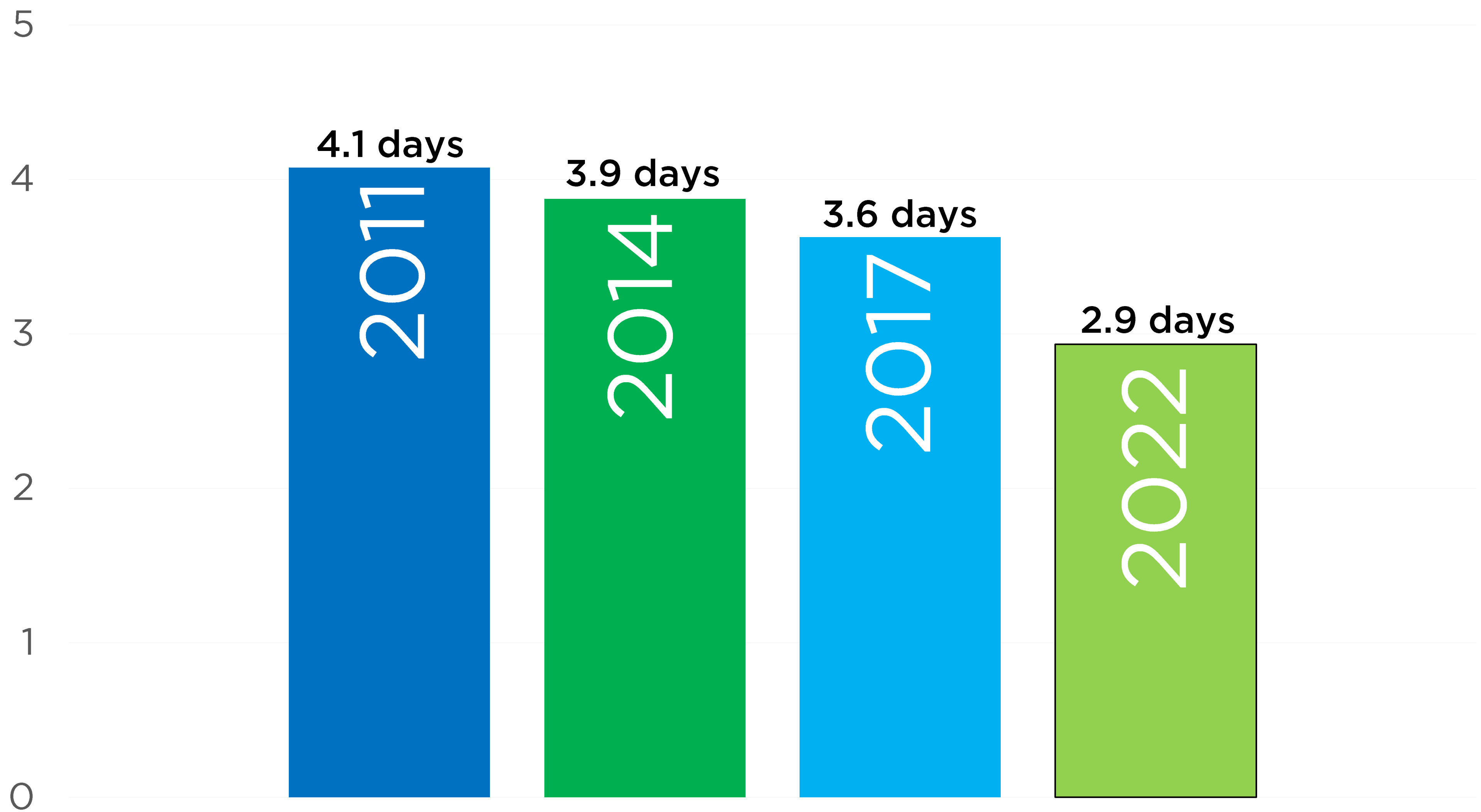


Figure 2-3 Annual Household Income by Route

OTHER FINDINGS

- Decrease in frequency
  - **5 days per week** riders fell from 49% in 2017 to 26% in 2022
  - **3-4 days per week** riders grew from 24% in 2017 to 34% in 2022
  - **1-2 days per week** riders grew from 8% in 2017 to 22% in 2022
  - Average weekday rider frequency: **2.9 days per week**, down from **3.6** days per week in 2017 and **3.9** days in 2014

WEEKLY FREQUENCY



OTHER FINDINGS

- Terminal access trends
  - Under 50% single-occupancy vehicles (SOV) at all East Bay terminals except Richmond (57%)
  - Significant decreases in SOV in Vallejo: 86% in 2014, 63% in 2017 and 43% in 2022
  - Minimal ride hail access except Vallejo, where there is a local Lyft-to-transit subsidy program
  - 46% of South S.F. passengers use a bike on the Peninsula side
  - Estimated ~7% of riders using scooters/e-boards based on "other" responses with comments

OTHER FINDINGS

- Reasons for riding trends
  - Stability in top 3 reasons: parking/traffic avoidance, ride quality, relaxing nature of ferry
  - Major increase in riders citing that the ferry is cheaper than other options: 7% in 2017 to 18% in 2022
- Ferry alternatives
  - Overall "drive alone" is the top ferry alternative, with BART rating higher for Richmond, Alameda and Oakland
  - 50%+ of South S.F. and Vallejo riders say the ferry is their only option or they would drive alone without the ferry

QUALITATIVE FEEDBACK

- Positive comments toward 2021 fare reductions, crews and cleanliness of ferries
- Consistent feedback that ferry service factored into relocation decisions during pandemic
- Passengers cited need for more frequency in peak periods and outside the peak
- Lack of morning concessions also came up

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FUTURE SURVEYS

- MTC regional intercept survey will be completed
- Shorter opt-in digital surveys on a regular basis
  - Next survey: asking about preferred arrival/departure times
  - Other topics include vessel amenities, fare products, rider alert notification preferences
- Developed interest list for focus groups
- Onboard survey cadence
  - Relatively expensive but valuable project
  - Analyzing options for frequency and scope in coming years

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Item 14: Fleet Electrification – BEACN Battery Study

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Fleet Electrification Study

Project Managers:
Eula Billaut
Shannon Paulson

Associate Consultants:
Emma Azhan
Liam McDonough
Luna Hohner
MaryClare Rovere
Paige Thionnet
Saniya Shrotriya

Presentation Agenda

- INTRODUCTION
- BATTERY TECHNOLOGY
- ENVIRONMENTAL & SOCIAL IMPACT ANALYSIS
- END OF LIFE PLAN
- NEXT STEPS

Meet the BEACN Team

Eula Billaut (she/her)
Project Manager
Chemical Engineering

Shannon Paulson (she/her)
Project Manager
Environmental Econ

Emma Azhan (she/her)
Associate Consultant
Environmental Econ

Saniya Shrotriya (she/her)
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Materials Engineering

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Env Econ, GIS, Accounting

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Associate Consultant
Society & Environment

Paige Thionnet (she/her)
Associate Consultant
Society & Environment

Liam McDonough (he/him)
Associate Consultant
Chemical Engineering

Project Overview

Answering the fundamental question: what is the best battery for WETA's ferry fleet electrification plan?

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Scope & Objective

WETA has obtained a grant to electrify the SF Bay Ferry fleet. The electrification of such large and fast ferries is unprecedented, so WETA has asked BEACN to predict the optimal battery technology for the job.

Battery Exploration		Supply Chain Analysis		End-of-Life Plan
Future Technology Forecasts		Materials and Sourcing Summary		Repurposing vs Recycling
Cost Projections	→	Environmental Impact Analysis	→	Battery Recycling Industry Readiness
Market Timeline		Social Impact Assessment		Recycling Policies (State & Federal)

Batteries vs Diesel Fuel

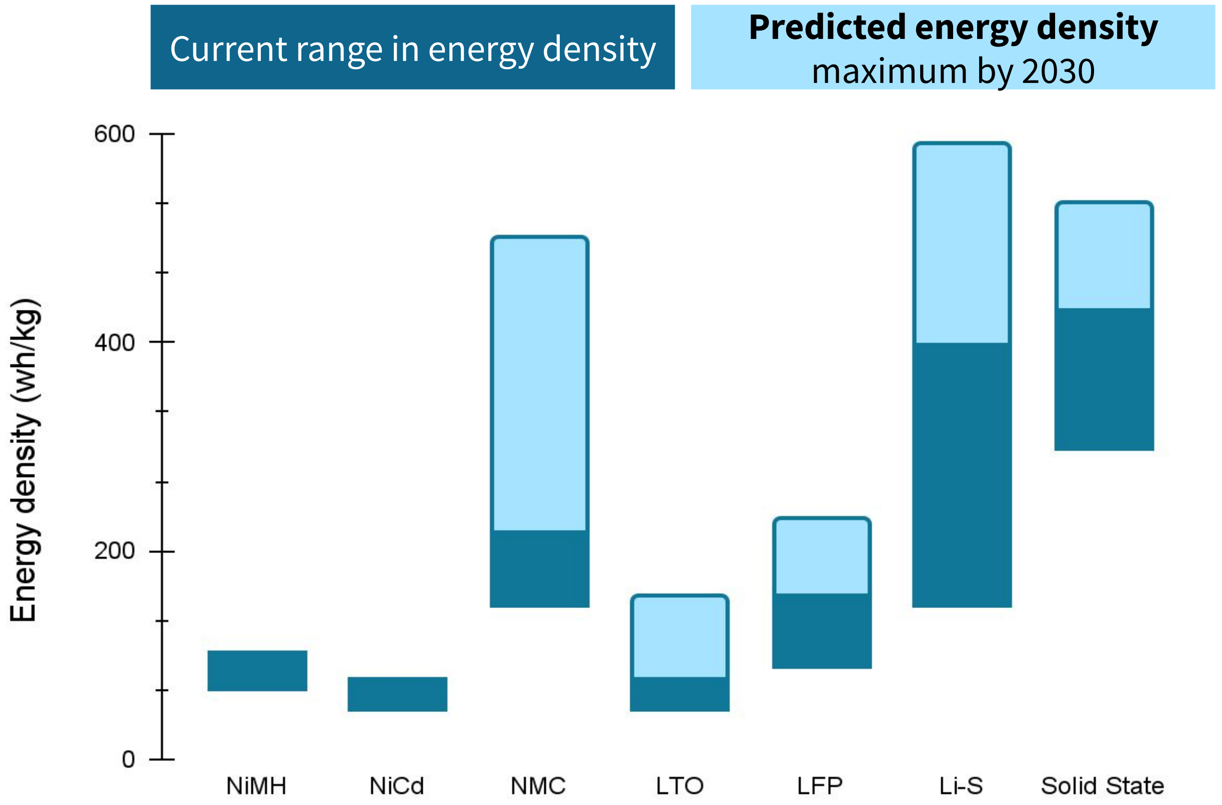
Batteries are more cost efficient and environmentally friendly compared to diesel

Fuel Type	Emissions	Costs	Overall Benefits
Electric	**Zero** Tailpipe Emissions ~ 0.088 kg CO_2 eq /kWh **99.6 kg CO_2 eq/Trip**	\$ 0.163 / kWh **\$ 185.7 / Trip** Less Cost Volatility	Over 10 years with 9 Oakland Alameda trips per day a vessel saves **\$3-5 million** and emissions are reduced by **~28 million kg eq CO_2**
Diesel	Tailpipe Emissions ~ 0.78 kg CO_2 eq /kWh **937 kg CO_2 eq/Trip** **Additional Pollutants** (NO_2, SO_2, PM, etc.)	\$0.32 / kWh \$ 4-5 / gallon **\$328 / Trip** **Variation in oil prices**	**Future Benefits** Renewable Energy Higher Energy Efficiency Improving Technologies

Energy Education, WETA Board Presentation, Energy Sage, AAA, AFDC, Epact, EIA EIA

Batteries are ready to replace diesel in coming years

Energy densities are increasing across all batteries, with some uncertainty of market availability



Battery Energy Density Comparison Considerations

NiMH & NiCd batteries will likely have no energy density increase.

NMC, LTO, & LFP batteries are on the market at given ranges, with potential for further density increases.

Solid State & Li-S energy density does not guarantee market availability.

Energy Density Spreadsheet

Battery Technology

Introducing the Top Five Contenders

Battery Technology

Top 5 Battery types for WETA to consider

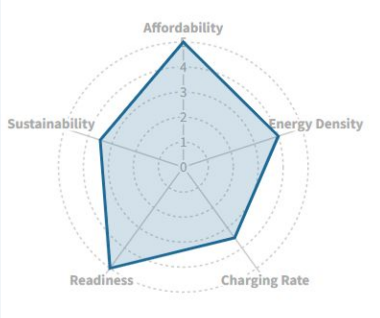
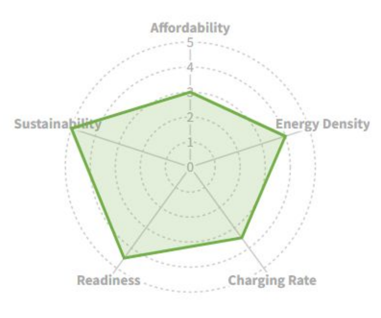
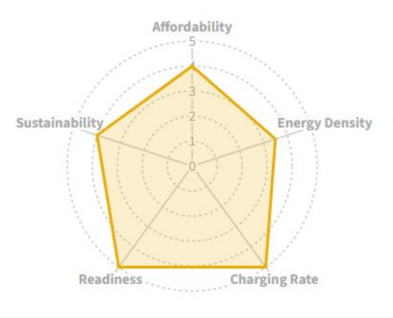
Current technologies (Li-ion chemistries)			Emergent technologies	
NMC	LFP	LTO	Solid State	Li-S

Parameters of Interest

Energy Density	Charging Rate
Cost	Lifetime

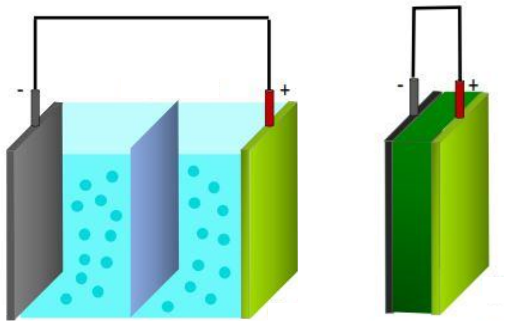
Current Batteries: Lithium Ion

NMC has the largest market share for Li-ion batteries and LFP's are the safest

	Nickel Manganese Cobalt (NMC)	Lithium Iron Phosphate (LFP)	Lithium Titanate (LTO)
Radar Chart			
Overview	**Leading tech in current market** High energy configuration	Primarily for special markets Used for energy storage, moderate growth	Used for powertrains, solar street lighting, etc
Advantages	Very long life span **Can be used as energy or power cells** High specific energy Lowest self-heating rate	Low resistance Tolerant to full charge systems Safe Long life	Thermal stability under high temps Long life, fast charge Safe **Ability to ultra-fast charge**
Disadvantages	Lower voltage with larger proportion of Nickel due to high Cobalt cost	Lower specific energy Cold temperature reduces Li-ion performance	Lower energy density/specific energy Expensive

Emerging Marine Batteries: Solid State

Solid state batteries have seen heavy investment for use in the near future



Advantages	Disadvantages
Higher Specific Energy	Difficulty with Connection
Faster Charging	Internal Resistance
Greater Safety	Implementable Cycle Life Lower
Potential for longer lifetime	Greater Uncertainty

Now — **2023** — **2025** — **2030**

- **Toyota implements solid state**
- **Volkswagen and QuantumScape Pilot Plant**
- **Mercedes e-Citaro Bus**
- **Mercedes and ProLogium Factory**
- **Literature predictions of commercial viability**

ABS, Flash Battery, Li et al. Euro. Com., Mercedes, Dörfler et al. (1)

Emerging Marine Batteries: Lithium Sulfide

Lithium Sulfide Batteries have high potential for 2025-2030 but leave some uncertainty

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Advantages

Density	Sulfur is **much lighter** than traditional cathode materials and Li has very low SRP resulting in high energy per unit weight. Reports as high as **470 Wh/kg vs standard 255 Wh/kg** for traditional Li-ion
Potential Development	**Solid state** or **quasi solid state** technology can be used in combination. Li-S batteries often also have **lower internal resistance** leading to lower electricity consumption.

Technological Readiness and Current Players

LG Chem & KARI	LG Chem and Korea Aerospace Research Institute successfully created a drone running on Li-S. Hopes to commercialize **late 2025** with energy density **1.5x Li-Ion**
OXIS	OXIS Energy Ltd. in the UK has produced **400 Wh/kg batteries regularly** in pilot and hope to reach 500-600 Wh/kg. They have **signed a lease on a site for plant**

Disadvantages

Lifecycle for Li-S remains low to do parasitic side reaction between sulfur, electrolyte, and lithium. There have been some promising results in stabilising the sulfur with carbon. **Volumetric energy density is low** due to low density of the materials and **power density is not expected to compete** with today's top end lithium ion batteries (LFP & NMC)

Wu et al. Lee et al. Zhu et al., Drexel, Dörfler et al. (2)

Marine Battery Safety Considerations

Safety requirements can significantly alter implemented maritime energy density

Safety Concerns for Boats

Vibration and Pounding	Marine batteries are designed with heavier plates and robust construction to withstand the vibration and pounding that can occur on board any powerboat.
Thermal Runaway	**Overheating is the most common issue** on boats and can be mitigated with cooling systems including: (1) air-based systems: electric fans & spacing (2) liquid-based systems: water or glycols (3) phase-change material -based cooling systems (4) heat pipe-based thermal management systems
Impact Resistance	The essential tests include **overcharging, crushing, subjection to impacts, short-circuiting,** and **penetration** with a nail.

Energy Density Impact

NMC battery specific energy in Tesla model 3:	**160 W h/kg**
NMC battery specific energy in Ellen Eferry:	**86 W h/kg**

Implemented Maritime Energy Density is **50%-200%** lower than standard energy density

Recent developments in energy storage systems for marine environment, electrical energy storage for ships, Li-ion battery safety concerns

Standard vs Implemented Maritime Energy Density

NMC, LTO, & LFP have adequate energy density, solid state does not show a large reduction due to safety

	Standard Energy Density	Implemented Maritime Energy Density	Notes
NMC	150 - 220 Wh/kg	111-180 Wh/kg	Most Commonly Used
LTO	50-90 Wh/kg	50-80 Wh/kg	Smaller reduction in energy density
LFP	90-160 Wh/kg	90-120 Wh/kg	Reduction in energy density
Li-S	150-400 Wh/kg	290 Wh/kg*	*Numbers not available for boats. **Energy density expected to be 50-200% of 290 Wh/kg.** Has only been implemented on one boat. Not expected to dominate industry.
Solid State	350-400 Wh/kg	300-400 Wh/kg	Gains increased due to safety

Marine batteries require additional safety features and casing when compared to EVs resulting in lower usable energy density in the installed battery

Energy Storage Systems for Ships, Electrical Energy Storage for Ships, Recent Progress Lithium–Sulfur Battery PMC, LTO for Marine Application LTO for Automotive Power

Ranking Technology by Parameters

Solid States and Li-S have the highest energy density potential, LTO has the best charging rate and lifetime

	Implemented Energy Density Wh/kg	Charging rate 0-80% SOC	Lifetime / # of cycles At 80% DOD	EFC / # of cycles At 3C, 25 C, 20-80%
NMC	111-180 Wh/kg	≥ 20 mins	> 6,000 cycles	> 1,500 Cycles
LTO	50-80 Wh/kg	**≥ 6 mins**	**> 20,000 cycles**	>> 1,000 Cycles
LFP	90-120 Wh/kg	≥ 20 mins	> 6,000 cycles	> 3,000 Cycles
Li-S	300-400 Wh/kg	≥ 30 mins	> 1,700 cycles *-5000 cycles*	~1000 - >2,000 Cycles
Solid State	290 Wh/kg*	≥ 25 min	> 1,000 cycles *-9000 cycles*	~ 400 - 4,000 Cycles

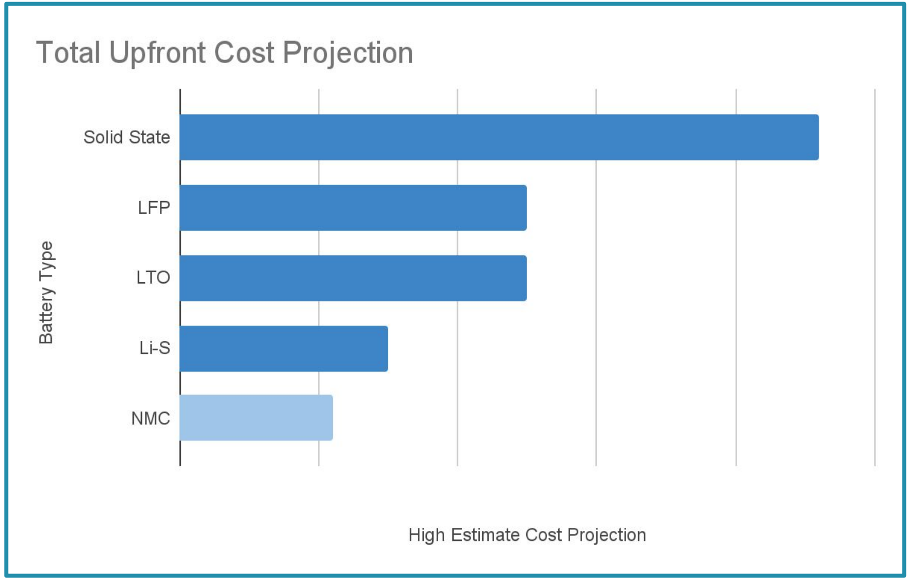
Spear Battery, Nature (1) , Faraday Institute, Electrek, Cision InsideEvs, LTO, NMC/LFP , Nature(2) , ACS

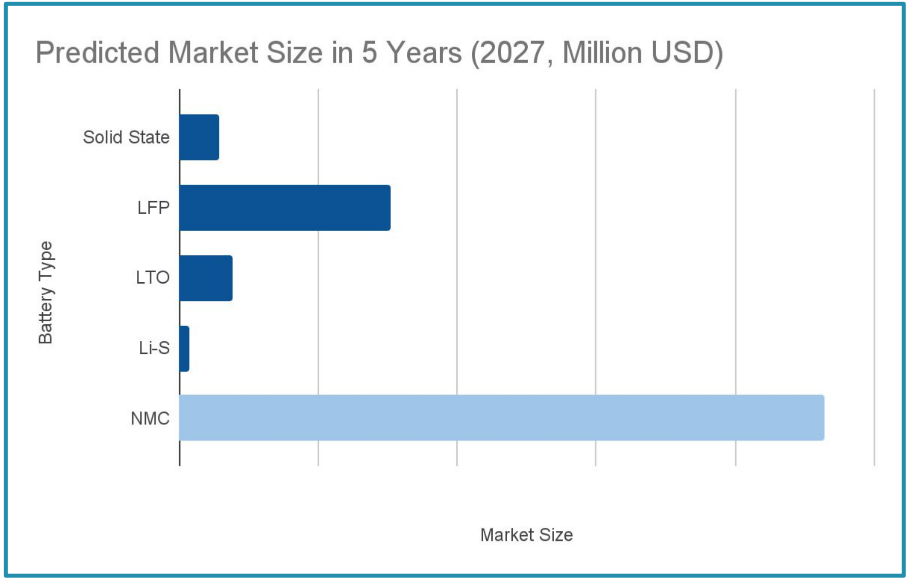
Cost Comparison Synthesis

All battery costs are projected to decrease, as market size increases in the near future.

When accounting for an average 1.3 kWh battery, **NMCs** are the most cost-effective option, with costs decreasing most significantly accounting for technological developments .

All battery markets are projected to grow in the near future, with **NMCs** seeing the largest growth to an estimated value of **46.4 billion USD by 2027**.





Douglas Insights, Mauler et al., Tvete et. al, FutureBridge, Kurzweil et. al, Berckmans et. al, Mauler et. al, Nemeth et. al, Penisa et. al, 2027 Battery Market Size

Impact Analysis

Environmental & Social Hotspots

Impact Analysis Overview

Multiple elements contribute to supply chain impact analyses, factoring in lifetime and other parameters of concern.

Environmental Impacts

- GHG Emissions
- Chemical Pollution
- Resource Use

Social Impacts

- Health
- Human Rights

Benchmarking and Impact Parameters

- Lifetime
- Recyclability
- Battery Chemistry
- Future Trends

NMC Supply Chain Impact

Impacts centred in mining processes, with possibility for elimination through recycling developments.

	Lithium	Nickel	Manganese	Cobalt	Total
GHG Emissions	1 tonne of mined Lithium corresponds to **15 tonnes of CO_2 emissions**	**11.19 kg CO_2 eq** of emissions (high energy-intensive process of extraction)	Cradle to gate life cycle of average manganese alloy produces ~ **6.0 kg CO_2 eq**	Extraction results in **10.81 kg CO_2 eq of emissions**, (9.52 kg CO_2 eq from fossil fuel based energy use)	Average of **136 CO_2 eq** of GHG emissions associated with cumulative NMC supply chain
Environmental Impacts	**500,000 gal per ton of Lithium** purified Chemical runoff and poor waste rock disposal	Chemical leaching from mining and end-of-life handling	Chemical leaching from mining and end-of-life handling	Water contamination associated with refinement and mining	High water wastage Aquatic pollution Chemical runoff
Social Impacts	**Resource exploitation** impacting marginalised communities Socio-political conflict associated with mining externalities	Toxic chemical exposure Poor end-of-life handling **High human toxicity potential**	Toxic chemical exposure Poor end-of-life handling **High human toxicity potential**	Child labor Human rights violations Human trafficking Sexual Exploitation Unsafe working conditions	**Political, social, health and human rights impacts** associated with the cumulative NMC supply chain

Farhana et al., MIT, Westfall et al.

LTO Supply Chain Impact

Due to the long lifetime of LTO batteries, these are more environmentally friendly

When taking energy density and cycle life into account, these environmental projections show that **LTO batteries have a lower energy demand relative to the other types of batteries**

CED per Wh Storage Capacity	HTP	GWP
1.90 MJ/Wh Has the highest CED (cumulative energy demand) out of the 7 most common EV batteries)	**0.160 kg 1.4-DCBeq*Wh^{-1}** Relatively low human toxicity	**0.185 kgCO2*wh^{-1}** High global warming product data has small number of data points, and high variability

Lifetime CED	Lifetime Specific Energy	Lifetime GWP
0.27 MJ/kWH Has the **lowest** lifetime **CED**	**401 kWH/kg** Highest lifetime specific energy Will last longer than the others	**25.1 g/kWh** Lowest lifetime GWP, contributing the least CO_2 overtime

Renewable and Sustainable Energy Reviews, Journal of Energy Storage

LFP Supply Chain Impact

LFP battery production does emit greenhouse gases, though less than ternary LIBs.

Total Energy Consumption of Assembly Process (MJ/kWh)

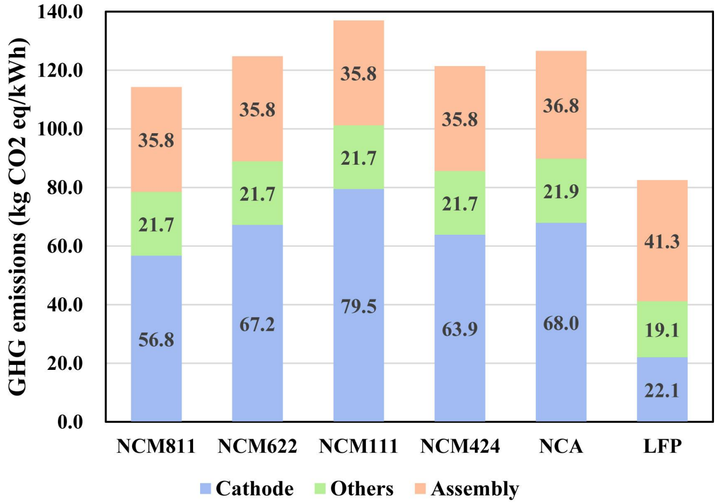
NMC	LFP
226.38 (MJ/kWh)	**261.75 (MJ/kWh)**

Assembly: mixing cathode and anode electrode pastes all the way to sealing the battery pack.

Comparing Environmental Impacts: NMC and LFP

This paper compares multiple ecological indicators: eutrophication, ecotoxicity and human toxicity, acidification potential, photochemical ozone creation potential, PM formation. **LFP is overall of least environmental concern.**

LFPs do pose **environmental risk during phosphate mining processes**. The environmental hazards are numerous, but those that are recurring throughout the mining stages are **air pollution and water contamination**.



GHG emission of LFP: 82.5 kg CO2-eq/kWh

> "The largest contribution comes from the battery assembly."
> "GHG emission of LFP batteries is far less than that of NCM batteries."

Cathode production: ~ 26.787%

Solid State Supply Chain Impact

Solid state supply chain emissions greater than NMC batteries, with the largest CO_2 output

Energy
Solid state batteries use as much as **30 times more energy per kWh capacity** to produce with **83% of that going to LLZ**

Lithium
SSBs with a lithium anode use much more lithium

Lanthanum
For **10% market SSB need 4x more global production**

Zirconium
Less constrained than lanthanum but still has supply concerns

Anode, Electrode and Packaging Materials
Anode materials can require more lithium but are fairly standard aluminum, copper, etc.

Lithium Cobalt Oxide
Cobalt raises ethical and economic concerns

LLZ solid electrolyte
The LLZ electrolyte uses the majority of the most costly materials but remains a dominant SSB electrolyte

Solid State Battery

1045* kg eq CO_2 / kWh GWP

3299* CTUe / kWh Freshwater Ecotoxicity

7821* kg eq U-235 / kWh Ionizing Radiation

Using regression models with thin film solid state microbatteries, **at 100% charge**, 80% capacity was hit at **~500 cycles** but with **75% charge** a battery was expected to **last over 4000 cycles** and **65% charge** lasting **7000 cycles**

Farjana et al., Troy et al.

Li-S: Supply Chain Impact

LiS batteries have lower impact than NMC batteries in all areas except ozone depletion

Overall Emission Analysis

GWP potential is estimated at 146.2 kg/ kWh when including dry room condition or at about 90 kg/kWh without their inclusion

The synthesis of graphene silicon composite and the maintenance of dry room condition are the two most energy intensive steps

When accounting for use phase or without use phase **Li-S batteries end up with lower GWP compared to NMC**

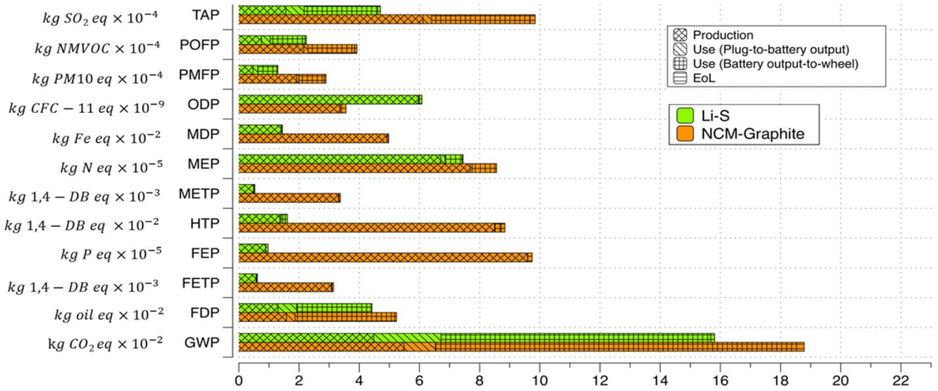
Supply Chain

Because lithium is in both the electrolyte and the anode, **higher amounts of lithium are presumably needed** but there are also better recycling prospects

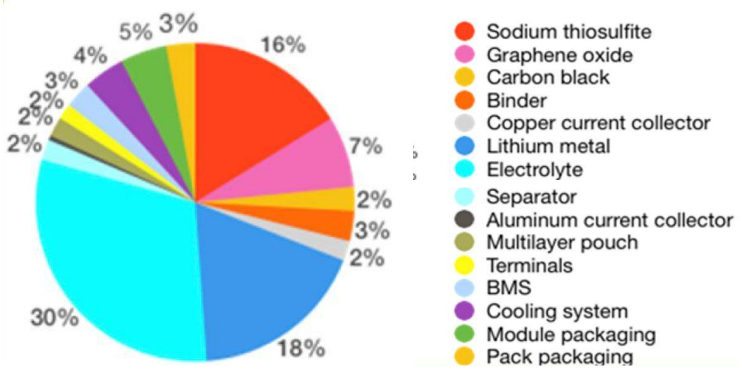
Lithium thiosulfate is the main sulfur contributor and can be synthesized from byproduct of Na_2S production minimizing impact for sulfur mining

Ozone depletion results from the production of organic solvents and hazardous waste from LTSFI production for the electrolyte

Environmental Impact of NMC (Orange) vs LiS (GreeN)



Share of Energy Use by Input Material



Total GHG Emission Comparison

Although batteries are not emission free, every battery emits less than diesel

	kg CO_2 eq per kWh capacity	g CO_2 eq per kWh delivered over lifetime (Low Scenario - High Scenario)
LFP	93.7	87
NMC	113	88
LTO (NMC cathode)	383.6	88
d State (LLZ)	1045	127-499
LiS	89.8	99-102
lrogen (Blue)	N/A	650
Diesel	N/A	780
arameters	High Scenario: 160 lbs CO_2 eq / kWh, 13 kg CO_2 eq / kg H_2, cycles lives from report	

The majority of the emissions for all batteries come primarily from electricity used for charging, not from battery production and manufacturing itself.

Batteries result in a **nearly 90% emission reduction from diesel** and a significant reduction from hydrogen.

Albatayneh et al. , NIH, DOE, NRDC, Ajanovic et al. PG&E

Li-Ion Battery Federal Planning

Federal report demonstrates a US emphasis on supply chain domestication, improvements to EOL infrastructure.

Blueprint Goals

1. Secure **access to raw and refined materials, discover alternates** for critical minerals for commercial and defense applications.
2. Support the **growth of a U.S. materials-processing base** able to meet domestic demand.
3. Stimulate the U.S. **electrode, cell, and pack manufacturing sectors.**
4. Enable **U.S. EOL reuse and critical materials recycling** at scale and a full competitive value chain in the U.S.
5. Maintain and advance U.S. battery technology leadership through **R&D, STEM education, and workforce development.**

Relevant Takeaways

The Federal push for better EOL infrastructure further suggests an **increase in recycling/reuse progress.**

Investments in research may **expedite technology developments.**

Key Points

National Blueprint for Lithium Batteries created by the Federal Consortium for Advanced Batteries.

Primary goals include equity, job creation, supply chain domestication, and climate change mitigation.

Includes market information for EVs, aviation, National Defense, and Aviation. **Marine technologies are noticeably absent.**

Making the U.S. a competitive force in the growing battery market.

National Blueprint for Lithium Batteries 2021-2030

End-of-Life Plan

Recycling and Repurposing

End-of-Life: Two Main Paths

Degraded batteries can be repurposed or recycled

End-of-Life Plan	
Repurposing	**Recycling**
Batteries have potential for a second life when no longer meeting marine performance standards but are still functional	When batteries are no longer functional or performance level is no longer useful, batteries must be recycled
Energy source for the grid	Mechanical separation: disassembly, shredding, and filtering
Residential energy storage at a discount	Chemical separation: smelting, dissolving, and recovery

State of recycling industry summary

Li battery recycling is already happening with generally no cost falling on the users

Industry leaders in Battery Recycling

Based in northern Nevada, **Redwood Materials** currently recycles over 6 gigawatt hours of batteries each year, equivalent to 60,000 EVs. They accept all lithium ion batteries and nickel manganese hybrid batteries in California, and are developing a software to source them.

Based in Georgia, **Battery Resources** runs the largest lithium-ion battery recycling gigafactory in North America, fully operational in August 2022 with capacity to process 30,000 metric tons annually.

With 4 locations in the US in Arizona, Ontario, Alabama, and New York, , **Li-Cycle** operates internationally. Across its factories in the US, Li-Cycles recycles 30,000 metric tons of lithium-ion batteries annually.

Recycling process

Redwoods , Li-Cycle, and international recycling leaders such as Mercedes and Volkswagen recycle batteries by dismantling, grinding materials into a "blackmass", and finally using a hydrometallurgical process to separate metals from their ores.

Recycling cost predictions

Redwood and other recyclers are actively seeking batteries and recycle them at no cost to the users. Similarly, Tesla recycles all of its own batteries at no cost to the user. This industry trend will likely continue with **no recycling cost falling on WETA.**

Redwood Materials, Georgia.com, Li-Cycle, Crux Investors, Britannica

Current vs. Future End-of-Life CA Policy

While recycling efforts are currently up to WETA, more regulatory support could be on the horizon.

Current

Little to no existing policy regulates LIB end of life management.

Until new policies are passed, **WETA will likely be responsible** for finding a recycling operation to take their batteries. **WETA would not have to pay for recycling**, but may be responsible for transporting the battery to the recycler.

Based in Nevada, **Redwood Materials** is worth looking into as they currently recycles 60,000 EVs worth of batteries annually.

Future

The advisory group from Cal EPA's Li-ion Car Battery Recycling report selected **two prospective pathways** for EOL policy.

Between both scenarios, possible responsible parties include battery suppliers, core exchange programs, dismantler/refurbishers, and OEMs.

Neither option includes a provision that would make the battery owner responsible for recycling.

TABLE 8. ADVISORY GROUP VOTE OUTCOMES AND LEVEL OF SUPPORT FOR EOL MANAGEMENT POLICY PROPOSALS.

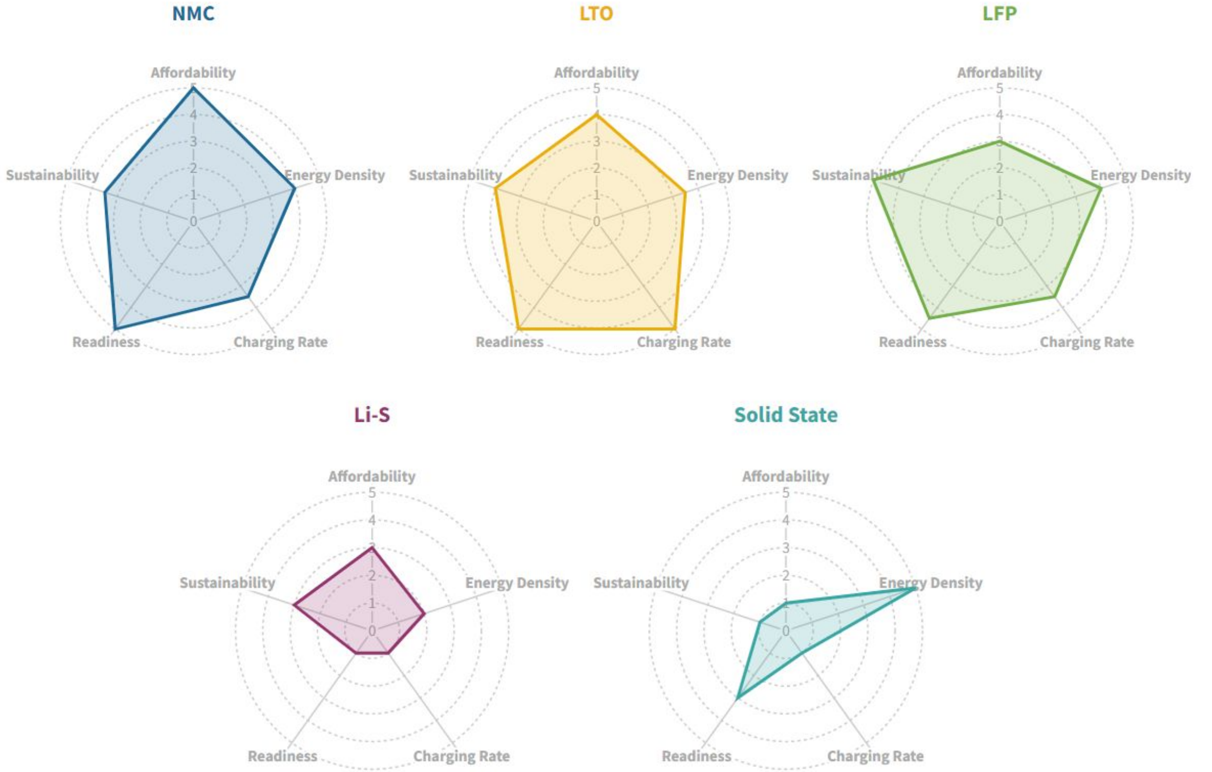
Policy proposal	In Favor	Opposed	Abstain	Level of support (%)
1. Core exchange and vehicle backstop	14	0	1	93%
2a. Producer take-back	10	4	1	67%

Lithium-ion Car Battery Recycling Advisory Group Final Report

Final Recommendation

Final Rankings

While LTO and NMC are both competitive, LTO is currently the most advantageous option for WETA



Radar Ranking Justifications

Affordability was based on benchmarking projected costs against battery size (kWh)

Energy density was ranked based on predicted implemented maritime density

Charging rate was ranked on cycle life at WETA sufficient charging rate of 3C/20 min

Readiness considered whether the batteries are currently available to WETA

Sustainability rankings were determined by env/social impact & GHG emissions

****Solid state** shows much potential and while currently not viable, could be an advantageous option in the future

Radar charts: underlying data

Check out the Report!

Technology Overview, Cost Predictions, Environmental Impact Analysis, EOL, and Final Comparisons

WETA

WETA Fleet Electrification Study: Future Battery Technology, Cost Projection, Environmental Impact, and End-of-Life

Emma Azhan, Eula Billaut, Luna Hohner-Shields, Liam McDonough, Shannon Paulson, MaryClare Rovere, Saniya Shrotiya, Paige Thionnet

Bay Area Environmentally Aware Consulting Network (BEACN)

Water Emergency Transportation Authority

December 8, 2022

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beacn
Consulting on behalf of the environment
beacn.berkeley.edu

WETA

Appendix A

Repurposing & Recycling

Repurposing Batteries for the Grid

These is great potential for their repurpussing of lithium ion batteries in electricity grid storage

Energy Supplies & Grid Operations	Batteries can provide backup storage for the grid to compensate for times of inefficiencies between power supply and demand.
Homes & Individuals w Distributed Energy	Individuals can store own energy supply (such as from rooftop solar) at a discounted battery price due to cost reduction during a batteries second life.
Energy Communities	Electricity storage for Energy Communities- systems that seeks to restructure energy with growing popularity and incentivization in Europe.

Growing Context

Lithium-ion batteries can have up to 12 years of useful life, but also have potential for a second life when no longer meeting EV (or marine) performance standards.
The mass disposal of EV batteries is prohibited through policy, resulting in **second life application becoming a necessary** part of the recycling process.

Application

Potential to repurpose WETA batteries for local grid electricity storage, especially in the context of growing threat of outages due to climate change conditions, such as recent heat wave in throughout California. Repurposing additanl Bay Area storage would allow resiliency in such situations.
However, regulatory, reconomic, technical, and logistical constraints as all important considerations in the application of repurposed EV batteries.

Hive Power, EU Commision

LIB Recycling Considerations

Recycling technology is developing and is not yet recycling all minerals

Key Factors	
Companies Early stage	Companies such as Li-cycle are in early stages & cannot yet handle the amount of recycling that will need to be done
Materials Collected Not Suitable for Reuse	Some Industrialized recycling processes are limited and only capable of recovering secondary raw materials, not suitable for direct reuse in new batteries.
Transportation	Estimates for transportation costs vary widely, from more than $0.30/kg to $5/kg, representing, on average, **41% of the total cost of recycling.**

General Market Trends

Automotive use is predicted to dominate the market for li-ion batteries and recycling from 2025-2030.

LI-NMC segment is projected to lead the automotive lithium-ion battery recycling market during the forecast period.

The Centre for Energy Economics states that the **rate of recovery of lithium is only 1-3% globally** from all applications.

High cost of recycling, **unavailability of proper storage systems** for collection of the spent batteries and **lack of technologies** for recycling are all challenges for the market.

Hard To Recycle Electric-Car Batteries, Transportation of batteries, Battery Recycling and Recovery Processes

Recycling methods for LIBs and applications for ASSBs

A combination of these methods is most effective for ASSB recycling as it optimises economic feasibility and efficient production

Worse → Better

Types	Advantages	Disadvantages
Pyrometallurgy	No required sorting/pre-treatment steps involved. Battery packs and modules can be **used directly as feedstock**. Minimal concern for worker safety and reactivity because high furnace temperatures break down potential hazards.	High smelting temperature incurs significant energy costs. Oxidation of materials can supplement energy required, but results in **irrecoverable loss**. This produces significant amounts of CO_2.
Mechanical Separation	"Separates major components using a combination of disassembly, shredding, crushing, and sievings." "**No other practical method exists** to separate and obtain the black mass from discarded batteries at industrial-scale levels."	Issue of Li metal anodes and pliability of sulphide- and polymer-based SSEs create issues with separating black mass from current collectors or passing through mesh filters.
Hydrometallurgy	Has the potential to recycle most LIB components at a **recovery rate over 90%.** Is able to regenerate high-purity materials, handle different cathode chemistries, and has **low-energy cost and gas emissions.**	Complicated process which can be **expensive** when factoring in materials and input costs. Significant amounts of **hazardous waste** solutions can be generated. May not be suitable for all ASSB systems.
Direct Recycling	Attractive for **low energy costs**, lack of significant chemical pollutant/negative externalities. Aged or degraded material can be **regenerated** to a pristine state. One can also achieve a relatively straightforward process of converting received material into components ready for new electricity generation.	**Not yet performed on a commercial scale**, but optimistic success has been recorded in lab-scale studies.

Ideal ASSB and LIB Recycling System

Ideal recycling system put forward by the Worcester Polytechnic Institute

Mechanical Separation

Separate cell packs based on internal chemistry and examine for state of health before being discharged completely.

Subsequent sieving allows for **separation of outer cell pack components** and/or current collectors.

Resulting anode, cathode and SSE powders can be dispersed and washed thoroughly in a polar solvent.

Chemical and Physical Processing

Solution can then be collected and evaporated to **recrystallise sulphide and SSE material**. (Direct Recycling)

Separation of potential PEO-based polymer SSEs is done through **additional washing steps** that can be performed using water or water/alcohol mixtures above 50 centigrade. (Direct Recycling)

Insoluble components can then be separated and **treated using hydrothermal or hydrometallurgical methods**. (Hydrometallurgy)

Policies

EU has demonstrated how "implementing a variety of battery recycling measures, can improve battery collection rates."

Effective policies should consider the **requirement of labels/identifiers and standardisation of cell modules** to assist in sorting and disassembly on industrial level.

Standardisation would allow for effective use of automation and would rely on **labels/identifiers** and **consistency of shape and size recognition to function efficiently**.

Recycling Development in Germany

Mechanical dismantling and a hydrometallurgical process are most effective for battery recycling

BMW	Volkswagen	Mercedes
Currently intending to develop methods to achieve a **96% recycling rate by 2030**. BMW does not publish current recycling rate	VW currently recycles 53% of its battery materials with goals of **achieving 97% battery recycling** in the coming future.	Mercedes has been generally **slower to the EV market**, the development of its battery recycling also lagging behind the other German car manufacturers.
Currently BMW recycles batteries by **shredding** and heating through a **pyrometallurgical process** to melt the materials. This process is generally less energy efficient as alternatives.	Opened first battery recycling plant in 2021. This plant uses a “disassemblage” process, grinding into “black powder”, and treatment by a *hydrometallurgical process*.	Operational in 2023, Mercedes EV recycling plant will have an intended 96% recovery rate. This plant's efficiency will be the highest yet, using mechanical dismantling and *hydrometallurgical process*.
BMW takes back all its battery packs globally, even when not required by local requirements. Batteries are given a second life (energy storage) before recycling.	***A hydrometallurgical process uses an aqueous solution to extract metals from their ores.** This process is outlined as ideal by the Worcester Polytechnic Institute, Volkswagen and Mercedes decisions to implement this same process emphasising the potential of this recycling method. the importance of this processes application to battery recycling.	

BMW, Carscoops, Volkswagen, Ethos, Britannica

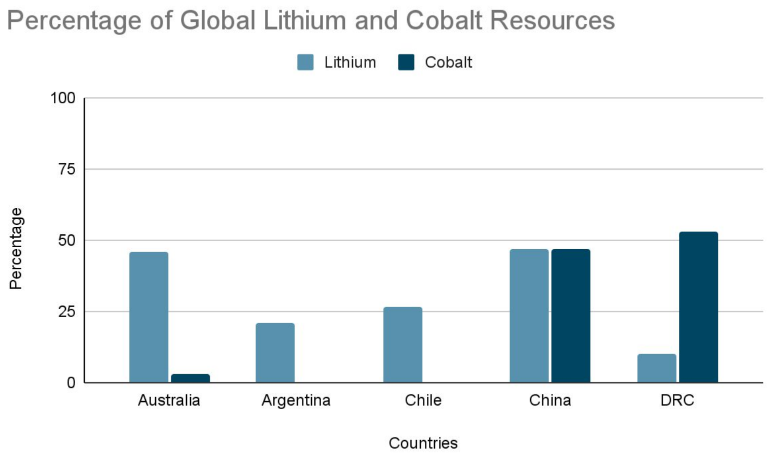
Appendix B

Supply Chain

Issues Associated with Economics of LIBs

Scarcity of resources and geographic monopoly of battery materials results in lack of market transparency.

Scarcity of Resources	Limited availability of lithium and cobalt sources results in **lack of market transparency** in labour regulations and trade policies.
Increasing Demand	Increased demand for LIB-powered vehicles such as EVs has resulted in an exponential increase the market value of associated materials.
Resulting Issues	Growing market of LIBs places additional external pressure for increased production of lithium and cobalt, perpetuating **unsustainable labour and environmental practices**.



Graphical distribution of global cobalt and lithium sources, most of which is concentrated within Australia, Argentina, Chile, China and the Democratic Republic of Congo.

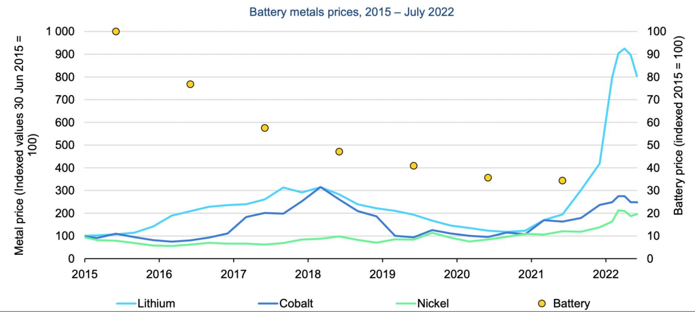
Friends of the Earth, CEMAC

Location of Raw Materials & Market Trends

Fragmented markets for material sourcing pose lower supply concerns

LTO batteries use Lithium Titanate to replace graphite in regular Li-ion batteries in the anode and NMC technology in the cathode

Battery metal prices increased dramatically in early 2022, posing a significant challenge to the EV industry



Li cost **increased sevenfold** from 2020 to 2021 due to increased demand but is expected to **decrease to pre-surge costs by 2025**

Material	Sourcing Location	Additional Comments
Lithium	44% - Australia 34% - Chile 13% - Argentina	LiOH needed for NMC batteries China is the leading consumer of lithium and receives majority of unprocessed Li
Cobalt	59% - DRC 5% - Russia 5% - Australia	Mined cobalt is a byproduct of Ni and Cu China is the biggest importer DRC is the largest exporter
Nickel	11% - Philippines 10% - Canada 9% - Russia 9% - Australia	Volatile market Low supply concerns
Manganese	33% - South Africa 16% - China 14% Australia	Due to higher geographic concentration of source locations, the markets are less transparent Low supply concerns

International Energy Agency, NREL

LFP: Sourcing & Processing

Contaminated water and air pollutants are primary concerns of phosphate mining/processing.

WETA

Development	Extraction	Handling	Beneficiation	Waste	Closure
Land surface disturbance	Land surface disturbance	**Air emissions**	Waste generation	Land surface disturbance	Long term stability
Air emissions	**Water contamination**	**Water contamination**	Water consumption	**Water contamination**	Safety
Water contamination	Water table lowering	Noise	**Water contamination**	**Air emissions**	Future land use
Noise and vibration	**Air emissions**		**Air emissions**	Stability	**Air emissions**
	Topsoil degradation		Noise and vibration	Aesthetic changes	Hazardous waste disposal
	Vegetation and wildlife disruption				
	Noise and vibration				

Potentially concerns with radioactive waste–more of an issue for the agricultural industry.

Air emissions and water contamination are the most frequent environmental issues. Also recurring are noise/vibration and land surface disturbance.

Beneficiation is a processing step that separates phosphates from rock contents.

Environmental Aspects of Phosphate and Potash Mining Radioactive Material From Fertilizer Production | US EPA

NMC Supply Chain: Raw Materials

NMC ratio plays a major role in the sustainability of NMC batteries with all 3 being constrained

Cobalt

The **DRC produces ~⅔ global cobalt** and **contains ~ ½ of global reserves**. **Concerns about labor practices** have been raised by UNICEF, Amnesty, etc. About **10kg CO_2 eq are used per kg cobalt**

Global Cobalt Production

Nickel

Nickel is used most heavily by steel with batteries only using about **5 to 8% of Ni** but that is growing

Batteries can **only use class 1 Ni** which is produced most dominantly by **Russia, China, and Canada**

7.64 kg CO_2 / kg and up to **2kg SO_2 / kg**

Manganese

About **6 kg CO_2 / kg**

Production mixed between South Africa, China, Gabon, Australia and Brazil but S.A. has 80% global reserves

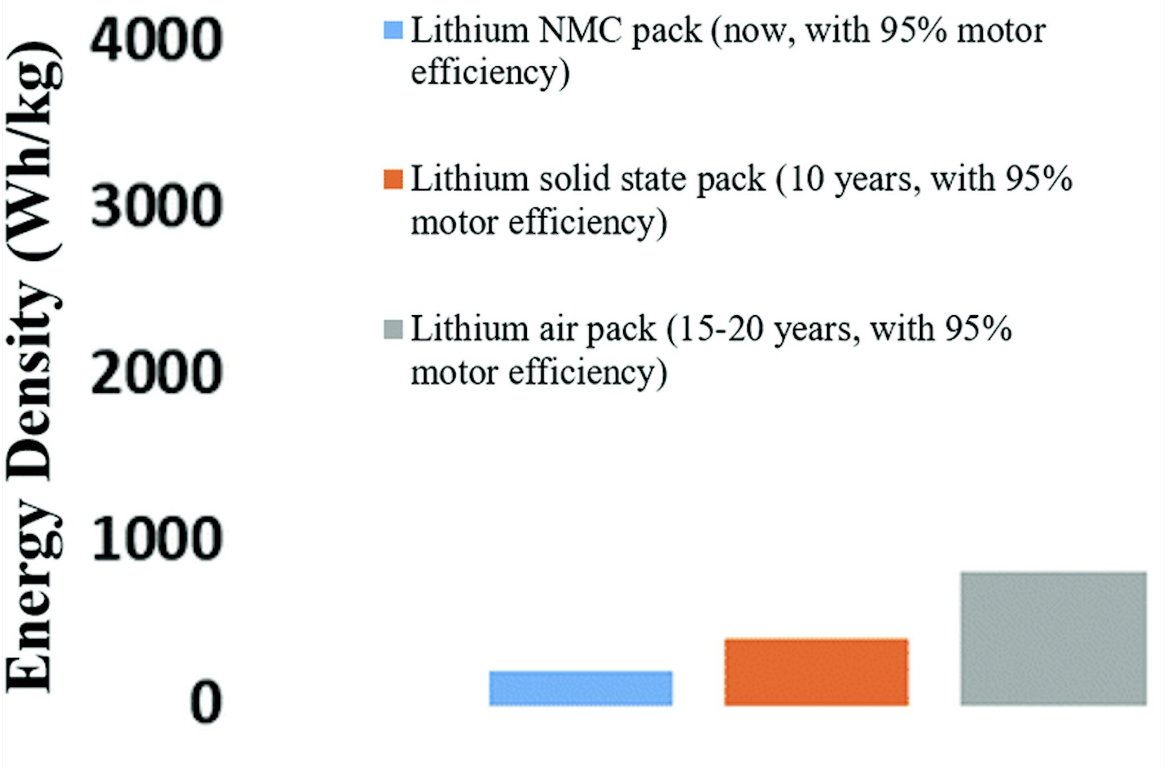
There are concerns about waterway contamination

McKinsey, Mistry et al., Winjobi et al., World Bank, ADBG, Westfall et al.

Energy Densities in Marine Applications Compared

Current energy density NMC and future technologies will allow for better batteries

Fig. 4 Estimated pack-level specific energy of different battery types NMC (currently available) on left, solid state in middle (available in 10 years), Lithium air available in 20



Safety Considerations for all LIBs

Electrical, thermal, and mechanical safety issues often result in overheating or explosions

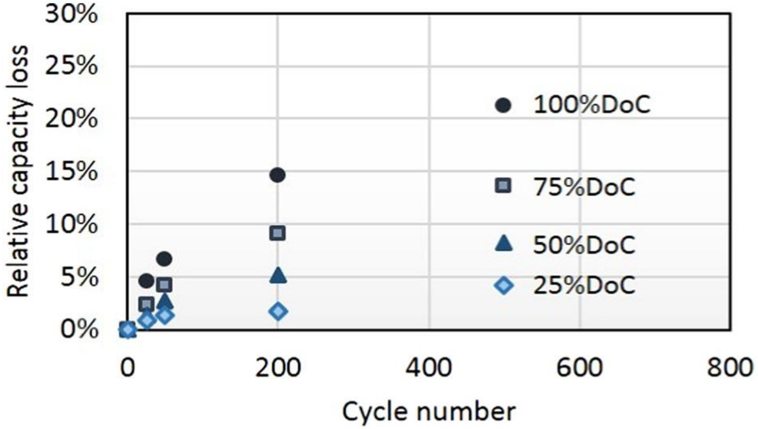
Safety Strategies	Description or implantation of strategy	Helps prevent
Chemical Internal strategies for LIB safety	Safety **enhancement** of each LIB **component**: **active materials**, **separator**, and **electrolyte**. Adding **appropriate additives**. **This would be done by the battery's manufacturer**.	At high-temperature and high-voltage conditions, the electrochemical reactions become complex, leading to **battery rupture and explosion** from hot flammable gases from the battery with the ambient oxygen
Making batteries smaller	Availability of large EV cells should decrease cost & increase performance of marine batteries. However for **safety**, the **authors prefer** many **small cells**, battery **incidents** mostly **start with one cell**. Though increasing the cell number increases probability of incidents, **keeping cell size small** may **reduce** the **severity** of incidents	Severity of most battery incidents regardless of cause
Cooling	**4 types of thermal management systems: (1) air-based systems** electric fans & spacing**, (2) liquid-based systems** containing water, glycols**, (3)** (PCM) **phase-change material -based,** and **(4) heat pipe-based** thermal management systems	Efficient **cooling** is the **most important strategy** for battery incidents most incidents involve overheating cooling also has a **significant effect** on the **actual density** batteries possible
Testing	The essential **tests include overcharging**, **crushing**, subjection to **impacts**, **short-circuiting**, and **penetration** with a **nail**. *standards are different for solid state batteries	Testing is essential for mitigating a broad range of safety issues
Cell Balance (eliminating voltage differences between cells)	comparison of the voltages of all cells after each charging cycle and can be either passive or active. Systems can be internal to the battery or external.	Prevents severe safety issues related to overcharging

[A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards - ScienceDirect]

Solid State Cycle Life

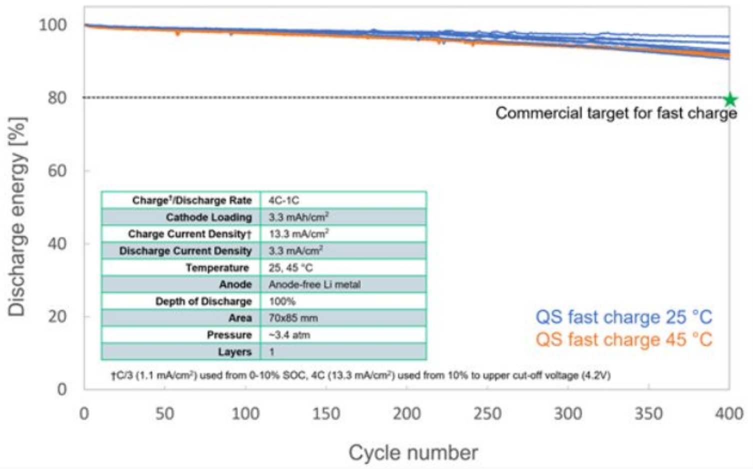
Depth of Discharge plays a significant role in cycle life but it remains high regardless

Complete studies on SSB cycle life and depth as related to depth of discharge were lacking but a few key examples indicate **~70% capacity** being an optimal condition for lifetime preservation



Using regression models with thin film solid state microbatteries, **at 100% charge**, 80% capacity was hit at **~500 cycles** but with **75% charge** a battery was expected to **last over 4000 cycles** and **65% charge** lasting **7000 cycles**

Startup QuantumScape has claims a battery capable of **fully discharging** and **charging from 10% to 80% at a rate of 4C** with about **90% retention** after **400 cycles**.



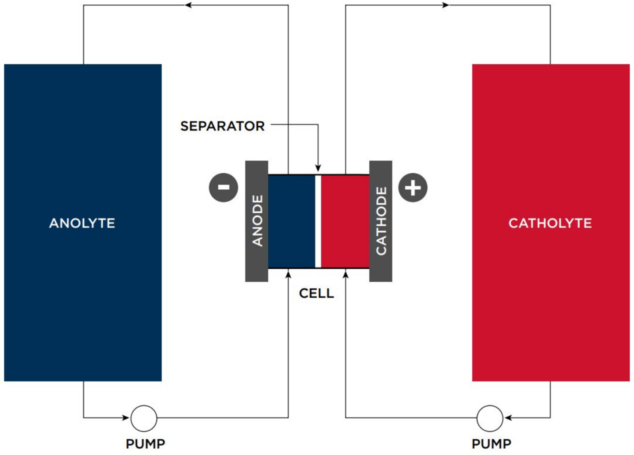
QuantumScape, Grillon et al.

Appendix C

Additional Battery Exploration

Emerging Marine Batteries: REDOX Flow

Redox flow batteries offer long term storage solutions but are not designed for WETA's needs



Redox Flow batteries use **large tanks of two chemicals** that are **pumped together** and reacted in a cell

Advantages

Benefits are easy scaling leading to high capacities and complete shut-off. High stability and low energy loss due to internal dissipation benefits long term storage

Disadvantages

The rates of charge and discharge, while scaleable are costly to increase and slow. **Not for WETA** due to low specific energy and large space requirements.

Current Use Cases

Used by CA for solar energy storage and wind energy storage in Japan. Proposed for auxiliary power and leveling in **large ships** but **not for passenger ferries**

Iron-Chromium Flow Battery

Lower voltage
Higher required internal temperature
Shorter operating Life
Cheaper

Vanadium Flow Battery

Better power density
Greater voltage per unit
Lower internal loss
Temperature dependent
More expensive

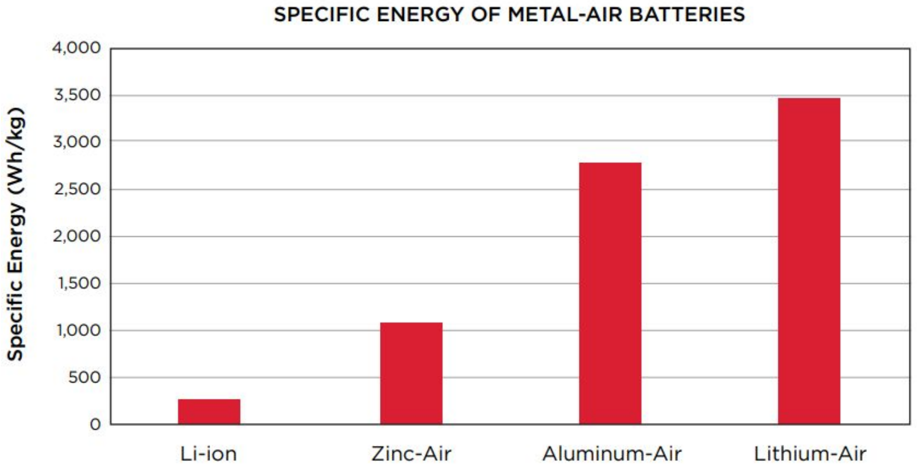
American Bureau Shipping Paper (Image)

Emerging Marine Batteries: MABs

Metal-Air batteries offer massive specific energies but suffer from instability

Metal Air batteries are an emerging technology with the potential for an incredibly **high specific energy** by using air as a cathode greatly **reducing the overall weight and volume**

Current limiting factors include slow cathode reaction requiring new **catalyst**, very low **life cycle** due to **electrolyte instability**, and lack of commercially viable and **rechargeable options**



Zinc-Air Batteries
Used Commercially
Cheapest Option
Not yet rechargeable
Lower of Energy Density

Aluminum-Air Batteries
Used Commercially
Cheaper than Li-Ion
Electrolyte must be replaced instead of recharged

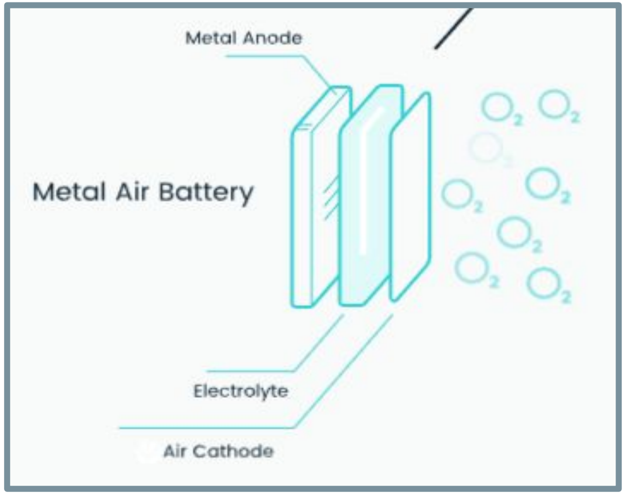
Lithium-Air Batteries
Most expensive
Potential for overheating
Sensitive to atmospheric makeup leading to instability

American Bureau Shipping Paper (Image), Li et al.

Metal-Air TRL and Current Use

Metal air batteries currently lack widespread industry use and rechargeable commercialization

Current Implementation	Currently zinc-air batteries have energy density around **500 Wh/kg** while **Al-air batteries are recycled but not rechargeable** and as such are not useful for WETA. **All other rechargeable MAB remain in R & D**
Future Outlook	**Stability** and **catalysis** are still issues without solutions for rechargeable batteries. Several promising electrolytes have been proposed but none have been used beyond lab scale. **Concrete timeline estimate seem to be too far out**
Industry Players	**Phinergy** which produces Zn-air batteries has signed **preliminary contracts** with material sources for Al-Air EV batteries in India. These would **presumably be rechargeable**. Not date or time estimate was given on their scale or commercialization. Duracell, Arotech, and Renata SA all produce Zinc Air batteries but **do not show plans** of looking **to commercialize a rechargeable** one.



Norway, other players & the state of electric planes

Norway has faced setbacks and other makers of electric planes are small or in early phase

Norway's Avinor

Norway's government airline Avinor's short-haul airliners should be **entirely electric by 2040** all flights lasting up to **1.5 hours**

In 2019, a two-seater **plane crashed** For Avinor, the state-run Norwegian company the **accident** was a **serious setback**. It was the **first** electric **model in the world** approved for **commercial production**.

Other players & batteries

More than **170 programs** aiming to **develop electric aircraft** are underway globally, with about half of them dedicated to urban **air taxis.** See comprehensive chart

All planes are **small** in and in **early stages**, some projects have faced setbacks and been **cancelled**. This lack of success leads to a **lack** of **detailed information** even **though** it **could be** useful for **WETA ferries** even if it didn't work planes.

Li-Ion was used but is having problems **"Lithium ion is not going to get us there,"** But **UCB**; Carnegie Mellon; & IBM, wrapped up a **3-year research** project to evaluate the **lithium-air battery.**

Batteries need a boost to fly the friendly skies, comprehensive chart, A Study of the Potential for Sustainable Aviation in Norway

Li-Air: Could it be the future of Plane Batteries?

Li-Air is promising but is not ready just yet

Li-Air potential and background

Li-O2 batteries **could have** a **maximum** specific energy of **3,460 W h/kg** at the moment, the technology is **limited to** the **lab**
Li-air batteries' **many challenges**, including **stabilizing the cathode**, **protecting the anode**, and **efficiently delivering oxygen** while keeping out other gas contaminants.

But perhaps the technology's **biggest problem** is that the **electrolyte decomposes** rapidly because of **destructive species** formed inside the battery, **limiting** its **rechargeability**.

To power aircraft, Li-air batteries need to **withstand** a **practical number** of **charging cycles**; for instance, current Li-ion batteries last for **thousands** of cycles.

Examples of Li-Air in development

Each pack is a five-cell unit made of a lithium-metal anode, a porous carbon cathode, and an ether-based electrolyte. The team calculates, it **should** have a **practical** specific energy of **about 200 W h/kg** at the cell level. This is only about **5% of Li-air batteries'** elusive **theoretical maximum** specific energy, Lawson says. But he thinks that **when optimized**, the battery pack **could reach 700–800 W h/kg**, the **estimated** energy **requirement for** regional **planes**.

NASA's **battery currently** lasts for only a handful of recharging cycles. By switching the electrolyte from an **ether-based liquid** to one made of **inorganic molten nitrate salts**, the team raised the **number** of **cycles from** about **5 to 25**. Inorganic electrolytes have previously been shown to be stabler than ether-based ones (J. Am. Chem. Soc. 2016, DOI: 10.1021/jacs.5b11744)

They have a long way to go **before becoming practical**, but **"recent progress has been very encouraging".**

Batteries need a boost to fly the friendly skies,

Tosa LTO E-Bus

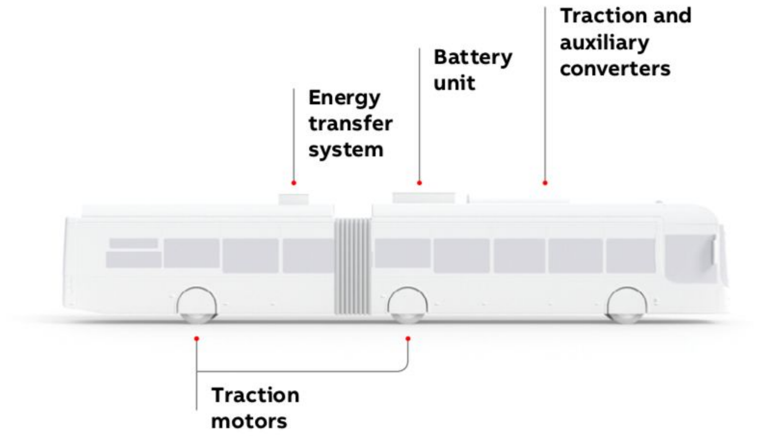
LTO batteries are currently being used in public transportation

Development

This project was first developed in 2013 in collaboration with Geneva public transport (TOSA), ABB engineering, SIG power grid, and OPI project management. This project has been **operational and expanding since 2018**, aiming to replace traditional diesel buses.

Implementation

These buses are engineered with an automatic articulated arm on the bus roof which rises when a bus approaches an equipped charging spot. Within 1 second the bus connects to the rapid charging port where **on-bus LTO batteries are charged for 20 seconds** (average length of a bus stop) with a **600-kilowatt 600 VDV** boost of power. At bus terminals an additional 4 to 5-minute charge enables a more full recharge of the batteries.



Additional considerations

These buses can be used year round in snow, rain, hail, fog, and ice, and are also resistant to dust and pollen pollution. The frequent charging through on bus batteries enables a lighter and more space efficient bus.

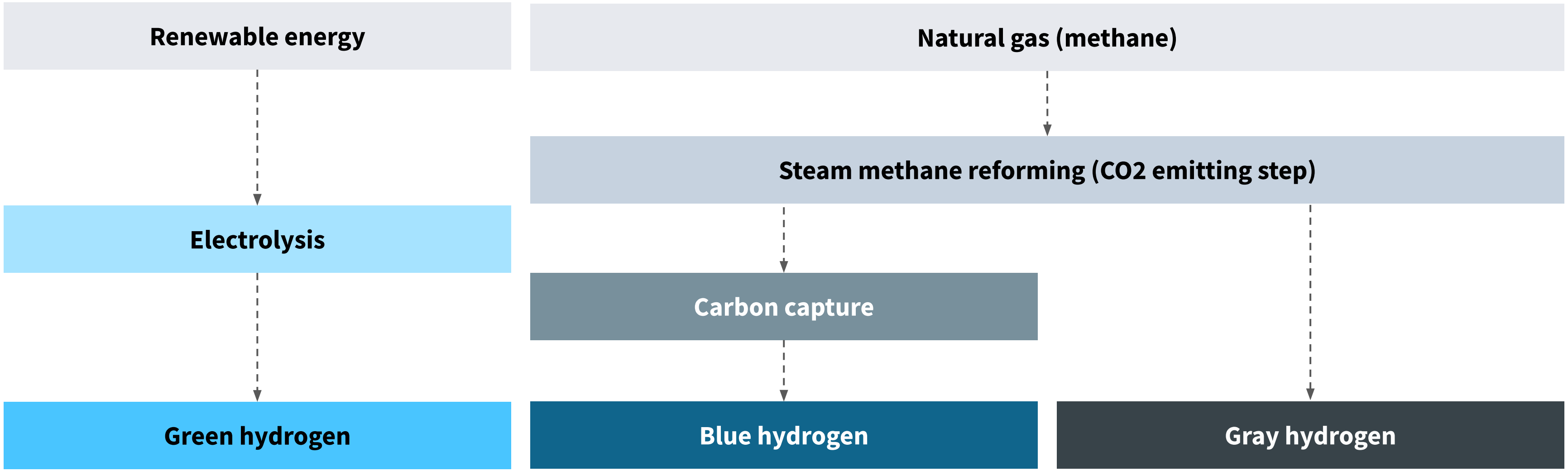
ABB, WirtschaftsWoche, Bundesamt für Energie, Hitachi Energy

Appendix D

Hydrogen

Is Hydrogen a Clean Source of Energy?

Hydrogen is only sustainable when produced through electrolysis



Green hydrogen has **zero carbon emissions** when clean energy is used. Less than 0.1% of global hydrogen is produced through this **expensive** method.

Although considered "low carbon", studies show blue hydrogen to be **dirtier than burning natural gas** directly for heat, producing **13 kg CO_2 per kg H_2.**

Gray hydrogen is **cheap and dirty**, producing **16 kg CO_2 per kg H_2**. It accounts for 75-95% of commercially produced hydrogen.

EIA, IRENA, Forbes, Argonne, PG&E, IEA