Battery BLUprint

Innovation & Investment Outlook

August 2023

BLUME

Contents

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However, any/all errors, omissions and inaccuracies are the sole responsibility of the lead author.

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Part 1:

Battery Basics

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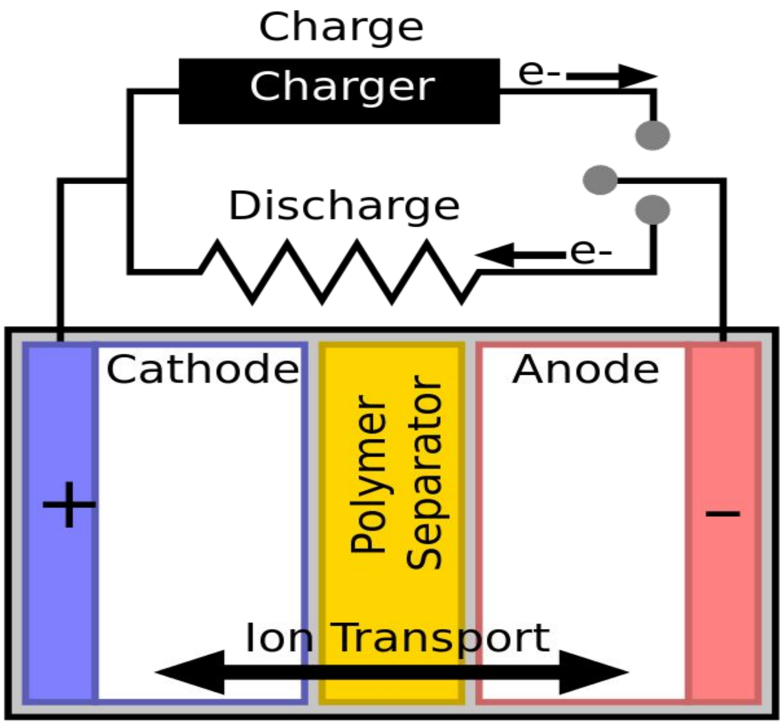
What is a Cell?



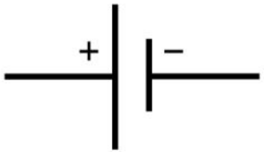
A **cell** is a device which converts chemical energy to electrical energy and vice versa. It consists of two electrodes, a positive electrode called the cathode and a negative electrode called the anode, immersed in an electrolyte solution separated by a separator. The electrodes are made of different materials, and their chemical reactions generate a flow of electrons.

During a discharging cycle, electrons flow from the anode to the cathode and the opposite occurs during a charging cycle.

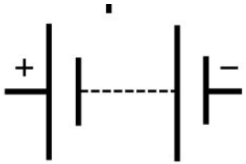
This flow of electrons between the electrodes can be used as a way to store energy over multiple charge-discharge cycles.

A **battery** is a combination of cells connected in series, parallel, or a combination of both to achieve the desired voltage and capacity. Sometimes “battery” is used interchangeably with “cell”.

Cell vs Battery



A cell is a device which converts chemical energy to electrical energy and vice versa



A battery is a collection of cells

- Battery
  - Primary Battery
  - Secondary Battery
- Cell
  - Dry Cell
  - Wet Cell
  - Reserve Cell
  - Fuel Cell

Types of Batteries

Primary Batteries: *Non-Rechargeable Single Use Batteries*

Alkaline Battery

Aluminium-air Battery

Lithium Coin Cell Battery

Secondary Batteries: *Rechargeable Multiple Use Batteries*

Li-ion Battery

Lead-Acid Battery

Ni-MH Battery

Na-Ion Battery

Making Sense of the Jargon… 1/2

Cycle Life

Cycle life refers to the number of complete charge and discharge cycles that a battery can undergo before its performance deteriorates significantly. It represents the lifespan of a battery.

Specific Energy/Power

Specific energy (Wh/kg) refers to the amount of energy that can be stored in a battery per unit mass.
Specific power (W/kg), on the other hand, refers to the rate at which a battery can deliver energy per unit mass.

Energy/Power Density (Volumetric and Gravimetric)

Volumetric Energy Density (Wh/L) is the nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Whereas, Gravimetric Energy Density is the same as Specific Energy (Wh/kg).
And similarly for Power (W/L or W/kg)

Making Sense of the Jargon... 2/2

C-Rate

A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour.

State of Charge (SOC%)

State of charge (SOC) % refers to the amount of energy remaining in a battery as a percentage of its total capacity. It provides an indication of how much energy is available in the battery at a given time.

Depth of Discharge (DoD)

Depth of discharge (DoD) refers to the extent to which a battery has been discharged relative to its total capacity. It is expressed as a percentage and indicates the amount of energy that has been drawn from the battery.

Geometries of Cells

Cylindrical Cells

PROS
1. Robust & Durable
2. Higher heat dissipation

CONS
1. Limited design flexibility
2. Lower packing efficiency

The 18650 & 21700 cells popularly used by Tesla are cylindrical

Pouch Cells

PROS
1. High Energy Density
2. Design Flexibility

CONS
1. Vulnerability to physical damage
2. Limited thermal stability

General Motors, Hyundai and Ford use pouch cells in their EVs

Prismatic Cells

PROS
1. Space efficient design
2. Enhanced stability & safety

CONS
1. Limited design flexibility
2. Poor heat dissipation

Panasonic, Samsung & LG use prismatic cells in several laptops

Button Cells

PROS
1. Long shelf life
2. Compact & Lightweight

CONS
1. Limited energy capacity
2. Limited current output

Button cells are used for testing chemistries at the lab scale

Evolution of Batteries

1859

Lead-Acid Battery, the oldest form of rechargeable battery was invented

1866

First dry cell, Leclanche battery made of **Zinc-Carbon** was manufactured

1899

First alkaline battery with higher energy density, the **Ni-Cd** battery was invented

1960s

Alkaline batteries replace Zn-C batteries supplying greater energy at high current

1991

The first **Li-ion battery** prototype was commercialized by Sony

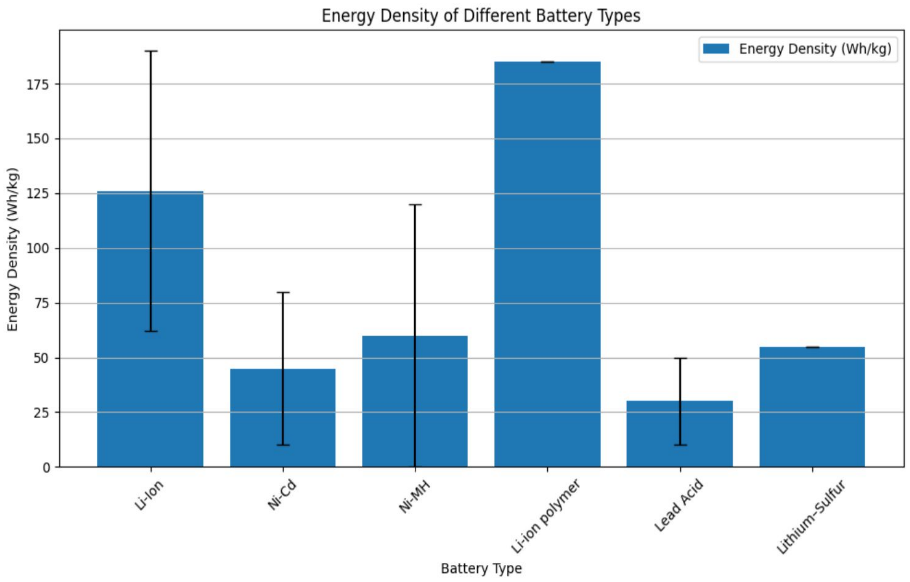
2020s

What's next?

Battery Type	Pros	Cons	Applications
Li-Ion	High Energy Density	High Cost	Laptops, smartphones, electric vehicles, drones, cameras
Ni-Cd	Long Cycle Life	Limited Voltage	Power tools, emergency lighting
Ni-MH	High Current Output	High Self Discharge	Hybrid vehicles, portable electronics
Na-Ion	Low Cost	Lower Energy Density	Grid energy storage, renewable energy systems
Lead Acid	High Power Output	Toxic Materials	Automotive batteries, UPS systems, backup power
Aluminium Air	Lightweight	Limited Cycle Life	Electric vehicles, energy storage, portable electronics
Dry Cell	Long Shelf Life	Non Rechargeable	Flashlights, remote controls, portable devices

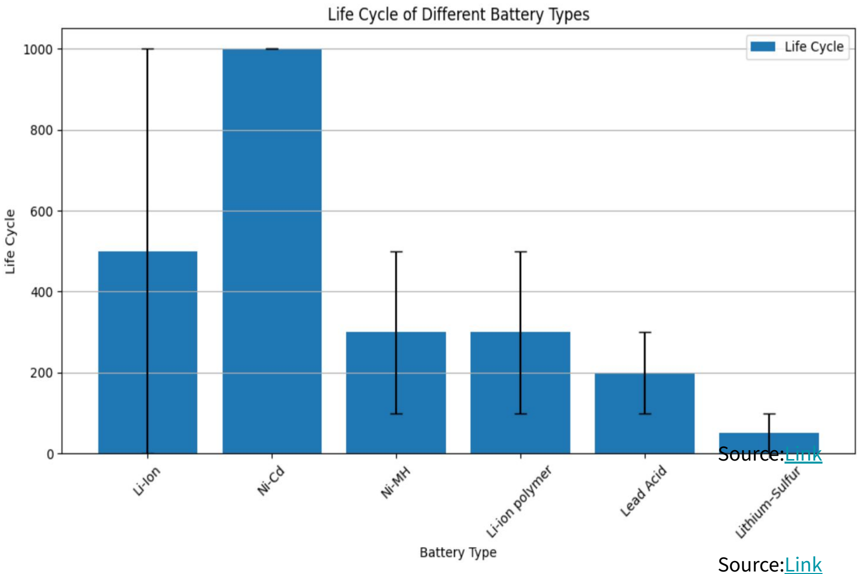
Energy density & cycle lives of batteries vary by orders of magnitude…

Energy Density vs Cell Type



Lithium Ion Polymer has the highest **energy density** across cell types

Cycle Life vs Cell Type

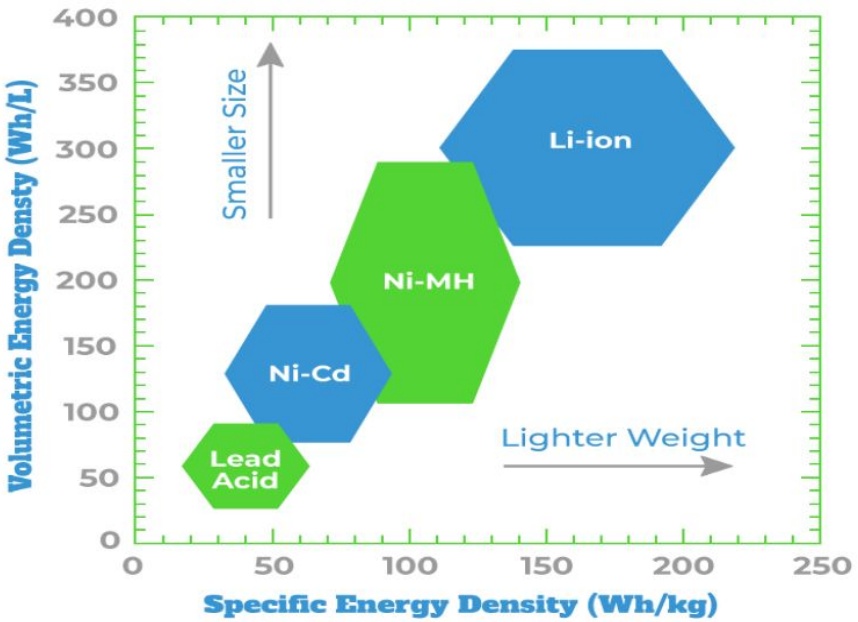


Source:[Link]

Nickel Cadmium Batteries have significantly higher **cycle life** across cell types

Why Lithium Ion Batteries are currently the standard...

- Higher Energy Density
- Lightweight & Longer Life
- Lower Self-Discharge & Faster Charge
- Low Maintenance & High Safety



Source: Link

$48B
Market Size of Lithium-Ion Batteries in 2023

16%
Expected CAGR of Lithium-Ion Battery Market (2022-2030)

$151/kWh
Average Lithium-Ion Battery Pack Cost

75%
Li-Ion Batteries are manufactured in China

1.5-2%
Self Discharge rate of Lithium-Ion Batteries/month

500-1000
Average Life Cycles of Lithium-Ion Batteries for 50% DoD

240 Wh/Kg
Average Energy Density of Lithium-Ion Batteries at Cell Level

Lithium Ion Batteries also have many types of 'Chemistries'...

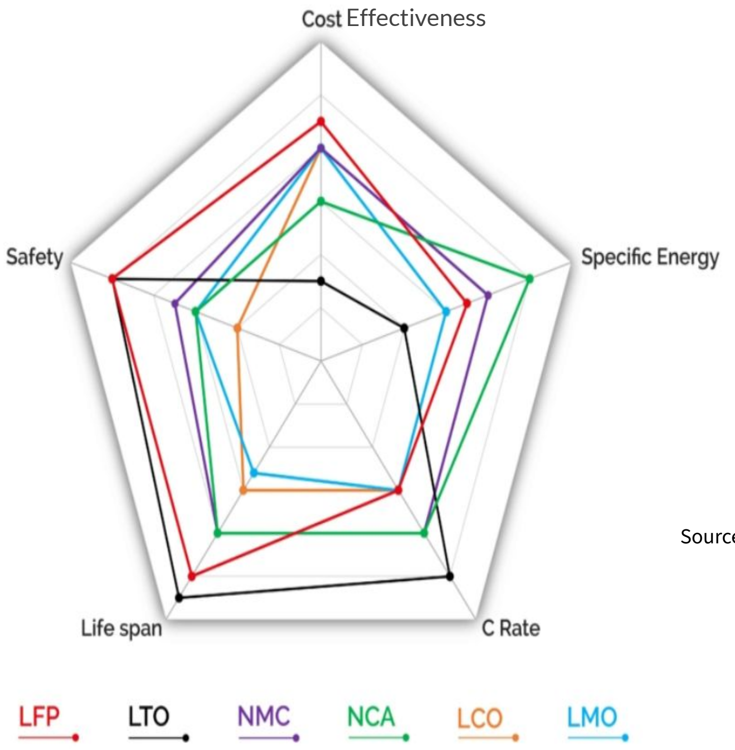
Lithium Ion Batteries

- Lithium Cobalt Oxide (LCO)
- Lithium Manganese Oxide (LMO)
- Nickel Manganese Cobalt (NMC)
- Nickel Cobalt Aluminium (NCA)
- Lithium Iron Phosphate (LFP)
- Lithium Titanate (LTO) Anode Material

LFP is the most **cost-effective** Li-ion chemistry currently

Nickel-based chemistries have the highest **Specific Energy**

Radar Comparison Chart



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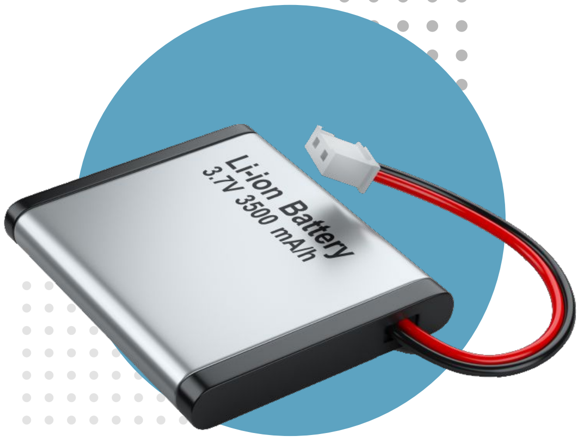
*Data as of 2022**

Use-Cases in EVs for various Lithium-Ion Chemistries



Anode || Cathode	Current user of Chemistry
Graphite || NCA	Tesla Model S/Model X
LTO || NMC	Honda Fit (US)
Graphite || NMC - LMO	Fiat 500
Graphite || LFP	Renault Zoe/BYD e6/Coda EV
Graphite || LMO-NMC	Mitsubishi / i-MiEV
Graphite || NMC	BMW i3/Chevrolet Bolt
Graphite || LMO - NCA	Nissan Leaf

The 18650 vs 21700 terminology

SONY

In 1990, Sony launched the **18650** cell

TESLA Panasonic

In 2017, Tesla & Panasonic jointly launched the **21700 cell**

Type	Size	Capacity	Weight	Energy Density	Cost
18650	Diameter 18mm Length 65mm	2200-3600 mAh	45-48g	250Wh/Kg Tesla	185$/KWh
21700	Diameter 21mm Length 70 mm	3000-4800 mAh	60-665g	300Wh/Kg Tesla	170$/KWh

Source:Link

Tesla Model S launched in 2012 uses **18650 Cells**

Tesla Model 3 launched in 2017 uses **21700 Cells**

The 0 at the end of the battery designation denotes a cylindrical cell

What type of batteries does Tesla use?

TESLA

Cylindrical Lithium Ion Cells

World's fastest charging network

Model S has a range of 370 miles

Cathode Chemistries Used

- Nickel Cobalt Aluminium (NCA)
- Nickel-cobalt-manganese (NCM)
- Lithium Iron Phosphate (LFP)

Main Suppliers

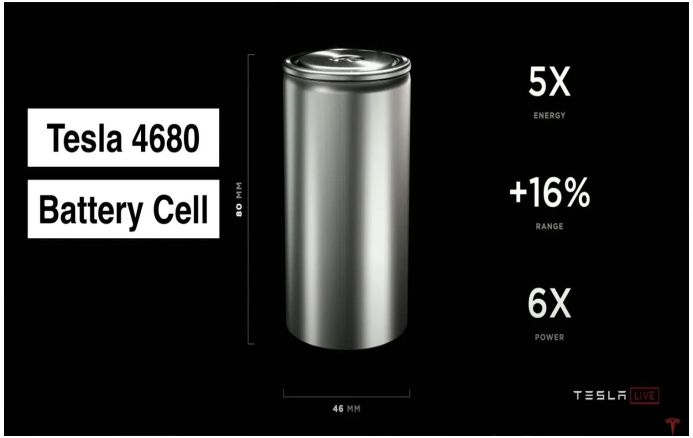
LG Energy Solution

Panasonic

CATL 宁德时代

BYD

Tesla 4680 Battery



Cathode Type	NCM
Anode Type	Graphite
Nickel Content	81.6%
Energy Density	272-296 Wh/kg (estimated)
Total Capacity	9,000 mAh (estimated)
Total Energy	96-99 Wh (estimated)
Tabbed or Tabless?	Tabless

- Size ↑
- Energy Capacity ↑
- Charging Efficiency ↑
- Internal Resistance ↓

Part 2:

Battery Costs, Structure & Metrics

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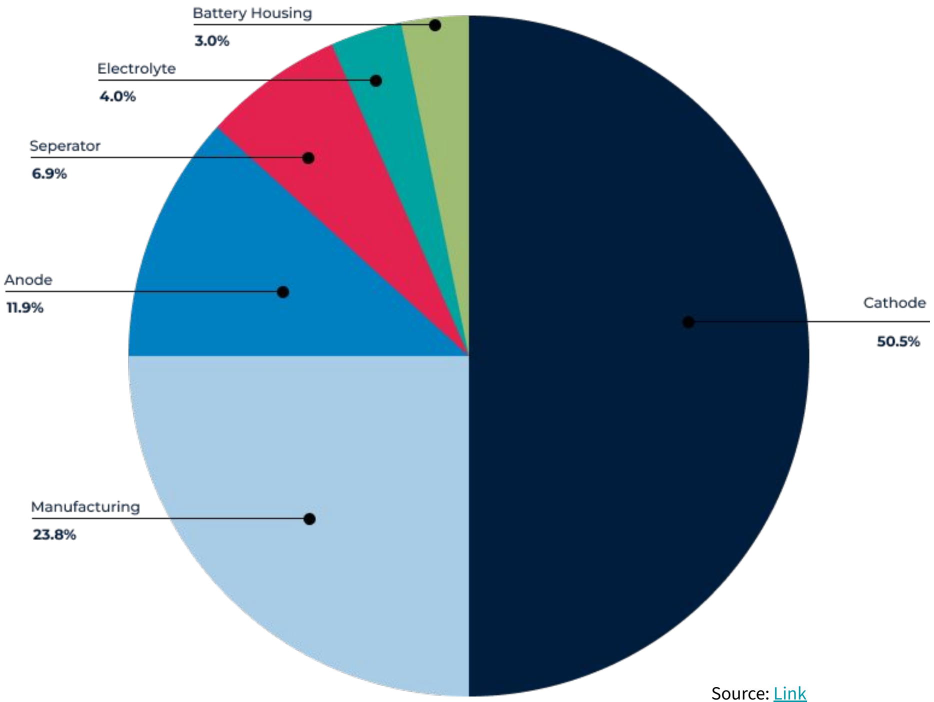
Cell Cost Structure - Ballpark

Cost Breakdown of a Li-Ion Battery

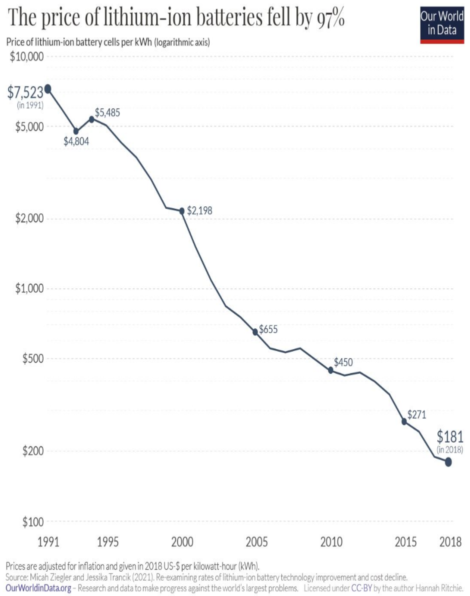


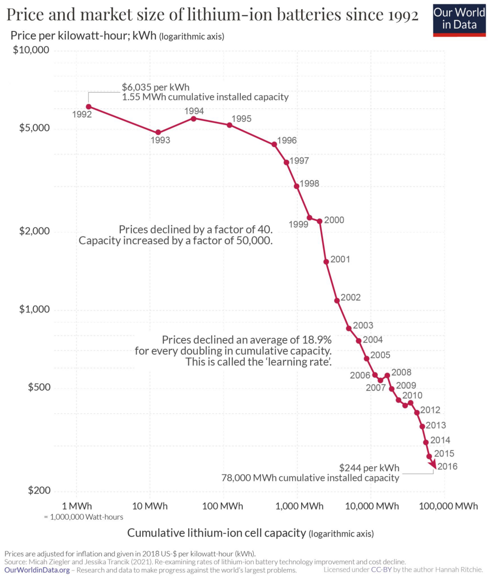
Source: [Link]

The cathode costs account for almost half of the cost of a battery

Variations in last 3 years have changed percentages substantially

Lithium Costs are falling as rapidly as Solar in the 2010s





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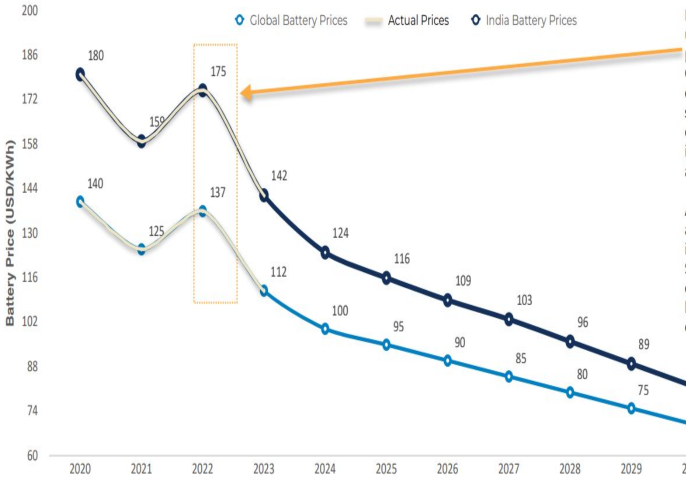


Prices in 2022 shot up due to higher prices of Li-Carbonate. We expect the prices to stabilise from 2024 onwards due to increased production and mining capacity.

Additionally, we anticipate introduction of Sodium Ion chemistries to help keep Li-Ion prices in check.

The upward cost pressure on batteries outpaced the higher adoption of lower cost chemistries like lithium iron phosphate (LFP).

Source:Link

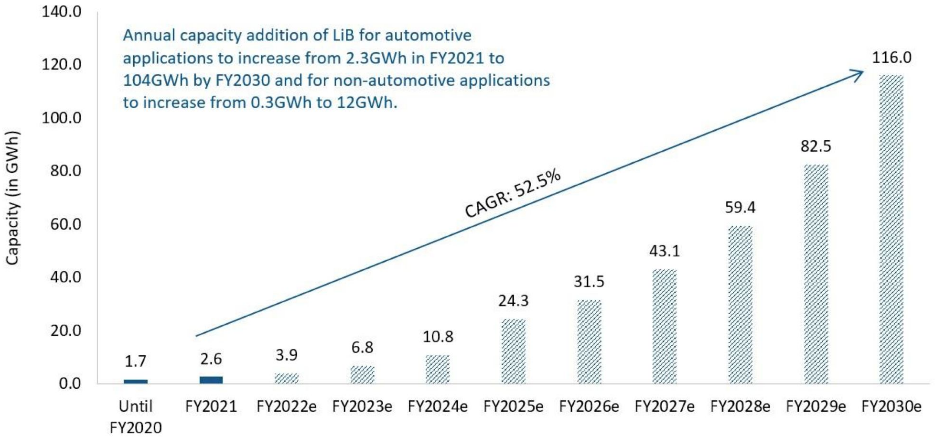
97%
Decline in Li-Ion battery prices in the last 3 decades

19%
Average drop in price for every doubling in capacity

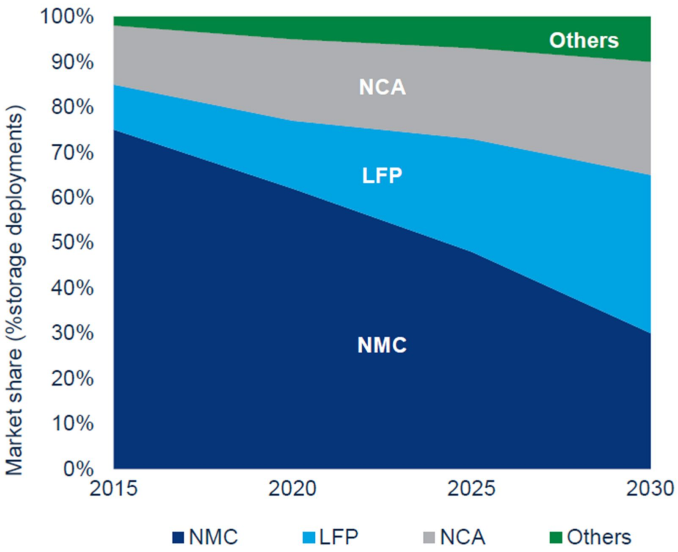
-$51/kWh
Expected drop in prices in Li-Ion batteries (2022-2026)

+$1/kWh
Expected increase in prices in Li-Ion batteries (2022-2023)

LFP will dominate the Indian market in upcoming years…



Source: JMK Research.

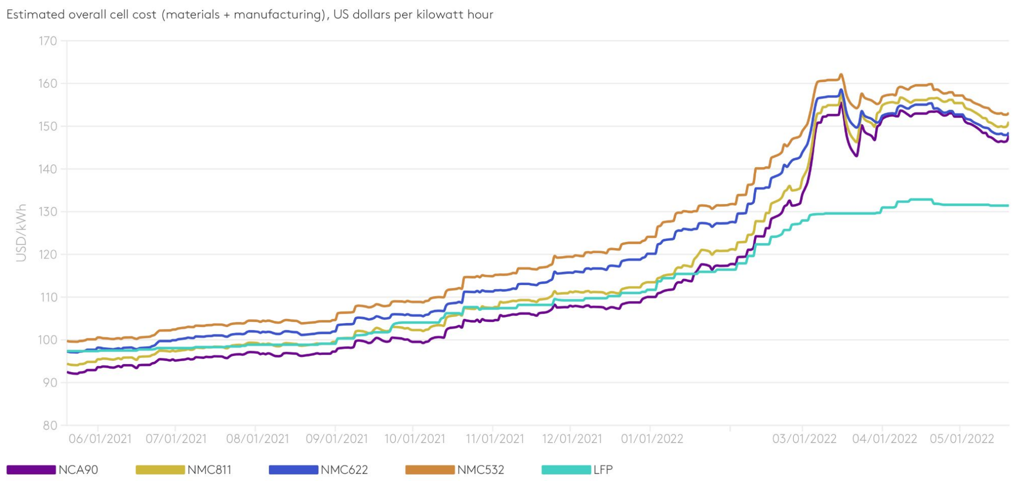


Source: Wood Mackenzie Energy Storage Service

Li-Ion Batteries capacity addition is increasing rapidly in India

The share of LFPs is expected to increase during this growth period especially in a price sensitive economy like India

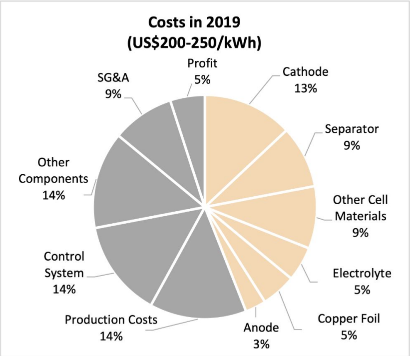
LFPs are getting a boost because of cheaper raw material

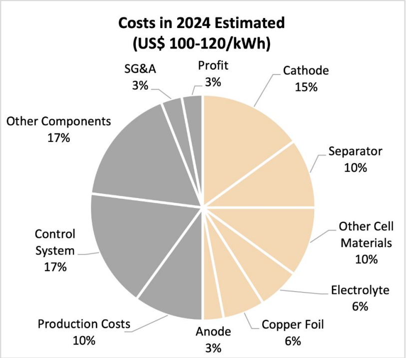


Source: Fast Markets

LFP has shown resilient raw material costs due to more earth abundant composition requirements

Materials costs will continue to become a higher proportion of overall cell costs as others costs come down through improved learning rates





Source: BNEF, Industry Interviews, JMK Research.

Important benchmarks for different types of EVs

2W EVs

Chemistry
Li-Ion batteries are used. Higher-end models use **LFP & NMC**

Capacity
Capacity generally ranges between **1-5 kWh**

Range
A 2W can travel between **48-80 km** on a single charge

3W EVs

Charging Time
Time taken to full charge on average is **3-5 hours**

Chemistry
Li-Ion batteries are used. **LFP** is used in higher-end models

Capacity
Capacity generally ranges between **40-100 kWh**

Range
There are short-range & long-range options. 60 kWh batteries run for 200-250 miles

Chemistry
Li-Ion batteries are used. **LFP** is used in higher-end models

Capacity
Capacity generally ranges between **2-10 kWh**

Range
Designed to travel between **60-150 km** on a single charge

4W EVs

Chemistry
NCA & NMC Li-Ion batteries are used with higher energy density & cycle life

Capacity
Capacity generally ranges between **100-500 kWh**

Range
Range varies with options.
300 kWh batteries run for 150-200 miles

4W Buses

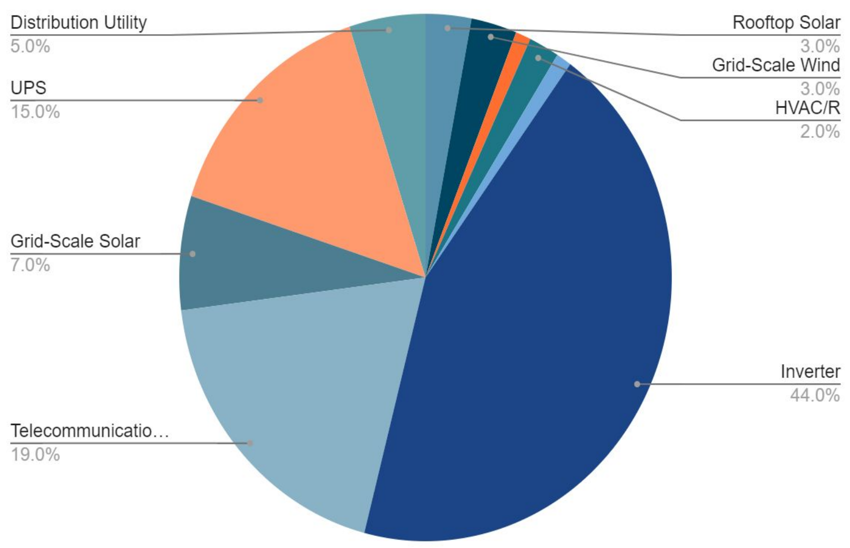
Cycle Life
Battery generally lasts for **8-12 years**

Part 3:

Energy Storage is the Fulcrum of a Net-Zero Future

Where does the demand for Stationary Storage in India come from?

Stationary Energy Storage Requirement in India (2019-2023)



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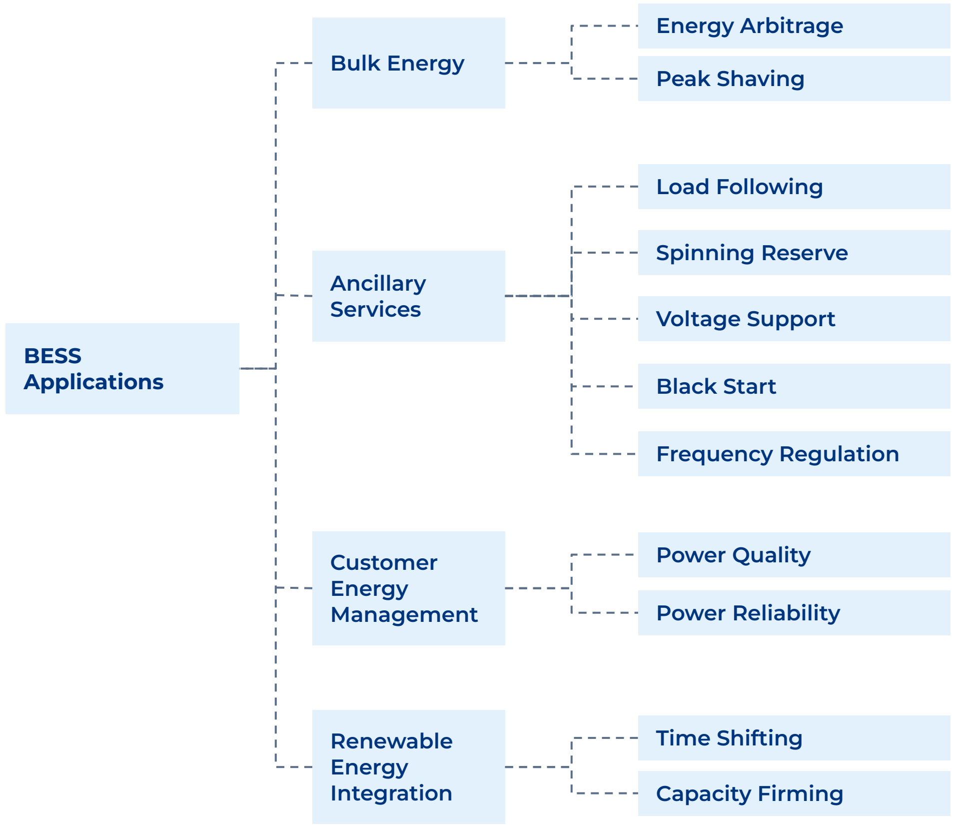
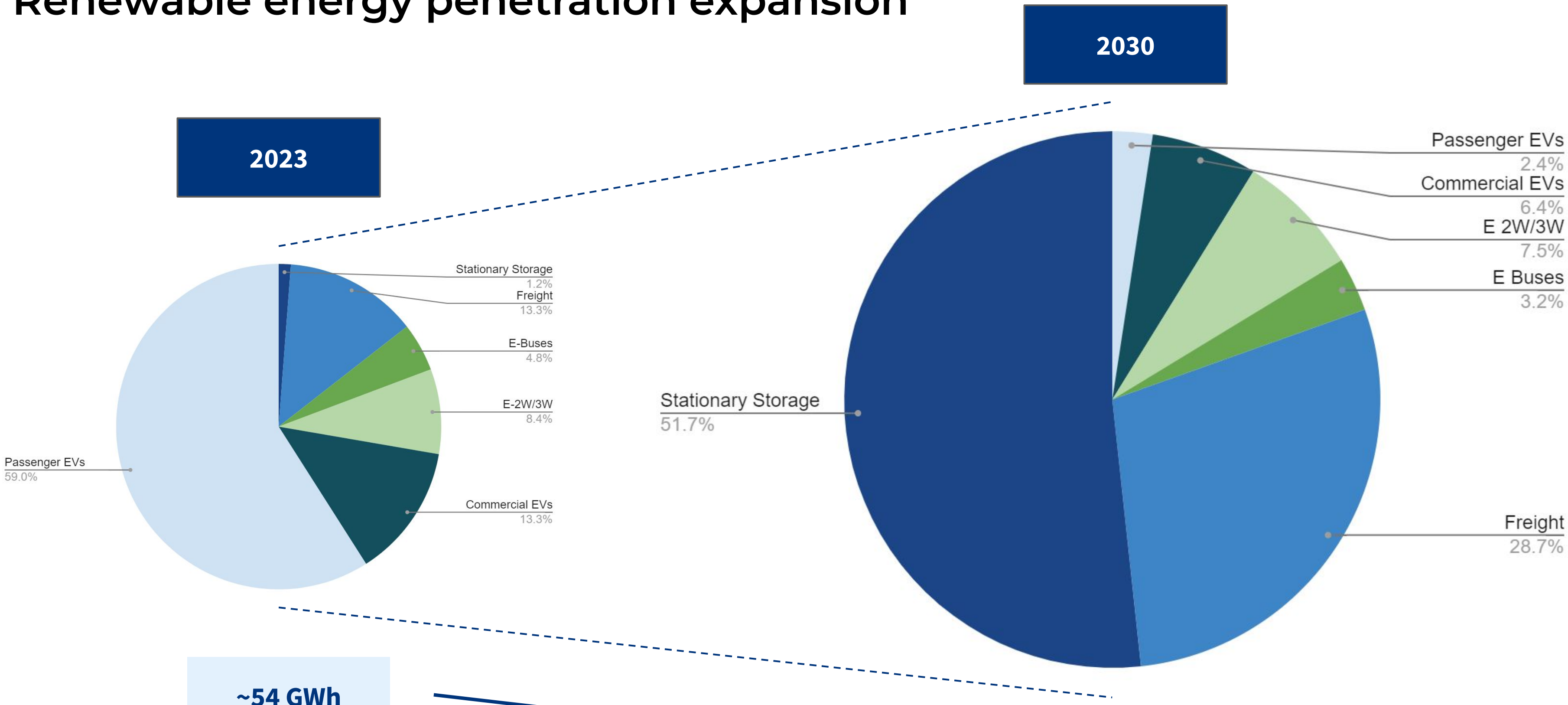


Source: Link

Battery Demand projection for the medium term: Renewable energy penetration expansion



~54 GWh

4x increase, driven by grid-connected storage

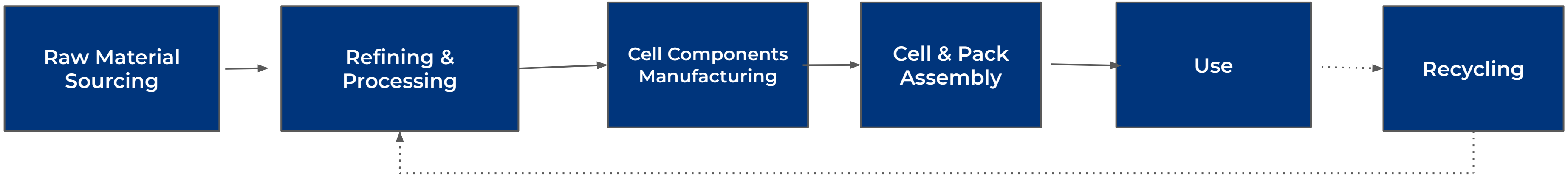
232.7 GWh
(1710 GWh from 2027-2032)

Source: Link, NITI Aayog estimates

Part 4:

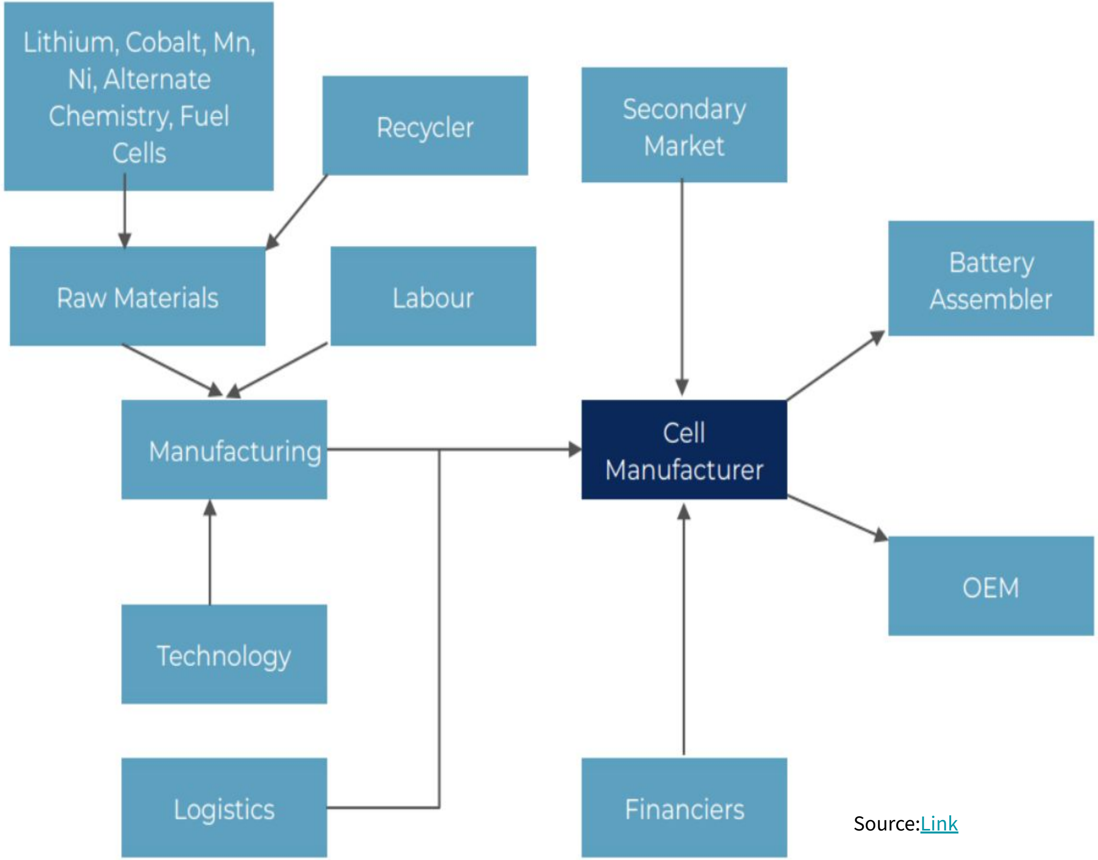
Battery Value Chain: Mining to Manufacturing to Recycling

The Battery Manufacturing Value Chain



Involves Sourcing raw materials mined around the world such as Lithium, Nickel, Cobalt for Lithium-Ion Cells	Refining of metals to convert into compounds suitable for batteries. Lithium is converted to Lithium Hydroxide & Lithium Carbonate	In this step, key components such as Cathode, Anode, etc are manufactured	All individual components are assembled together along with the BMS to form a market ready battery	Refers to the use of battery till end of life	A new addition to the value chain with increasingly crucial significance

Cell Manufacturer Value Chain



Source:Link

Procurement of the raw materials and investment into technology are the most important inputs

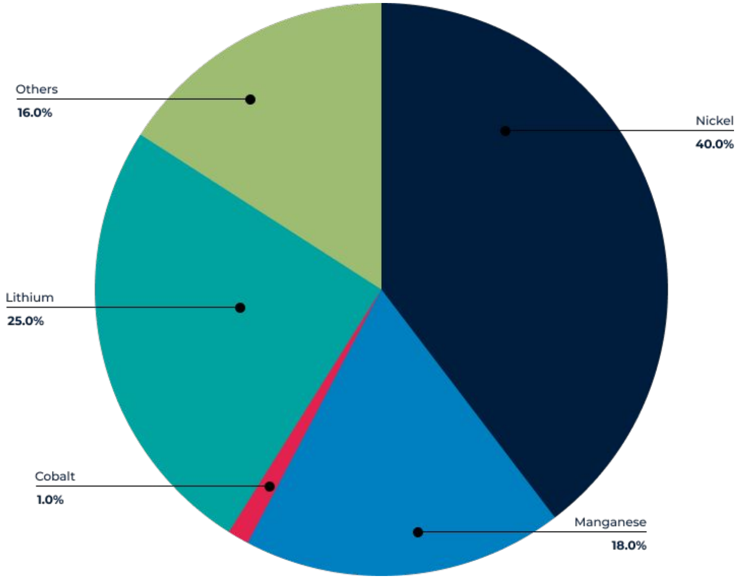
The pace at which the technology is advancing and the amount of money that is required in R&D to be able to get the right chemistry is challenging

The cost to put up a factory of 1 GWh output is in the range of $80-150M, with PLI schemes 4-5 consortiums are emerging in India

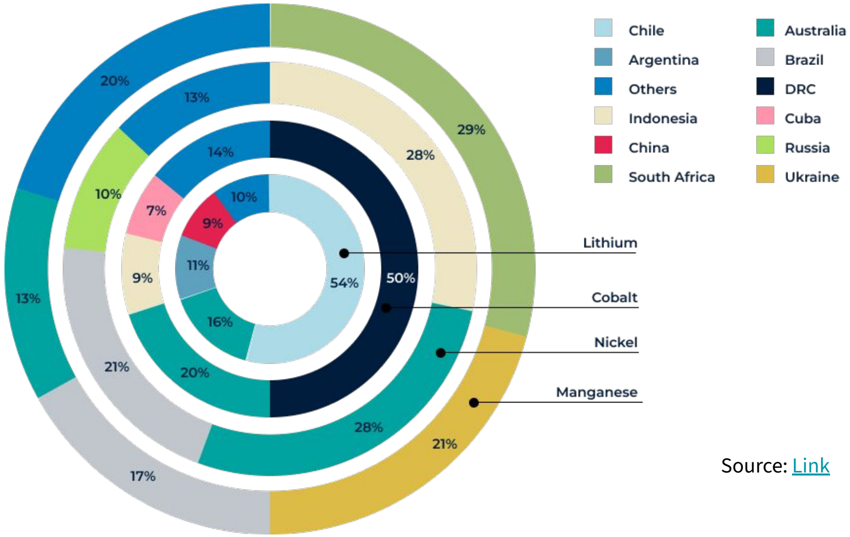
Outputs of the cell manufacturers feeds into battery assembler and OEMs (who may want to assemble their own batteries)

Is Lithium the new Oil, and not Data?

Lithium Cost is a fraction of the Cathode's cost



Broad Geographic Distribution of Raw Material Reserves



Source: [Link]

Source: US Geological Survey (USGS), 2019

Lithium	Nickel	Cobalt
Lithium is controlled by Australia, Chile & Argentina	Global Nickel supply is fragmented between Brazil, Indonesia, Australia.	60% of Global Cobalt is mined in Democratic Republic of Congo.

Lithium Cell Raw Material - costs by materials

CATHODE

LITHIUM — 10-15%

India imports 100% of Lithium demands 14,100 tonnes of Lithium reserves found in Karnataka

COBALT — <1%

India imports 100% of Cobalt demands. Reports state 44.9M tonnes of untapped potential

MANGANESE — 5-10%

20% of world's ores are found in India. Total reserves amount to around 167M tonnes

NICKEL — <1%

Total reserves amount to 193M tonnes present majorly in Orissa (93%)

IRON — 20-25%

India has abundant iron ore, around 18,000M tonnes of Haematite & 10,500M tonnes of Magnetite

PHOSPHATE — 5-10%

India is deficient in Apatite reserves (24M tonnes) & Rock Phosphate (48M tonnes)

ANODE

GRAPHITE

India has graphite reserves of 11M tonnes & resources worth 158M tonnes. There are 3 main graphite belts, present in Andhra Pradesh & Orissa

ELECTROLYTE

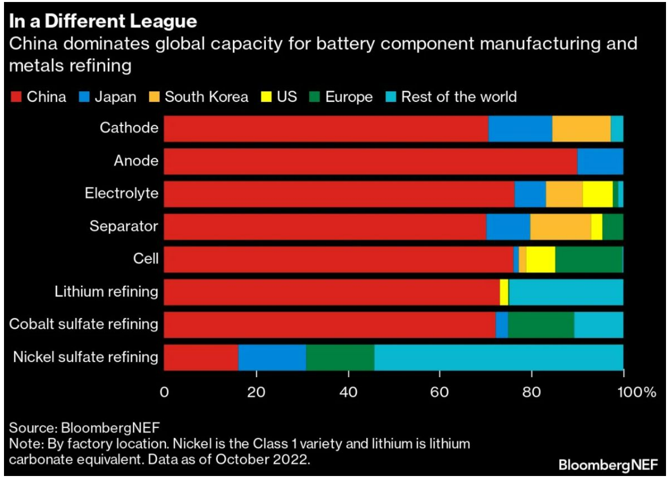
FLUORSPAR

Total Fluorite reserves in India are around 17.9M tonnes. Gujarat accounts for 66%, followed by Rajasthan at 29%

[dashed box] : %Total Cost of Lithium Battery

Source: Link

China dominates the global value chain…



75%
Li-Ion Batteries are manufactured in China

80%
World's refining capabilities are controlled by China

64%
World's graphite is produced by China

70% | 80%
World's production capacity for cathode & anodes respectively lies in China

Source: Link

China is the **largest importer** of Lithium in the world

Ganfeng & Tianqi Lithium are Chinese companies accounting for **26%** share of the lithium market

CATL & BYD are Chinese Companies that control **32%** of the battery manufacturing market.

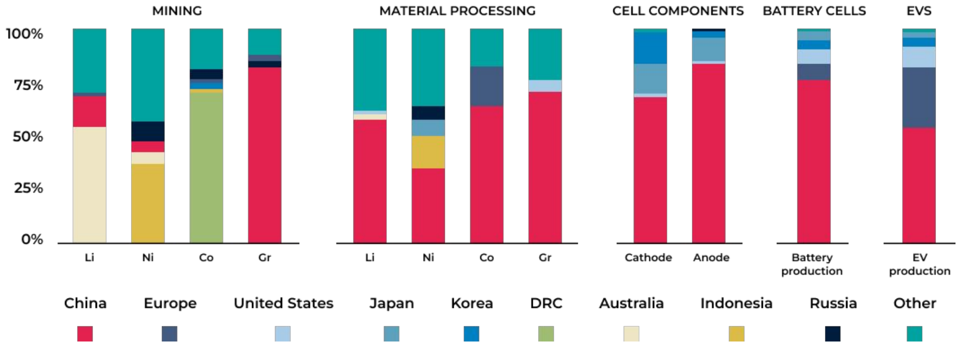
China is projected to be the top producer of Batteries till **2027** at least

...and the rest of the world is trying to catch up...

Figure 1: BNEF 2022 global lithium-ion battery supply chain ranking

Country	Raw Materials	Battery manufacturing	ESG	Industry, innovation and infrastructure	Downstream demand	Overall ranking
China	1	1	17	9	1	1
Canada	3	8	6	4	10	2
US	6	4	16	5	2	3
Finland	9	15	2	1	11	4
Norway	18	10	1	3	7	5
Germany	21	6	4	7	2	6
South Korea	17	2	10	6	5	7
Sweden	21	9	3	2	8	8
Japan	13	3	8	12	8	9
Australia	2	15	9	13	11	10
France	24	10	5	10	5	11
UK	26	15	7	8	1	12
Czechia	23	10	11	11	18	13
Poland	24	5	15	16	15	14
Hungary	26	6	13	14	20	15
Chile	7	18	14	1	19	16
Turkey	15	18	21	15	13	17
India	13	10	26	21	13	18
Vietnam	20	10	20	18	17	19
South Africa	8	18	19	17	26	20
Brazil	4	18	23	22	20	21
Indonesia	5	18	22	27	25	22
Argentina	11	18	12	19	26	23
Slovakia	26	18	18	25	24	24
Thailand	26	18	24	20	16	25
Philippines	10	18	29	28	22	26
Mexico	16	18	27	26	23	27
Morocco	19	18	25	24	28	28
DRC	11	18	30	29	30	29
Bolivia	26	18	28	30	28	30

Source: bloombergNEF. Note: "III" stands for infrastructure, innovation and industry. Source: Link



Source: Link

- Russia was the world's largest supplier of Class 1 battery-grade nickel (pre-conflict), producing around **20%** of global supply
- Europe is responsible for **25%** of battery assembly facilities & **20%** of Cobalt processing
- Korea is responsible for **15%** of cathode production, Japan for **14%** of cathode & **11%** of anode, while USA produces **7%** of world's battery production

Battery Recycling Value Chain (more details in Blume's EV Primer)

Mechanical Processing

Physical methods such as crushing and sieving etc. are used to separate the different components of the battery and extract the valuable metals

Simplest and inexpensive process, but not as effective

Pyrolysis Process

Thermal decomposition process used to break down organic materials into their constituent elements.

Used to recycle batteries by breaking down the plastic and electrolyte components.

Pre Treatment

Hydrometallurgical Process

Chemicals are used to dissolve the battery and extract the valuable metals. The dissolved metals are extracted and purified.

More environmentally friendly but expensive

Pyrometallurgical Process

Heat is used to break down the batteries and extract valuable metals, in a furnace. The molten metals are collected and refined.

Most commonly used process

Treatment

Source: Link

What does the recycling market look like?

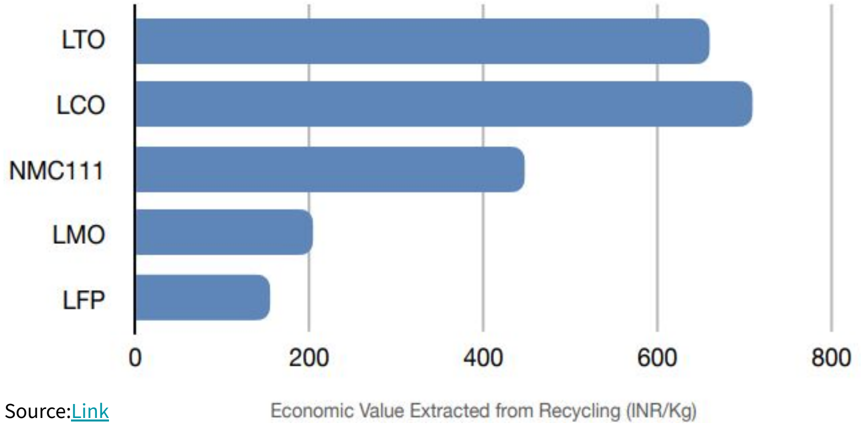
95%
Material can be recovered from Lithium Ion battery waste

90%
Li-Ion Batteries are manufactured in China

19.6%
CAGR of Global Recycling Industry

50,000+
Tonnes of Lithium-Ion battery waste generated In India every year

Chemistry-wide analysis



Source:Link

Indian Startups in the space

ATTERO

BATX ENERGIES Beyond Limitations

KARO SAMBHAV

ZIPTRAX ADVANCED CLEANTECH

GRAVITA Gravita India Limited

recykal

ACE Green Recycling

LOHUM

Part 5:

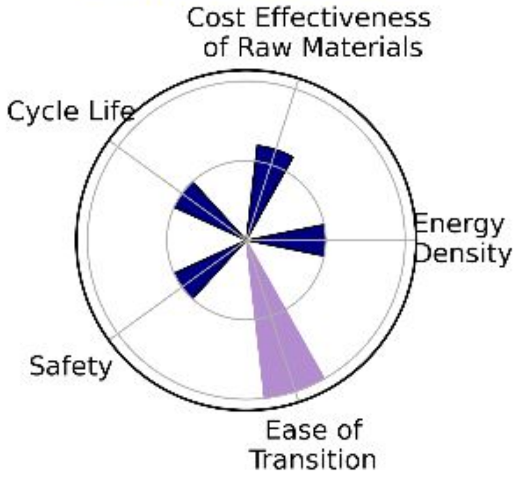
Blume's #BatteryBLUprint

A framework for investments beyond the current Lithium-ion standard

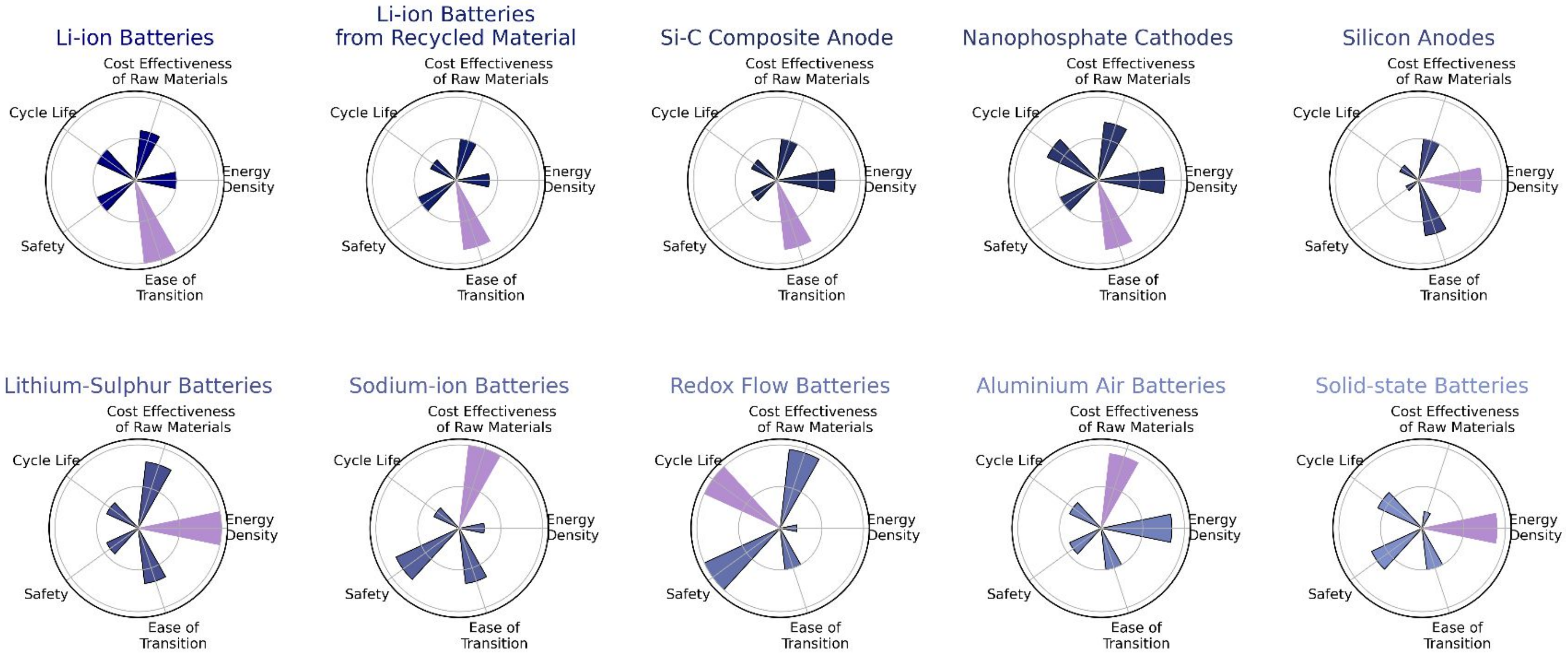
Blume's #BatteryBLUprint is a venture investment approach to evaluate technologies in the near-to-medium term

Blume's #BatteryBLUprint for technologies

Performance	Cost	Ease of Transition
How well does it perform compared to commercial Lithium-ion batteries/battery components? We want to evaluate along the following facets: - Energy Density - Cycle Life - Safety	How much more or less does it cost to make it compared to Lithium-ion batteries/battery components? We want to evaluate across the value chain for costs and risks associated with: - CAPEX - OPEX - International Import Risks	Can the technology leverage the manufacturing knowledge and infrastructure of commercial Li-ion batteries? We define "Degrees of Disruption" to compare how different new technologies are from the incumbent commercial scale technologies. These "Degrees" are in indicator of lab-to-market time.



Each technology shows promise on a different **front**



0 Degree of Disruption

Conventional Li-ion Cell

1 Degree of Disruption

Li-ion batteries from spent li-ion batteries

Li-ion Polymer

Silicon-Carbon Composite Anodes

Nanophosphate Technology

2 Degrees of Disruption

Silicon Anode Battery

Lithium Sulphur Batteries

Sodium-ion Batteries

3 Degrees of Disruption

Redox Flow Batteries

Aluminium-Air Batteries

Solid-state Batteries

Ease of Transition

Based on similarity to conventional Li-ion cells and the current knowledge, infrastructure and market they can capture

0 Degree of Disruption

1 Degree of Disruption

2 Degrees of Disruption

3 Degrees of Disruption

Conventional Li-ion Cell

Lucas TVS
OLA ELECTRIC
EXIDE
C4V Charging Ahead!
LithiumWerks New Energy. New World.
cygni

faradion
GRINNTECH
amprius
Gegadyne Energy
GODI
INVERTED
Zeta ENERGY

NERVE SMART SYSTEMS
ENEVATE
Factorial
FLOW TECH
LOG 9
Capacitech ENERGIA
SAKUÚ
Ampcera®

Ease of Transition

Based on similarity to conventional Li-ion cells and the current knowledge, infrastructure and market they can capture

#BatteryBLUprint can beat technology and market risks

Reduced Technology Risks

Matching disruption ease with investment timeline helps mitigate technology risks.

Reduced Market Risk

Matching key performance metrics with market identification helps mitigate market risks.

Recognising Innovation White Spaces

Benchmarking across performance, cost and disruption ease helps in identifying where innovation is required in the industry.

Most technologies do not show a big improvement in safety over Lithium-ion Batteries.

Upcoming technologies push the boundaries on all of these fronts

Si-C Composite anodes, Nanophosphate cathodes, Silicon anodes, Lithium-sulphur batteries, Solid-state batteries push for an improved **energy density**.

Sodium-ion batteries and Aluminium-air batteries push for a better **cost effectiveness**.

Redox flow batteries aim at a superior **cycle life**.

Sodium-ion batteries and redox flow batteries also focus on higher **safety**.

Prominent research labs and innovation hubs for disruptive Li-ion alternatives

North America

Universities
StorageX (Stanford)
Yet-Ming Chiang (MIT)
Jeff Dahn (Dalhousie)
Ceder Group (Berkeley)

Labs
Shirley Meng (Argonne)
Jun Liu (PNNL)

Industry
Polaris Battery Labs
Raytheon Technologies
Joint Center for Energy Storage Research (JCESR)
Battery500 Consortium

Europe

Universities
Jurgen Janek Germany (KI), Dirk Uwe Sauer Germany (RWTH)

Labs
Battery Energy Storage Laboratory

Industry
Batteries Europe

India

Universities
HTEM (IITB)
ABRL (IITD)
CBEEV (IITM)
Lohum R&D (IITK)
Solid-state Ionic Lab (IITI)

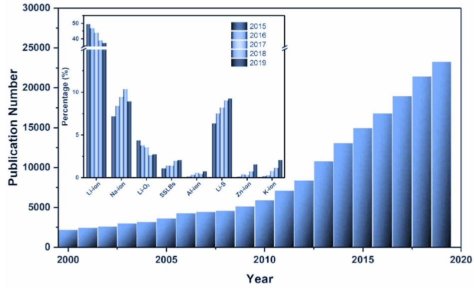
Industry
E-Vega Mobility Labs
Ola Battery Inno. Centre

Asia

Universities
Minggao Ouyang (Tshing-Hua)
Yang-Kook Sun (Hanyang)
Rui Xiong (Beijing Institute of Technology)

Labs
Advanced Batteries Research Group (Chinese Academy of Sciences)

Industry
21C Lab (CATL)



Jianmin Ma et al 2021 J. Phys. D: Appl. Phys. 54 183001

Battery publications are rising exponentially!

There's space for a lot more companies and innovators

(Indian Battery Market Revenues to Reach USD 27.70 billion by 2028: Estimates)

IN THE NEWS

How this Nikhil Kamath-Backed Battery Tech Startup Is 'Making A Dent' In The EV Space

DEALSTREETASIA

Indian battery startup Log9 gets recharged with $40m in funding

Company plans to to boost production capacity, look abroad

Explained: The innovative role of battery startups in India's transition to renewable energy

Energy storage holds the key to the faster adoption of renewable energy sources in our quest for a sustainable future. By addressing the intermittency of solar and wind power, advanced battery technologies enable stable grid integration, reduce energy costs, and complement the economics of renewable energy production.

Mongabay Series: Clean Energy

In the EV era, Bengaluru startups innovate for a more sustainable battery ecosystem

**Technologies evolve, but,
quality of founder team is the most critical.**

Thank you

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