Creating a Sustainable Battery Framework for a Climate Neutral Future

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Today, according to the Mauna Loa Observatory in Hawaii, the atmospheric CO₂ levels increased to an average of nearly 420 parts per million, about 50% higher than before the Industrial Revolution levels (280 ppm).

According to Berkeley Earth and UK Hadley Center, the global mean surface temperature in 2020 is estimated as 1.27 °C above the average temperature in the late nineteenth century.
Use of Li-ion batteries TODAY

→ Total lifecycle greenhouse gas emissions of EVs are around half those of internal combustion engine cars on average, with the potential for a further 25% reduction with low-carbon electricity.
Traditional Li-ion

During discharge, the lithium ions leave the graphite, and move to the cathode then intercalate into the layered structure of the LiCoO$_2$. And during charge, the lithium ions leave the cathode and move to the anode side, then intercalate into the layered structure of graphite, so the chemistry of traditional lithium-ion batteries is the intercalation/deintercalation of lithium ions.

- For the traditional graphite-LiCoO$_2$ battery, the theoretical capacity of graphite is 372 mAh/g, and the theoretical capacity of LiCoO$_2$ is 270 mAh/g.
- So for the full cell, the cathode limits the overall capacity of Li-ion batteries.
- But in reality, the specific capacity for LiCoO$_2$ is only 140 mAh/g, that is because the LiCoO$_2$ cannot to be fully transferred into CoO$_2$, because Co$^{4+}$ is not stable, the cathode lose layered structure at this point, so only half amount of Li can be fully extracted. That further reduce the capacity of the full cell.
- For the next-generation Li-ions, we need far more capacity than this.

\[ \text{Li}_{0.5}\text{CoO}_2 + 0.5 \text{Li}^+ + 0.5e^- \leftrightarrow \text{LiCoO}_2 \text{ (cathode)} \]
\[ \text{LiC}_6 \leftrightarrow C_6 + \text{Li}^+ + e^- \text{ (anode)} \]
The global demand for batteries is expected to increase from 280 GWh in 2021 to over 2,035 GWh by 2030. This large increase is mainly due to the electrification of transport which will account for the vast majority of battery demand in 2030 in terms of total energy storage capacity.

US battery production capacity could increase to about 80 GWh per year by 2023.
Understanding the battery supply chain is particularly important for the strategic planning and to secure critical materials supply and enable a circular economy.

Beyond the US, South Korea and Japan are major countries supplying batteries to the US market.

70% of battery cells and 87% of battery packs produced in the US in 2020 is from a single player, Tesla/Panasonic
### China Leads

<table>
<thead>
<tr>
<th>Rank</th>
<th>Company</th>
<th>2021 Market Share</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>CATL</td>
<td>32.5%</td>
<td>China</td>
</tr>
<tr>
<td>#2</td>
<td>LG Energy Solution</td>
<td>21.5%</td>
<td>Korea</td>
</tr>
<tr>
<td>#3</td>
<td>Panasonic</td>
<td>14.7%</td>
<td>Japan</td>
</tr>
<tr>
<td>#4</td>
<td>BYD</td>
<td>6.9%</td>
<td>China</td>
</tr>
<tr>
<td>#5</td>
<td>Samsung SDI</td>
<td>5.4%</td>
<td>Korea</td>
</tr>
<tr>
<td>#6</td>
<td>SK Innovation</td>
<td>5.1%</td>
<td>Korea</td>
</tr>
<tr>
<td>#7</td>
<td>CALB</td>
<td>2.7%</td>
<td>China</td>
</tr>
<tr>
<td>#8</td>
<td>AESC</td>
<td>2.0%</td>
<td>Japan</td>
</tr>
<tr>
<td>#9</td>
<td>Guoxuan</td>
<td>2.0%</td>
<td>China</td>
</tr>
<tr>
<td>#10</td>
<td>PEVE</td>
<td>1.3%</td>
<td>Japan</td>
</tr>
<tr>
<td>n/a</td>
<td>Other</td>
<td>6.1%</td>
<td>ROW</td>
</tr>
</tbody>
</table>

- China alone covers nearly 44% of the EV battery manufacturing market.
- Contemporary Amperex Technology Co. Limited (CATL) has risen in less than 10 years to become the biggest global battery group.
- China also hosts the fourth biggest battery manufacturer, Warren Buffett-backed BYD.
The Success Story of CATL

- CATL market share in China is 50%, accounting for nearly 33% globally. CATL valuation is nearly $186bn in just 10 years.

- The Chinese company provides lithium iron phosphate (LFP) batteries to Tesla, Peugeot, Hyundai, Honda, BMW, Toyota, Volkswagen, and Volvo, and shares in the company gained 160% in 2020, lifting CATL’s market capitalization to almost $186 billion.

- CATL counts nine people on the Forbes list of global billionaires. Its founder, Zeng Yuqun, born in a poor village in 1968 during the Chinese Cultural Revolution, is now worth almost as much as Alibaba founder Jack Ma.

- They have become a critical supplier to the country's fast-rising EV industry and recently signed Tesla as a big customer. This is a nonbinding production pricing agreement.
CATL grew rapidly with the help of government policies, and a ban on foreign companies.

CATL passed LG Chem and Samsung SDI for consumer electronics.

Chinese government acquires lithium, nickel and rare earth materials to the battery manufacturers. These Chinese companies are responsible of the global 62% of Co supply.

CATL produces prismatic cells --> safer

LiFeP batteries without Co, Ni, Mn, 80 Gigawatt hour cells, lower cost, --> Tesla will save $600-1200 per car with LFP batteries from CATL

CATL’s Cell --> Pack technology, increases energy density by 10-15% and improves volume utilization by 15-20%, reduces parts needed by 40%

Na battery moving forward --> shortage in lithium

CATL’s 1/5th of 24,000 staff are working on R&D. CATL’s spent 11% of their revenue on R&D.

CATL announces $5 Billion battery recycling facility for their battery materials Co and Li

Figure 1 EV sales, by region

Sources: IEA 2019, “Global EV Outlook 2019.”
Subsidies for Competitiveness

- **China**, spent $58 billion on subsidies through 2018, keeping EV prices low.
  - In **China**, EV purchase was exempted from vehicle purchase tax.
  - China’s subsidy program encourages automakers to sell EVs below manufacturing costs. China’s subsidies fueled its electric-vehicle boom.
  - China’s new energy vehicle mandate, has set a quota for zero-emissions vehicles that automakers must cell and provides credit targets. EVs must account for 3-4% of Chinese automaker’s production.
  - China now provides performance-based subsidies.
  - Many provincial and local governments also promote EV charging.
  - China has one nationwide EV fast charging standard, known as China GB/T and government helps to build the infrastructure for charging stations.
  - Policies to study from the Chinese government’s multiyear planning with respect EV charging infrastructure, as well as China’s investment in data collection on EV charging.

- In **Norway**, incentives including tax exemptions — purchase and import tax, 25% VAT, annual road tax, 50% of road and ferry tolls, 50% parking fees.
Subsidies for Competitiveness

- **The European Union mandate,**
  - Starting in the years 2025 and 2030, Regulation (EU) 2019/631 sets stricter EU fleet-wide CO2 emission targets, which are defined as a percentage reduction from the 2021 starting points.
  - **Tax reduction and exemptions**
  - **Clean Vehicles Directive,** requires public procurement of electric buses
  - **Energy Performance Directive,** EV charging infrastructure in new buildings

- **California’s zero emission vehicle mandate,**
  - Auto manufacturers are required to produce a number of ZEVs and plug-in hybrids each year, based on the total number of cars sold in California by the manufacturer. Manufacturers with higher overall sales of all vehicles are required to make more ZEVs. Requirements are in terms of percent credits, ranging from 4.5 percent in 2018 to 22 percent by 2025. Auto manufacturers are to produce vehicles and each vehicle receives credits based on its electric driving range.
  - **IRS** tax credit up to $7,500 per EV purchase up to 200,000 EVs sold. Colorado, Lousiana, Maryland and New York give additional tax credits. Inspection exemptions from North Carolina and Columbia. Free access to the carpool lane and parking in Arizona, Hawaii and California. However, Alabama charge annual EV ownership fees in additional to registration fees to offset the cost of building infrastructure.
Battery Rush and Competitiveness

- In 2021 the USA has the following battery plants in production:
  - Tesla Gigafactory (Sparks, Nevada)
  - Tesla Pilot Plant (Fremont, California)
  - Envision AESC (Smyrna, Tennessee)
  - LG Energy Solution (Holland, Michigan)
  - SK Innovation (Commerce, Georgia)

- Panasonic plans to invest $100M in a battery plant in US for Tesla

- GM and LG Chem announced plans to produce battery cells in Ohio

- Samsung SDI opened a facility in Hungary

- CATL is building a plant in Germany

- Volkswagen announced to build six-gigawatt factories, Germany and Sweden to start

- SK Innovation a new plant in Georgia
Pros and cons of different lithium-ion positive electrode materials

Kia, Hyundai, BMW, Mercedes-Benz

Tesla

CATL

Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.
A single car lithium-ion battery pack (of a type known as NMC532) could contain around 8 kg of lithium, 35 kg of nickel, 20 kg of manganese and 14 kg of cobalt, according to figures from Argonne National Laboratory.
→ **Lithium** sees the fastest growth, with demand growing by **over 40 times** in the Sustainable Development Scenario by 2040, followed by **graphite, cobalt and nickel** (around **20-25 times**).
A typical electric car requires six times the mineral inputs of a conventional car.
Where do minerals come from?

<table>
<thead>
<tr>
<th>Table 2 LIB materials mining production, 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LIB material ores and concentrates</strong></td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Lithium</td>
</tr>
</tbody>
</table>

→ Lithium

- Rio Tinto, an Anglo-Australian conglomerate, announced in October 2019 that a large source of lithium in California is discovered.
- Lithium has generally not faced political instability risks.
Where do minerals come from?

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Source Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>Democratic Republic of Congo (64 percent), Cuba (4 percent), Russia (4 percent),</td>
</tr>
<tr>
<td></td>
<td>Australia (3 percent)</td>
</tr>
<tr>
<td>Graphite (natural)</td>
<td>China (68 percent), Brazil (10 percent), India (4 percent)</td>
</tr>
<tr>
<td>Nickel</td>
<td>Indonesia (24 percent), Philippines (15 percent), Russia (9 percent)</td>
</tr>
</tbody>
</table>


→ Cobalt
Because of Congo’s political instability, poor labor conditions, sourcing Co faces significant challenges. --> **Companies attempting to eliminate or reduce the amount of Co in batteries.**

→ Graphite
Obtaining graphite for EVs does not currently pose difficult geopolitical obstacles. China, Japan and US are the world’s larger exporters of artificial graphite.

→ Nickel
Lower cost, high energy density and storage capacity. US has minimal reserves. The largest competing demand for nickel is for use in stainless steel manufacturing. In 2018, China exported almost all reserves from Indonesia and Philippines.
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→ 8300 million metric tons of plastics are produced.
→ In 2015, 6300 Mt of plastic waste had been generated.
→ 9% had been recycled, 12% was incinerated
→ 79% was accumulated in landfills or the natural environment
• Plastic bottles estimated decomposition is 450 years
• Glass bottles is undetermined

→ Can we use both plastic and glass waste to make batteries?
**OZKAN GROUP Innovative Battery Materials: Batteries from Sustainable and Natural Resources**

**Portabello Mushroom Battery**
1. **Biomass, no harsh chemicals**
2. ~15% Cost saving
3. Lightweight: without binder
4. Capacity of 410 mAh/g at C/5 1700 cycles

**Sand Battery**
1. **Silicon from beach sand**
2. ~30% Cost saving
3. Capacity of 1024 mAh/g after 1000 cycles at C/2

**Glass Waste Bottle Battery**
1. **Silicon from glass waste**
2. ~30% Cost saving
3. Capacity at C/2 1800 mAh/g
4. 1420 mAh/g at C/2 rate after 400 cycles

Source: Ozkan et. al. Technology and Innovation, the Proceedings of National Academy of Inventors, 2021
OZKAN GROUP Innovative Battery Materials: Batteries from Sustainable and Natural Resources

Carbon Coated Silicon Nanofiber Paper

1. ~25% cost saving and ~6% weight saving
2. Freestanding electrode without binder or current collector,
3. Capacity of 802 mAhg⁻¹ after ~700 cycles at C/10

Diatomite Battery

1. Bio-silicon from diatoms
2. Capacity of 1102 mAhg⁻¹ after 50 cycles at C/5.
3. Capacity of 654 mAhg⁻¹ at 4C.

Plastic Waste Bottle Battery

1. Carbon from plastic waste
2. Supercapacitors and batteries

Source: Ozkan et. al. Technology and Innovation, the Proceedings of National Academy of Inventors, 2021
Ozkan Advanced Battery Technology
Great Battery Candidate for EVs!

➢ LCO-Si-C Rechargeable Pouch Format Battery

PERFORMANCE & COST:
➢ 33% better performance compared to commercial Panasonic NCA/NMC (TESLA) with 805 Wh/L; 290 Wh/kg
➢ ~30% reduced cost with about 120 $/kWh

Pouch Battery: 15 layers, 85x50x4 mm; 4.2-4.3V; 805 Wh/L; 290 Wh/kg

UCR Confidential
OZKAN GROUP Innovative Battery Materials: Lowering the cost and minerals use

Ni–NiO nanofiber cloth anode

1. High capacity
2. High rate
3. Capacity of 680 mAh/g @ C/2
4. Free-standing no Cu

NiO Nanowire Foam

1. Long Cycle Life
2. Ultrahigh Rate Capability
3. Capacity of 1054 mAh/g @ 3C
4. Template Free and Binderless

Source: Ozkan et. al. Technology and Innovation, the Proceedings of National Academy of Inventors, 2021
Ni-rich Cathodes

Cathodes. High-nickel layered cathode materials. HF Attack,

- HF is generated by liquid electrolyte decompose
- HF react with NMC cathode and cause metal ions dissolve into electrolyte
- The cathode lose Ni, Mn and Co elements – surface structure damaged

Nano-layer MnF2 coated NMC811 was designed to stop HF attack on the surface of electrode.

There are 3 reasons that we choose MnF2 as the coating materials:
1. Metal fluoride coating layer provides better conductivity than metal oxide.
2. Metal fluoride is stable in HF, which can protect the cathode particles against HF attack.
3. Based on the literature results, Mn dissolution is the most severe one among Ni, Co and Mn, we hope MnF2 coating could decrease the Mn dissolution.
All solid state batteries

ASSB. Inflammable, safer. High interfacial resistance, low ionic conductivity, electrochemical/mechanical/thermal instability

Ionic conductivity $\sigma = \frac{d}{R_b \times A}$

$d =$ thickness
$R_b =$ bulk resistance
$A =$ area of the solid electrolyte pellet

$\sigma = 0.14 \, \text{cm}^{-72.148 \times 0.51335 \, \Omega} \times 3.78 \, \text{mS/cm}$

Proposed Li-S all-solid-state battery
Future of Batteries

→ Solid state batteries is a step towards moving away from traditional liquid electrolytes

Japan's Toyota Motor Corp (7203.T) is one of the front runners to mass produce solid-state batteries. It has said it is struggling with their short service life but still intends to start making them by mid 2020s. read more

In addition to Toyota's in-house research, it has teamed up with Japan's Panasonic Corp (6752.T) to develop these powerpacks with their Prime Planet Energy & Solutions Inc venture.

Close on their heels Germany's Volkswagen (VOWG.p.DE) has invested in Bill Gates-backed U.S. battery firm QuantumScape Corp (QS.N), which aims to introduce its battery in 2024 for VW's EVs and eventually for other carmakers.

VW says the battery will offer about 30% more range than a liquid one and charge to 80% capacity in 12 minutes, which is less than half the time of the fastest charging li-ion cells now available.

Stellantis (STLA.MI), formed in January by the merger of Italian-American automaker Fiat Chrysler and France's PSA, has a venture called Automotive Cells Co with TotalEnergies (TTEF.PA) and a partnership with China's Contemporary Amperex Technology Co Ltd (CATL) (300750.SZ). Stellantis intends to introduce solid-state batteries by 2026. read more

Ford Motor Co (F.N) and BMW AG (BMW.DE) have invested in startup Solid Power, which says its solid-state technology can deliver 50% more energy density than current lithium-ion batteries. Ford expects to cut battery costs by 40% by mid-decade. read more

South Korea's Hyundai Motor (005380.KS), which has invested in startup SolidEnergy Systems, plans to mass produce solid-state batteries in 2030. read more

Samsung SDI Co Ltd (006400.KS), an affiliate of Samsung Electronics Co Ltd (005930.KS), is working on developing solid-state batteries.

EV market leader Tesla Inc (TSLA.O) has so far not said it wants to develop or use solid-state cells in its cars.
Future of Batteries

→ Moving beyond Li: Na, Mg, Ca, Al
→ None of the beyond Li chemistries are straightforward, with the possible exception of Na, where many of the learnings for LIBs can be applied. But even here, there are distinct differences, due to the larger size of Na which favors different coordination environments and lattices (e.g., graphite cannot accommodate Na), and the higher solubility of the Na salts in the SEI, which means that different electrolyte additives are required.

→ LIBs require four key materials, lithium, cobalt, nickel and graphite. Because these materials are globally dispersed and face sourcing challenges in a setting of anticipated demand growth, comprehending their global value chain is vital.
→ With expected EV rush, stakeholders will need to expand LIB material resource availability. Import, export, and trade policies need to be polished.
→ Chip shortage for EVs
→ **We must learn how to control metastable materials**—from their initial synthesis, to their stability in non-equilibrium and harsh environments—be it temperature or voltage.

→ **We must learn how to control interfacial structures**—from the SEI, to the interfaces between two components in a solid state-state battery.

→ **Better structural models of these interfaces are needed**, to improve our ability to compute the relevant processes with realistic computational resources, and improve our understanding of how they function.

→ **Ideas of self-healing systems** have emerged in the polymer space and have been suggested as potential safety shut-down mechanisms, but looking forward, these concepts must translated into cathode and anode chemistry.

→ **We must continue to develop new methods to increase our understanding of the multiple non-equilibrium processes in batteries**: with increasing technology demands, coupled with Zero-Carbon goals that dictate reduced and more sustainable energy usage, the need for basic and applied research is more important than ever, with many fundamental scientific challenges remaining in the road ahead.
The END

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