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

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

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

- **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

<table>
<thead>
<tr>
<th>Fare Integration Policy</th>
<th>Wayfinding &amp; Mapping</th>
<th>Accessibility</th>
<th>Key Takeaways</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Set the <strong>regional vision</strong> for fare integration <em>(C/F)</em></td>
<td>▪ Set the <strong>regional vision</strong> for wayfinding <em>(C/F)</em></td>
<td>▪ Align on current-state findings and confirm what a regional vision for accessibility (fixed route and paratransit) entails <em>(C/F)</em></td>
<td>1) <strong>Regional Role:</strong> 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.</td>
</tr>
<tr>
<td>▪ Establish regional fare integration policies *(e.g., Tier 3/4) <em>(C/E/F)</em></td>
<td>▪ Establish regional wayfinding policies *(e.g., design standards, compliance requirements) <em>(C/E/F)</em></td>
<td>▪ Establish regional <strong>policies</strong>, definitions, and metrics for accessibility *(e.g., eligibility requirements) <em>(C/E/F)</em></td>
<td>2) <strong>Operator Role:</strong> Operators will be highly involved in regional decision making, provide local stakeholder perspectives / needs, and implement regional policies.</td>
</tr>
<tr>
<td>▪ Establish policy implementation plans, including the <strong>identification of funding</strong> <em>(E/F)</em></td>
<td>▪ Establish policy implementation plans, including the <strong>identification of funding</strong> <em>(E/F)</em></td>
<td>▪ Establish policy implementation plans, including the <strong>identification of funding</strong> <em>(E/F)</em></td>
<td>3) <strong>RNM Framework:</strong> 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).</td>
</tr>
</tbody>
</table>

### 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

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
Item 12: Onboard Passenger Survey Report
ONBOARD PASSENGER SURVEY RESULTS

December 8, 2022
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
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
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
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 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

- 2011: 4.1 days
- 2014: 3.9 days
- 2017: 3.6 days
- 2022: 2.9 days
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
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
WATER EMERGENCY TRANSPORTATION AUTHORITY
Item 14: Fleet Electrification – BEACN Battery Study
Fleet Electrification Study
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 Shrotiyya (she/her)
Associate Consultant
Materials Engineering

MaryClare Rovere (she/her)
Associate Consultant
Env Econ, GIS, Accounting

Luna Hohner (she/her)
Associate Consultant
Society & Environment

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

Liam McDonough (he/him)
Associate Consultant
Chemical Engineering
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.
# Batteries vs Diesel Fuel

Batteries are more cost efficient and environmentally friendly compared to diesel

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Emissions</th>
<th>Costs</th>
<th>Overall Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electric</strong></td>
<td><strong>Zero</strong> Tailpipe Emissions</td>
<td>$0.163 / kWh</td>
<td>Over 10 years with 9 Oakland Alameda trips per day a vessel saves <strong>$3-5 million</strong> and emissions are reduced by <strong>~28 million kg eq CO₂</strong></td>
</tr>
<tr>
<td></td>
<td>~ 0.088 kg CO₂ eq /kWh</td>
<td><strong>$ 185.7 / Trip</strong></td>
<td>Less Cost Volatility</td>
</tr>
<tr>
<td></td>
<td><strong>99.6 kg CO₂ eq/Trip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Diesel</strong></td>
<td>Tailpipe Emissions</td>
<td>$0.32 / kWh</td>
<td><strong>Future Benefits</strong></td>
</tr>
<tr>
<td></td>
<td>~ 0.78 kg CO₂ eq /kWh</td>
<td><strong>$ 4-5 / gallon</strong></td>
<td>Renewable Energy</td>
</tr>
<tr>
<td></td>
<td><strong>937 kg CO₂ eq/Trip</strong></td>
<td><strong>$328 / Trip</strong></td>
<td>Higher Energy Efficiency</td>
</tr>
<tr>
<td></td>
<td><strong>Additional Pollutants</strong> (NO₂, SO₂, PM, etc.)</td>
<td></td>
<td>Improving Technologies</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Variation in oil prices</strong></td>
</tr>
</tbody>
</table>
Batteries are ready to replace diesel in coming years

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

Current range in energy density

Predicted energy density maximum by 2030

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)

- NMC
- LFP
- LTO

## Emergent technologies

- Solid State
- Li-S

## Parameters of Interest

<table>
<thead>
<tr>
<th>Energy Density</th>
<th>Charging Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>Lifetime</td>
</tr>
</tbody>
</table>
Current Batteries: Lithium Ion

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

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

Battery University
Emerging Marine Batteries: Solid State

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

**Advantages**
- Higher Specific Energy
- Faster Charging
- Greater Safety
- Potential for longer lifetime

**Disadvantages**
- Difficulty with Connection
- Internal Resistance
- Implementable Cycle Life Lower
- Greater Uncertainty

**Now**

- **2023**
  - Toyota implements solid state
  - Volkswagen and QuantumScape Pilot Plant

- **2025**
  - Mercedes e-Citaro Bus
  - Mercedes and ProLogium Factory

- **2030**
  - 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

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Technological Readiness and Current Players</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td><strong>LG Chem &amp; KARI</strong></td>
</tr>
<tr>
<td>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</td>
<td>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</td>
</tr>
<tr>
<td><strong>Potential Development</strong></td>
<td><strong>OXIS</strong></td>
</tr>
<tr>
<td>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.</td>
<td>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</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Vibration and Pounding</th>
<th>Marine batteries are designed with heavier plates and robust construction to withstand the vibration and pounding that can occur on board any powerboat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overheating is the most common issue on boats and can be mitigated with cooling systems including:</td>
<td><strong>Energy Density Impact</strong></td>
</tr>
<tr>
<td>(1) air-based systems: electric fans &amp; spacing</td>
<td></td>
</tr>
<tr>
<td>(2) liquid-based systems: water or glycols</td>
<td>NMC battery specific energy in Tesla model 3:</td>
</tr>
<tr>
<td>(3) phase-change material -based cooling systems</td>
<td>86 W h/kg</td>
</tr>
<tr>
<td>(4) heat pipe-based thermal management systems</td>
<td></td>
</tr>
</tbody>
</table>

- The essential tests include **overcharging, crushing, subjection to impacts, short-circuiting**, and **penetration** with a nail.

**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*

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

Marine batteries require additional safety features and casing when compared to EVs resulting in lower usable energy density in the installed battery.
## Ranking Technology by Parameters

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

<table>
<thead>
<tr>
<th>Implemented Energy Density Wh/kg</th>
<th>Charging rate 0-80% SOC</th>
<th>Lifetime / # of cycles At 80% DOD</th>
<th>EFC / # of cycles At 3C, 25 C, 20-80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMC</td>
<td>111-180 Wh/kg</td>
<td>≥ 20 mins</td>
<td>&gt; 6,000 cycles</td>
</tr>
<tr>
<td>LTO</td>
<td>50-80 Wh/kg</td>
<td>≥ 6 mins</td>
<td>&gt; 20,000 cycles</td>
</tr>
<tr>
<td>LFP</td>
<td>90-120 Wh/kg</td>
<td>≥ 20 mins</td>
<td>&gt; 6,000 cycles</td>
</tr>
<tr>
<td>Li-S</td>
<td>300-400 Wh/kg</td>
<td>≥ 30 mins</td>
<td>&gt; 1,700 cycles -5000 cycles</td>
</tr>
<tr>
<td>Solid State</td>
<td>290 Wh/kg*</td>
<td>≥ 25 min</td>
<td>&gt; 1,000 cycles -9000 cycles</td>
</tr>
</tbody>
</table>

**Referenced Sources:**
- 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.**

---

**Total Upfront Cost Projection**

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Cost Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid State</td>
<td>High Estimate</td>
</tr>
<tr>
<td>LFP</td>
<td></td>
</tr>
<tr>
<td>LTO</td>
<td></td>
</tr>
<tr>
<td>Li-S</td>
<td></td>
</tr>
<tr>
<td>NMC</td>
<td></td>
</tr>
</tbody>
</table>

**Predicted Market Size in 5 Years (2027, Million USD)**

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Market Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid State</td>
<td></td>
</tr>
<tr>
<td>LFP</td>
<td></td>
</tr>
<tr>
<td>LTO</td>
<td></td>
</tr>
<tr>
<td>Li-S</td>
<td></td>
</tr>
<tr>
<td>NMC</td>
<td></td>
</tr>
</tbody>
</table>

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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.

## GHG Emissions

<table>
<thead>
<tr>
<th></th>
<th>Lithium</th>
<th>Nickel</th>
<th>Manganese</th>
<th>Cobalt</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lithium</strong></td>
<td>1 tonne of mined</td>
<td></td>
<td>Cradle to gate life cycle of</td>
<td>Extraction results in 10.81 kg CO₂ eq of</td>
<td>Average of 136 CO₂ eq of</td>
</tr>
<tr>
<td></td>
<td>Lithium corresponds to</td>
<td></td>
<td>average manganese alloy</td>
<td>emissions, (9.52 kg CO₂ eq from fossil</td>
<td>GHG emissions associated</td>
</tr>
<tr>
<td></td>
<td>15 tonnes of CO₂</td>
<td></td>
<td>produces ~ 6.0 kg CO₂ eq</td>
<td>fuel based energy use)</td>
<td>with cumulative NMC</td>
</tr>
<tr>
<td></td>
<td>emissions</td>
<td></td>
<td></td>
<td></td>
<td>supply chain</td>
</tr>
<tr>
<td><strong>Nickel</strong></td>
<td>11.19 kg CO₂ eq of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>emissions (high energy-intensive</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>process of extraction)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Manganese</strong></td>
<td>Cradle to gate life cycle of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average manganese alloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>produces ~ 6.0 kg CO₂ eq</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cobalt</strong></td>
<td>Extraction results in 10.81 kg CO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO₂ eq of emissions,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(9.52 kg CO₂ eq from fossil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fuel based energy use)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>Average of 136 CO₂ eq of GHG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>emissions associated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>with cumulative NMC supply chain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Environmental Impacts

<table>
<thead>
<tr>
<th></th>
<th>Lithium</th>
<th>Nickel</th>
<th>Manganese</th>
<th>Cobalt</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lithium</strong></td>
<td>500,000 gal per ton of lithium</td>
<td></td>
<td>Chemical leaching from mining</td>
<td>Water contamination associated with refinement</td>
<td>High water wastage</td>
</tr>
<tr>
<td></td>
<td>purified</td>
<td></td>
<td>and end-of-life handling</td>
<td>and mining</td>
<td>Aquatic pollution</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td>Chemical runoff and poor waste</td>
<td></td>
<td>Chemical leaching from mining</td>
<td></td>
<td>Chemical runoff</td>
</tr>
<tr>
<td><strong>Impacts</strong></td>
<td>rock disposal</td>
<td></td>
<td>and end-of-life handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lithium</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Social Impacts

<table>
<thead>
<tr>
<th></th>
<th>Lithium</th>
<th>Nickel</th>
<th>Manganese</th>
<th>Cobalt</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lithium</strong></td>
<td>Resource exploitation</td>
<td></td>
<td>Toxic chemical exposure</td>
<td>Child labor</td>
<td>Political, social, health</td>
</tr>
<tr>
<td></td>
<td>impacting marginalised</td>
<td></td>
<td>Poor end-of-life handling</td>
<td>Human rights violations</td>
<td>and human rights impacts</td>
</tr>
<tr>
<td></td>
<td>communities</td>
<td></td>
<td></td>
<td>Human trafficking</td>
<td>associated with the</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sexual Exploitation</td>
<td>cumulative NMC supply chain</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unsafe working conditions</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

*Farhana et al., MIT, Westfall et al.*

Battery Tech | Impact | End-of-Life | Next Steps | 18
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**.

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

<table>
<thead>
<tr>
<th>Lifetime CED</th>
<th>Lifetime Specific Energy</th>
<th>Lifetime GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.27 MJ/kWh</td>
<td>401 kWh/kg</td>
<td>25.1 g/kWh</td>
</tr>
<tr>
<td>Has the lowest lifetime CED</td>
<td>Highest lifetime specific energy</td>
<td>Lowest lifetime GWP, contributing the least CO₂ overtime</td>
</tr>
</tbody>
</table>
LFP Supply Chain Impact

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

### Total Energy Consumption of Assembly Process (MJ/kWh)

<table>
<thead>
<tr>
<th></th>
<th>NMC</th>
<th>LFP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>226.38 (MJ/kWh)</td>
<td>261.75 (MJ/kWh)</td>
</tr>
</tbody>
</table>

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%

---

Xin Lai et al, UNEP
Solid State Supply Chain Impact

Solid state supply chain emissions greater than NMC batteries, with the largest CO₂ 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.

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 \( \text{Na}_2\text{S} \) 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)

- **Production**: Use (Plug-to-battery output)
- **Use (Battery output-to-wheel)**
- **End of Life (EoL)**

### Share of Energy Use by Input Material
Although batteries are not emission free, every battery emits less than diesel

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>kg CO₂ eq per kWh capacity</th>
<th>g CO₂ eq per kWh delivered over lifetime (Low Scenario - High Scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFP</td>
<td>93.7</td>
<td>87</td>
</tr>
<tr>
<td>NMC</td>
<td>113</td>
<td>88</td>
</tr>
<tr>
<td>LTO (NMC cathode)</td>
<td>383.6</td>
<td>88</td>
</tr>
<tr>
<td>LiFePO4 (LFP)</td>
<td>1045</td>
<td>127-499</td>
</tr>
<tr>
<td>LiS</td>
<td>89.8</td>
<td>99-102</td>
</tr>
<tr>
<td>LiFePO4 (Blue)</td>
<td>N/A</td>
<td>650</td>
</tr>
<tr>
<td>Diesel</td>
<td>N/A</td>
<td>780</td>
</tr>
</tbody>
</table>

Parameters:
- High Scenario: 160 lbs CO₂ eq / kWh, 13 kg CO₂ eq / kg H₂, 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.

### Relevant Takeaways

**Key Points**

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.**

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

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

### Blueprint Goals

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

### National Blueprint for Lithium Batteries

**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.
End-of-Life Plan

Recycling and Repurposing
End-of-Life: Two Main Paths

Degraded batteries can be repurposed or recycled

<table>
<thead>
<tr>
<th>Repurposing</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries have potential for a second life when no longer meeting marine performance standards but are still functional</td>
<td>When batteries are no longer functional or performance level is no longer useful, batteries must be recycled</td>
</tr>
</tbody>
</table>

- Energy source for the grid
- Residential energy storage at a discount

- Mechanical separation: disassembly, shredding, and filtering
- Chemical separation: smelting, dissolving, and recovery

Hive Power, EU Commission, Worcester Polytechnic Institute
# State of recycling industry summary

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

<table>
<thead>
<tr>
<th>Industry leaders in Battery Recycling</th>
<th>Recycling process</th>
<th>Recycling cost predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based in northern Nevada, <strong>Redwood Materials</strong> 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.</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Based in Georgia, <strong>Battery Resources</strong> 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.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>With 4 locations in the US in Arizona, Ontario, Alabama, and New York, <strong>Li-Cycle</strong> operates internationally. Across its factories in the US, Li-Cycles recycles 30,000 metric tons of lithium-ion batteries annually.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Policy proposal</th>
<th>In Favor</th>
<th>Opposed</th>
<th>Abstain</th>
<th>Level of support (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Core exchange and vehicle backstop</td>
<td>14</td>
<td>0</td>
<td>1</td>
<td>93%</td>
</tr>
<tr>
<td>2a. Producer take-back</td>
<td>10</td>
<td>4</td>
<td>1</td>
<td>67%</td>
</tr>
</tbody>
</table>

---

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 charts: underlying data

**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
Check out the Report!
Technology Overview, Cost Predictions, Environmental Impact Analysis, EOL, and Final Comparisons

[BEACN x WETA] Fleet Electrification Study

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

Emma Ashan, Eula Billaut, Luna Hohner-Meeks, Liam McDonough, Shannon Paulison, Mary Clare Roven, Sanjita Shrestha, Paige Thoonet
Bayside Engineered Transportation Authority (BEACN)

Fleet Electrification Study

December 8, 2022

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Appendix A
Repurposing & Recycling
### Repurposing Batteries for the Grid

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

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

#### 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 additional Bay Area storage would allow resiliency in such situations. However, regulatory, economic, technical, and logistical constraints as all important considerations in the application of repurposed EV batteries.
## LIB Recycling Considerations

Recycling technology is developing and is not yet recycling all minerals.

<table>
<thead>
<tr>
<th>Key Factors</th>
<th>General Market Trends</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Companies Early stage</strong></td>
<td><strong>Automotive use</strong> is predicted to dominate the market for li-ion batteries and recycling from 2025-2030.</td>
</tr>
<tr>
<td></td>
<td>LI-NMC segment is projected to lead the automotive lithium-ion battery recycling market during the forecast period.</td>
</tr>
<tr>
<td><strong>Materials Collected Not Suitable for Reuse</strong></td>
<td>The Centre for Energy Economics states that the rate of recovery of lithium is only 1-3% globally from all applications.</td>
</tr>
<tr>
<td>Companies such as Li-cycle are in early stages &amp; cannot yet handle the amount of recycling that will need to be done</td>
<td><strong>High cost of recycling, unavailability of proper storage systems</strong> for collection of the spent batteries and <strong>lack of technologies</strong> for recycling are all challenges for the market.</td>
</tr>
<tr>
<td>Some Industrialized recycling processes are limited and only capable of recovering secondary raw materials, not suitable for direct reuse in new batteries.</td>
<td></td>
</tr>
<tr>
<td>Estimates for transportation costs vary widely, from more than $0.30/kg to $5/kg, representing, on average, <strong>41% of the total cost of recycling</strong>.</td>
<td></td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Types</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrometallurgy</td>
<td>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.</td>
<td>High smelting temperature incurs significant energy costs. Oxidation of materials can supplement energy required, but results in irrecoverable loss. This produces significant amounts of CO₂.</td>
</tr>
<tr>
<td>Mechanical Separation</td>
<td>“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.</td>
<td>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.</td>
</tr>
<tr>
<td>Hydrometallurgy</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Direct Recycling</td>
<td>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.</td>
<td>Not yet performed on a commercial scale, but optimistic success has been recorded in lab-scale studies.</td>
</tr>
</tbody>
</table>

---

**Worcester Polytechnic Institute**
## Ideal ASSB and LIB Recycling System

*Ideal recycling system put forward by the Worcester Polytechnic Institute*

<table>
<thead>
<tr>
<th>Mechanical Separation</th>
<th>Chemical and Physical Processing</th>
<th>Policies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Separate cell packs based on internal chemistry</strong> and examine for state of health before being discharged completely.</td>
<td>**Solution can then be collected and evaporated to <strong>recrystallise sulphide and SSE material</strong> (Direct Recycling)</td>
<td><strong>EU has demonstrated how “implementing a variety of battery recycling measures, can improve battery collection rates.”</strong></td>
</tr>
<tr>
<td>Subsequent sieving allows for <strong>separation of outer cell pack components</strong> and/or current collectors.</td>
<td><strong>Separation of potential PEO-based polymer SSEs is done through additional washing steps</strong> that can be performed using water or water/alcohol mixtures above 50 centigrade. (Direct Recycling)</td>
<td><strong>Effective policies should consider the requirement of labels/identifiers and standardisation of cell modules</strong> to assist in sorting and disassembly on industrial level.</td>
</tr>
<tr>
<td>Resulting anode, cathode and SSE powders can be dispersed and washed thoroughly in a polar solvent.</td>
<td><strong>Insoluble components</strong> can then be separated and <strong>treated using hydrothermal or hydrometallurgical methods</strong>. (Hydrometallurgy)</td>
<td><strong>Standardisation would allow for effective use of automation and would rely on labels/identifiers and consistency of shape and size recognition to function efficiently.</strong></td>
</tr>
</tbody>
</table>

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Worcester Polytechnic Institute
# Recycling Development in Germany

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

<table>
<thead>
<tr>
<th>BMW</th>
<th>Volkswagen</th>
<th>Mercedes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently intending to develop methods to achieve a <strong>96% recycling rate by 2030</strong>. BMW does not publish current recycling rate.</td>
<td>VW currently recycles 53% of its battery materials with goals of <strong>achieving 97% battery recycling</strong> in the coming future.</td>
<td>Mercedes has been generally <strong>slower to the EV market</strong>, the development of its battery recycling also lagging behind the other German car manufacturers.</td>
</tr>
<tr>
<td>Currently BMW recycles batteries by <strong>shredding</strong> and heating through a <strong>pyrometallurgical process</strong> to melt the materials. This process is generally less energy efficient as alternatives.</td>
<td>Opened first battery recycling plant in 2021. This plant uses a “disassemblage” process, grinding into “black powder”, and treatment by a <strong>hydrometallurgical process</strong>.</td>
<td>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 <strong>hydrometallurgical process</strong>.</td>
</tr>
<tr>
<td>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.</td>
<td><em>A hydrometallurgical process uses an aqueous solution to extract metals from their ores.</em> 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.</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Sourcing Location</th>
<th>Additional Comments</th>
</tr>
</thead>
</table>
| 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 |

Li cost increased sevenfold from 2020 to 2021 due to increased demand but is expected to decrease to pre-surge costs by 2025.
LFP: Sourcing & Processing

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

<table>
<thead>
<tr>
<th>Development</th>
<th>Extraction</th>
<th>Handling</th>
<th>Beneficiation</th>
<th>Waste</th>
<th>Closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land surface disturbance</td>
<td>Land surface disturbance</td>
<td>Air emissions</td>
<td>Waste generation</td>
<td>Land surface disturbance</td>
<td>Long term stability</td>
</tr>
<tr>
<td>Air emissions</td>
<td>Water contamination</td>
<td>Water contamination</td>
<td>Water consumption</td>
<td>Water contamination</td>
<td>Safety</td>
</tr>
<tr>
<td>Water contamination</td>
<td>Water table lowering</td>
<td>Noise</td>
<td>Water contamination</td>
<td>Air emissions</td>
<td>Future land use</td>
</tr>
<tr>
<td>Noise and vibration</td>
<td>Air emissions</td>
<td>Air emissions and water contamination are the most frequent environmental issues. Also recurring are noise/vibration and land surface disturbance.</td>
<td>Air emissions</td>
<td>Stability</td>
<td>Air emissions</td>
</tr>
<tr>
<td>Potentially concerns with radioactive waste–more of an issue for the agricultural industry.</td>
<td>Topsoil degradation</td>
<td>Vegetation and wildlife disruption</td>
<td>Noise and vibration</td>
<td>Aesthetic changes</td>
<td>Hazardous waste disposal</td>
</tr>
</tbody>
</table>

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 CO₂ eq are used per kg cobalt.

- **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 CO₂ / kg and up to 2kg SO₂ / kg.

- **Manganese**
  - About 6 kg CO₂ / kg.
  - Production mixed between South Africa, China, Gabon, Australia and Brazil but S.A. has 80% global reserves.
  - There are concerns about waterway contamination.

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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

- Lithium NMC pack (now, with 95% motor efficiency)
- Lithium solid state pack (10 years, with 95% motor efficiency)
- Lithium air pack (15-20 years, with 95% motor efficiency)
### Safety Considerations for all LIBs

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

<table>
<thead>
<tr>
<th>Safety Strategies</th>
<th>Description or implantation of strategy</th>
<th>Helps prevent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Internal strategies for LIB safety</td>
<td>Safety enhancement of each LIB component: active materials, separator, and electrolyte. Adding appropriate additives. This would be done by the battery’s manufacturer.</td>
<td>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</td>
</tr>
<tr>
<td>Making batteries smaller</td>
<td>Availability of large EV cells should decrease cost &amp; 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</td>
<td>Severity of most battery incidents regardless of cause</td>
</tr>
<tr>
<td>Cooling</td>
<td>4 types of thermal management systems: (1) air-based systems electric fans &amp; spacing, (2) liquid-based systems containing water, glycols, (3) (PCM) phase-change material-based, and (4) heat pipe-based thermal management systems</td>
<td>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</td>
</tr>
<tr>
<td>Testing</td>
<td>The essential tests include overcharging, crushing, subjection to impacts, short-circuiting, and penetration with a nail. *standards are different for solid state batteries</td>
<td>Testing is essential for mitigating a broad range of safety issues</td>
</tr>
<tr>
<td>Cell Balance (eliminating voltage differences between cells)</td>
<td>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.</td>
<td>Prevents severe safety issues related to overcharging</td>
</tr>
</tbody>
</table>

*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.
Emerging Marine Batteries: REDOX Flow

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

**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**.

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**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

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

Olabi Et al., Phinergy
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 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.

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

<table>
<thead>
<tr>
<th>Development</th>
</tr>
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<tbody>
<tr>
<td>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 <strong>operational and expanding since 2018</strong>, aiming to replace traditional diesel buses.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Implementation</th>
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<tbody>
<tr>
<td>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 <strong>on-bus LTO batteries are charged for 20 seconds</strong> (average length of a bus stop) with a <strong>600-kilowatt 600 VDV</strong> boost of power. At bus terminals an additional 4 to 5-minute charge enables a more full recharge of the batteries.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Additional considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
</tr>
</tbody>
</table>

**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.

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

- **Natural gas (methane)** → **Steam methane reforming (CO2 emitting step)** → **Carbon capture** → **Blue hydrogen**
  - Although considered “low carbon”, studies show blue hydrogen to be **dirtier than burning natural gas** directly for heat, producing **13 kg CO2 per kg H2**.

- **Natural gas (methane)** → **Steam methane reforming (CO2 emitting step)** → **Carbon capture** → **Gray hydrogen**
  - Gray hydrogen is **cheap and dirty**, producing **16 kg CO2 per kg H2**. It accounts for 75-95% of commercially produced hydrogen.

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