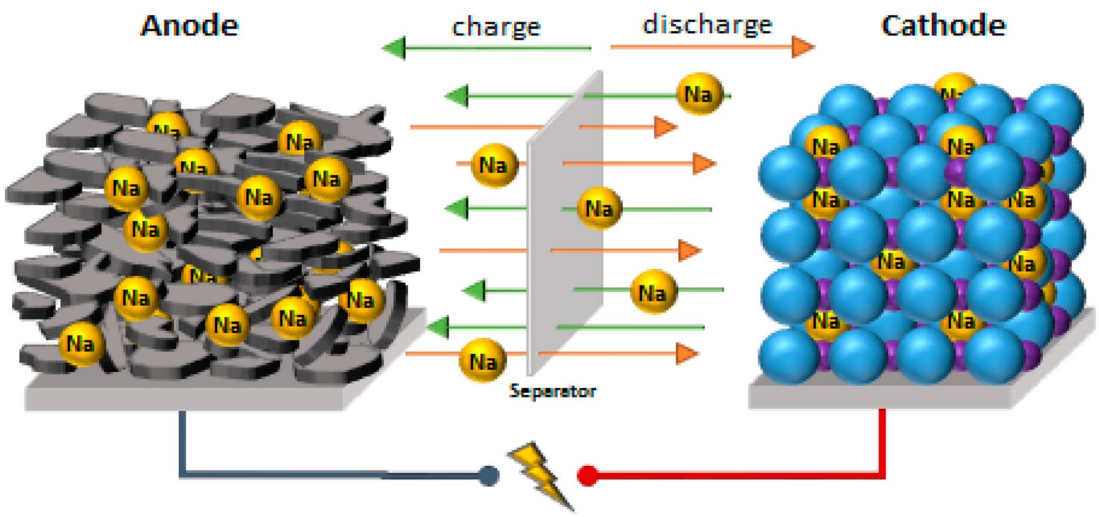

The race between Sodium-ion battery(SIB) and Lithium-ion battery(LIB)

November 30, 2023

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Speaker

Andreas Sakellaris

Director, Emerging Technologies

a proven track record of bringing complex energy projects to fruition in diverse and challenging environments across the world.

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Story of LIB taking surpassing SIB

In a sodium-ion battery, lithium ions are replaced with sodium ions in the battery’s cathode, and lithium salts swapped for sodium salts in the electrolyte.

Research on SIBs has been ardently pursued concurrently with LIB development during batteries' 200-year existence. It wasn't until the 1970s that the electrochemical activity of Titanium Disulfide (TiS_2) for lithium and its viability for energy storage were first proposed. Early in the 1980s, it was realized that Na+ ions may be injected into TiS_2 because of this finding.

The result of the failure to intercalate sodium ions and the discovery of graphite as a low-cost, moderate-capacity anode material for LIBs, This accelerated the development in the 1990s, outpacing the development of sodium chemistry.

The availability of sodium storage in hard carbon (HC), which would produce an energy capacity equivalent to that of Li+ in graphite, then rekindled study in 2000.

Nov. 2023: **Northvolt announces 160 Wh/kg SIB product**

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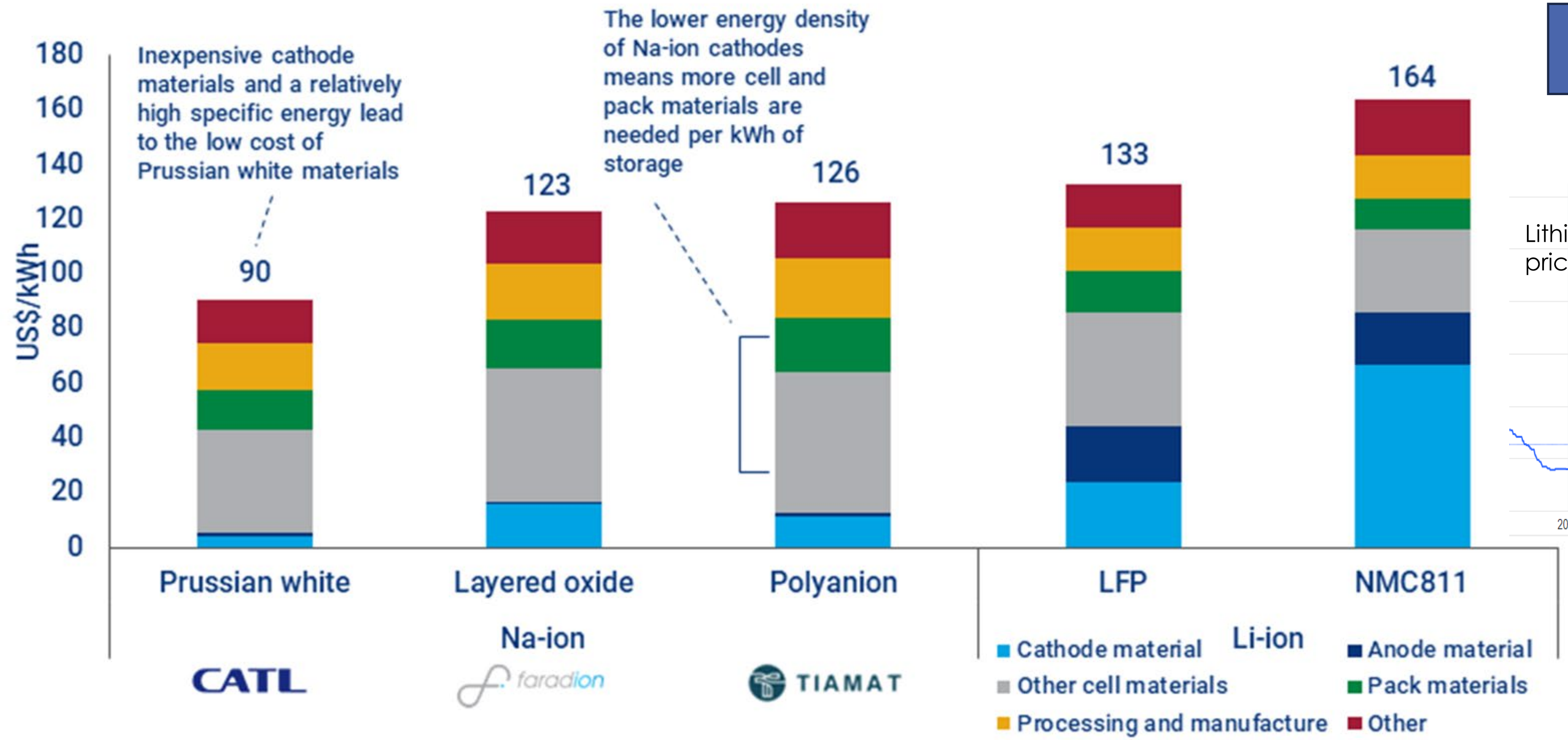
Source: CES analysis and research.

Sodium-ion (Na-ion) batteries present a lower cost option than lithium-based counterparts

2022 battery pack costs by chemistry



Source: Wood Mackenzie

Source : Wood Mackenzie

Futuristic roadmap for Sodium ion Battery

Early research and material advancements

2020 - 2026

1. Breakthrough in cathode and anode material will increase cycle life and energy density
2. Close attention is given to solid state batteries which may be available by 2026-2028
3. Scaling up production of key battery materials for large scale testing

Adoption

2030-2040

Application in grid and Electric Vehicles will be adopted

Commercialization and scaling

2026 – 2030

1. Efforts to reduce cost
2. Recycling and sustainable efforts to minimize impact on environment
3. Introduction of government policies and incentives

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Source : CES analysis and research/

Overview

SIB	LIB
No thermal runaway	Thermal runaway is the biggest issue
Size of sodium is larger than Lithium which **reduces the risk of dendrite formation**	Less safety due to dendrite formation
Runs at greater voltage which **reduces the possibility of overcharging**	Reduces the battery life due to overcharging
Only aluminum is used for current collector which makes it **cheaper comparatively to LIB**	Aluminum and copper is used as a current collector
Can **be stored and transported in zero voltage** makes it environmentally friendly	LIB should be stored in some minimum charge(varies from Different chemistry)
SIB have **3 times higher life cycle** than LIB	LIB have 3 type less life cycle from SIB

- To integrate renewable energy sources, SIB can be used in grid energy storage.
- SIB may also be used in portable devices, but have a greater advantage vs. LIB for stationary applications.
- Safer chemistry and abundance of sodium makes them a good option.

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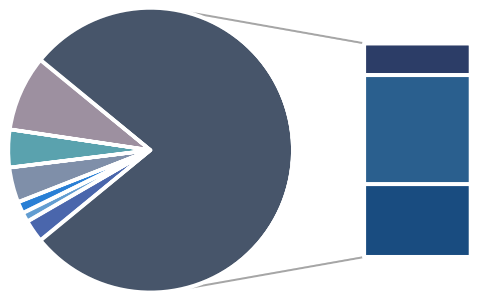
Source : CES analysis and research.

Availability of primary salts

Dominators in supply chain
- Li Mining: Australia, Chile
- Refining: China

NaOH is considered over Na2Co3 due to availability & small difference in Cost



For LIB(Li)

Country	Extractable Lithium (metric tons)
Portugal	0.06
Brazil	0.25
Zimbabwe	0.31
Canada	0.93
USA	1.00
China	2.00
Argentina	2.70
Chile	**9.30**
Australia	6.20

For SIB(Na)

Country	Company
India	Tata Chemicals ltd
USA	Olin corporation
USA	Westlake corporation
Belgium	Solvay S A
Germany	BASF
China	Xinjiang Zongtai Chemicals

Opportunities for countries to produce Sodium Salts(primary requirement) will be increased which is environmentally friendly and produced by most of the country in the world

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Source : CES analysis and research.

Largest producers of primary salts of SIB(NaOH, Na2CO3)

The price of lithium salts is approximately $13,000 per ton, looms large because minerals account for about one-fourth of the cost of a battery. Sodium salts cost $150-200 per ton, making SIBs much cheaper.

Na_2CO_3

Rank	Country	World Production, By Country (Thousand metric tons)
1	**China**	**24,290**
2	United States	11,500
3	Russian Federation	2,810
4	Germany	2,650

42 million metric ton production annually

NaOH

Rank	Country	World Production, By Country (Thousand metric tons)
1	China	**37,800**
2	India	15,930
3	European Union	13,560
4	Russia federation	7,810

70 million metric ton production annually

Approximately 3-3.5 kg of cathode powder is required to produce 1 KWh* for Sodium Vanadium Phosphate (NVP)

Information about lithium availability is stated in slide 22

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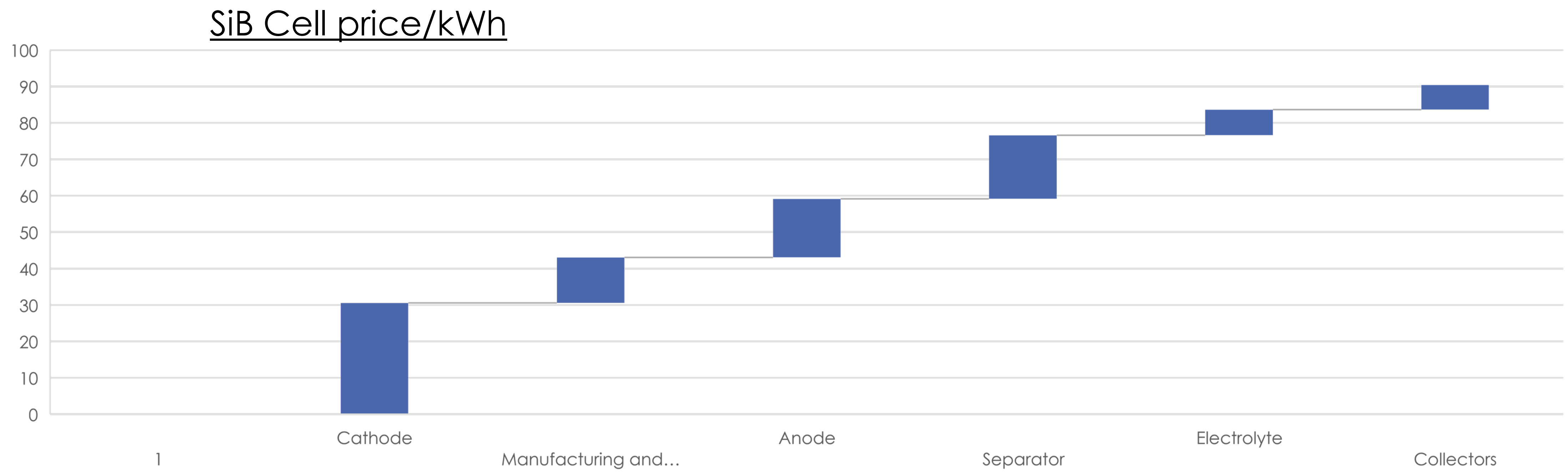
Source : https://www.indexmundi.com/minerals/?product=soda-ash&graph=production

* rough estimated value

Cost breakdown



- Most companies are in early commercialization. Earliest SiB Gigafactory is expected to start production between 2024-25. SiB price is estimated to be ~$70-120/kWh. Ongoing efforts may reduce cost by 15-25% (cheap vs. LIB).
- Cost could come down 25-30% during scaleup.
- Using aluminium makes Collector less costly vs. LIB
- Electrolyte conductivity in SIB is very high, so little is required, reducing cost.

Cell Cost of SIB ranges from $70 - $120 / KWh

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Source : www.nature.com/natrevmats , article no. 18013|vol 3
CES analysis and research.
*Taking different chemistries into account (PB, PW, NVP). Cost breakdown is done taking the avg of different chemistry

Different chemistries of SIB with their theoretical capacity

SIB Cathode Types

SIB Cathode Type	Expected Commercialization 2025-2030
Polyanion	117 mA h g^{-1}
Prussian White	170 mA h g^{-1}
Prussian Blue	165 mAh g^{-1}
Sodium Sulphur (NaS)	1200 mAh g^{-1}
Layered	190 mAh g^{-1}

SIB Anode Types

- Hard Carbon
- Metal Oxide
- Prussian Blue
- Prussian White

Information about lithium chemistry is given in slide 23 for comparison

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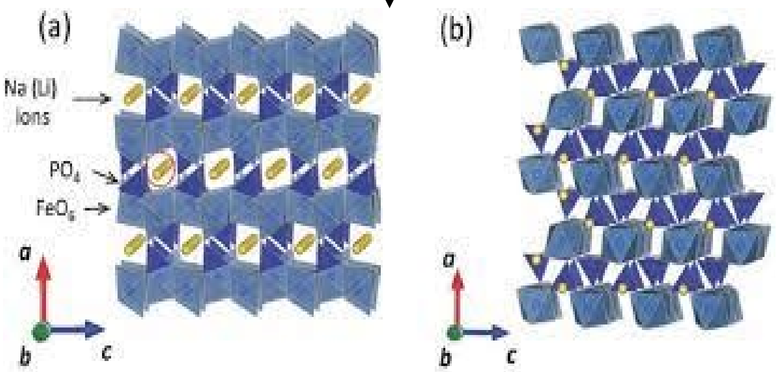
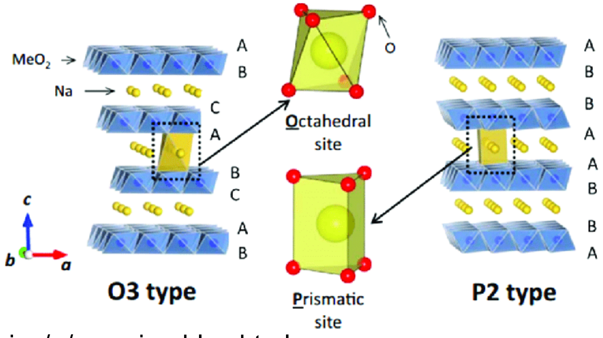
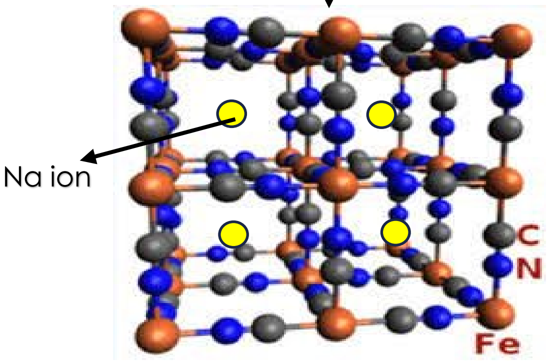
Source : 1. CES analysis and research.

Introduction to different chemistries for SIB

Polyanion	Layered	Prussian
Contain negatively charged polyanion groups	Contain stacked layers of transition metal oxides	Contain metal cations
High stability and safety	High stability with good cycle rate	Good capacity with being suitable for high power application
3-D crystal structure , provide good ion diffusion pathway for sodium ions	Have layered structures with open spaces between the layers, allows for good intercalation/deintercalation	Metal cations coordinated with cyanide ion (CN) in 3D framework
Ex: Na3Fe2(PO4)3	Ex: Na_xMeO_2, Me = transition metal/s	Ex: NaFe[Fe(CN)6]3



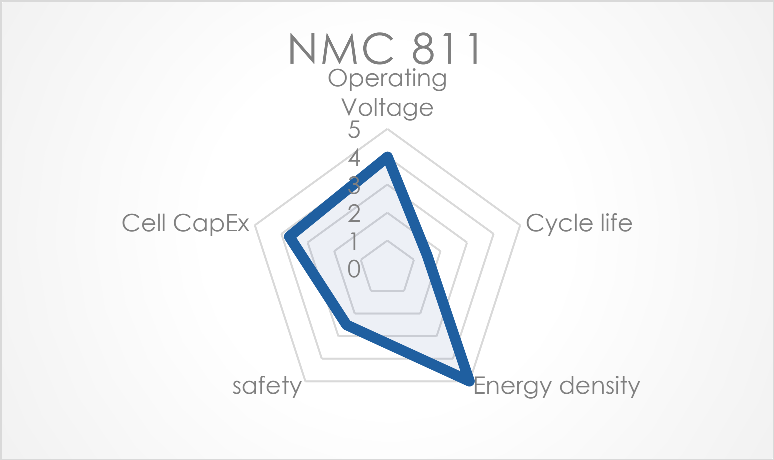


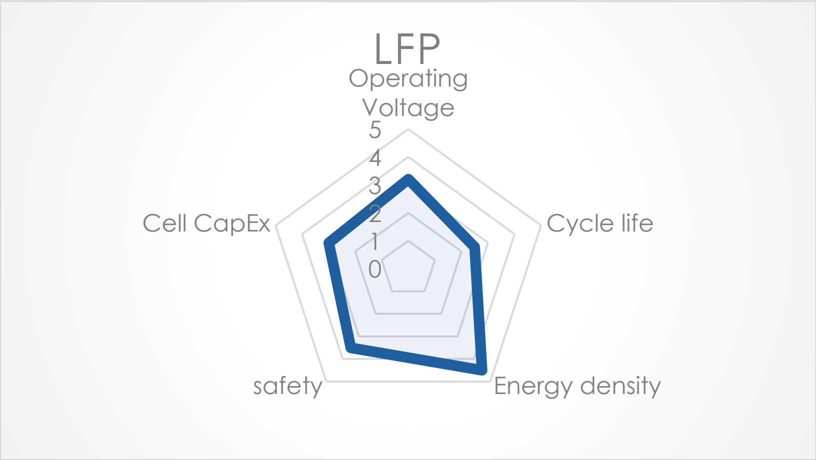


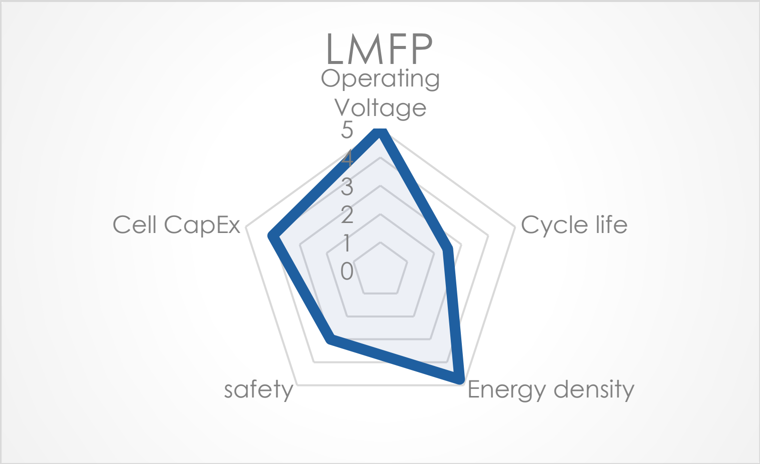
Source : doi.org/10.1021/acsami.9b03937
doi.org/10.1002/advs.201600275
https://www.acs.org/molecule-of-the-week/archive/p/prussian-blue.html

Technical parameters

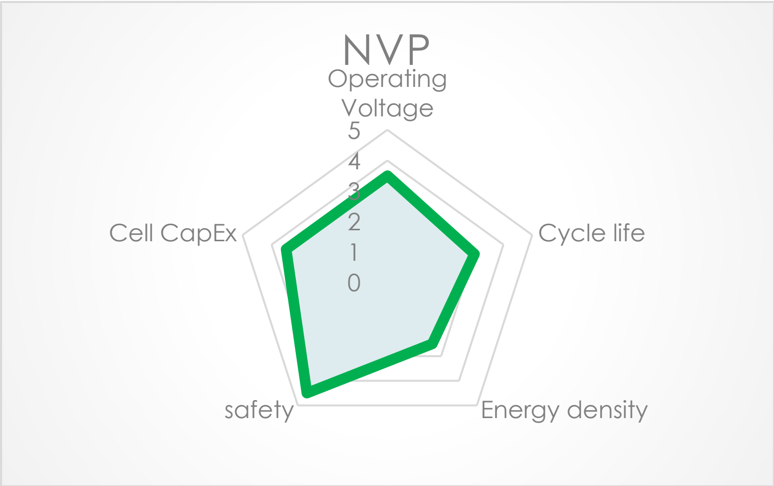
LIB Chemistries:

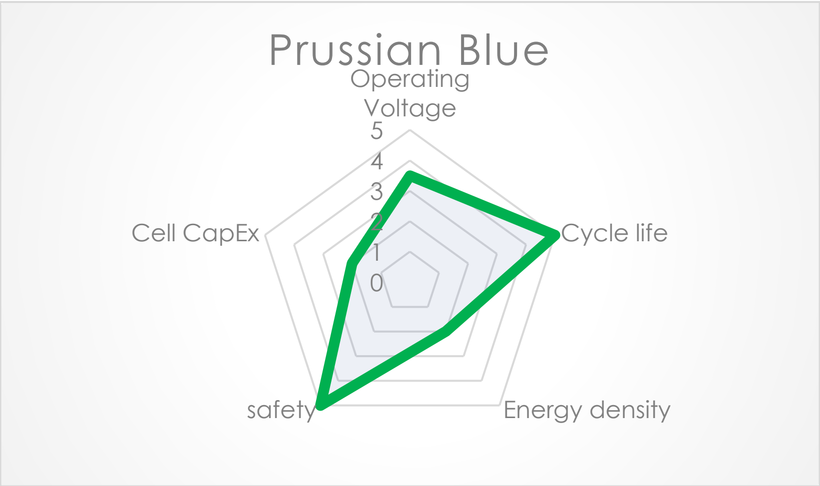


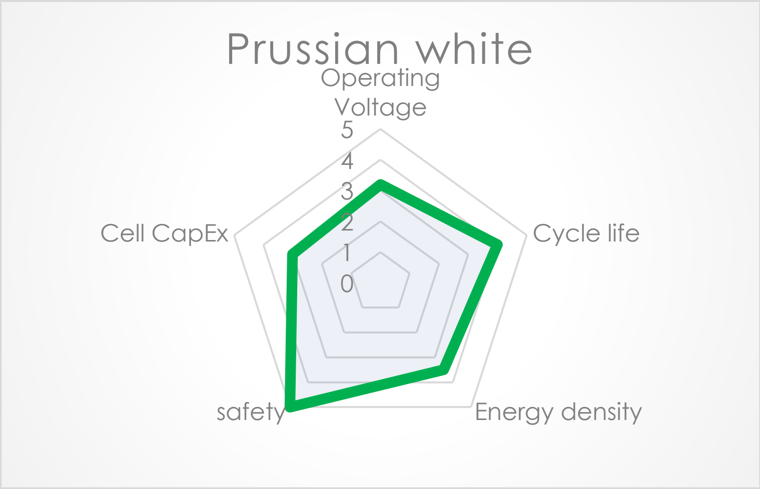




SIB Chemistries:







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Source : CES analysis and research.

Note: Cell CapEx =1 denotes the cost is high

NMC = (lithium) Nickel Manganese Cobalt
LMFP = Lithium Manganese Iron Phosphate
LFP = Lithium Iron Phosphate
NVP = Sodium Vanadium Phosphate

Performance comparison| Cathode variants application in companies for commercialization

SIB

Criteria	Prussian Blue vs PB	PB vs HC	Prussian white	NVP vs HC	NaS
Operating Voltage (V)	1.8	3.4	3.2	3.4	2
Cycle life	> 1,00,000 ** At 1 C	10,000	>40,000	>10,000	>5,000 At 0.2C
Energy density (Wh/kg)	17.3	NA	>100	60	222
Safety	High	high	High	High	High
Cell Capex ($ / KWh)	NA	228*	< 100	120	<200***
TRL (Predicted)	5-7	5-7	5-6	5-6	6

LIB

Criteria	NMC vs graphite	LFP vs graphite	LMFP vs graphite	NCA vs graphite
Operating Voltage (V)	3.7	3.2	4.1	3.6
Cycle life	2000	4500-5000	>4000 (Expected)	2000-2500
Energy density (Wh/Kg)	265-290	160-180	200-230	250
Safety	Low	Moderate	Moderate	Low
Cell Capex ($ / KWh)	110-130	100-110	115(Expected)	130-140
TRL (Predicted)	9	9	5-6	8-9

Lower TRL levels have window for improvements in Upcoming updates

* based on Argonne national laboratory
** Natron energy data
*** as of 2020 by NGK
Safety is given based on temperature profile and thermal runaway - LFP is given moderate in comparison to SIB chemistries

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Source : CES analysis and research.

Companies which are near commercialization

Altris AB	Natron energy	HiNa battery
Faradion	AMTE Power	Tiamat SAS

Source : CES analysis and research.

Role and location

Company	Role	Location	TRL	Fast charging
Altris AB	Commercialize Prussian White	Jiangsu Province, China	3-4	NA
Faradion limited	Cell manufacturer	Sheffield, UK	5-6	2 C
AMTE Power	Cell manufacturer	Oxford, UK	5-6	2.5 C
Tiamat	Cell manufacturer	Amiens, France.	5-6	12 C (5 min)
Natron energy	Commercialize Prussian blue, Cell manufacturing	Santa Clara, USA	5-7	6C (<10 min)
HiNa battery tech	Cell manufacturer	Jiangsu Province, China	6-7	3 C – 4 C
CATL	Cell Manufacturer	Ningde, China	6-7	3 C – 4 C (15 min)

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Source : CES analysis and research.
TRL = Technology Readiness Level

Takeaway

SIB matches market needs and could scale up to 100 GWh production capacity by 2030; 160 Wh/kg energy density could reach over 200 Wh/kg; cell costs could reach ~$74-105/KWh…

…but LIB will not wait for SIB to catch up, and also keeps improving (e.g., silicon doping of anode)

After thoroughly examining the intricate specifications and strategies of various companies, it is conceivable that SIB may surpass LIB due to their cost effectiveness and rapid charging capabilities.

This also ensures high safety to users.

Lower energy density of SIB is less of a concern when readily available charging stations are equipped for rapid charging, and for stationary storage

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Source : CES analysis and research/

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Thank You.

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Appendix

	Faradion limited	AMTE Power	HiNa battery tech	Altris AB	Natron energy	Tiamat	CATL
Form factor	Pouch cell	Pouch	cylindrical	Prismatic	Prismatic*	cylindrical	Prismatic/cylindrical
Nominal voltage (cell)	4.2	3.1	3.2	3.2	1.8	3.7 - 4****	NA
Chemistry	Layered	PolyAnion based	Na-Fe-Mn-cu (NFMC) vs anthracite-based carbon	Prussian white(PW) vs PW	Prussian blue(PB) vs PB	NVP/NFP/NVTP vs hard carbon	Prussian white vs HC
Cell capacity (Ah), @RT	32	30	25	25, 140	26.5	NA	NA
Energy density (Wh/kg)	160	135-140	145	165-170(mAh/g)	17.3	90-120	160
Cycle life (@80% DOD)	3700	>1000	>4500***	3000	>100000**	>5000	>1500
Operating temp. range (°C)	-20 to +60	-40 to 80	-40 to 80	Yet to identify	-20 to 45	-20 to 60	-20 to 60
Applications	Stationary energy storage	Battery energy storage for renewable power	Electric tricycle, motorcycle, industrial and household energy storage	Yet to identify	UPS, EV charging stations	Hybrid electric vehicles	EV
Mass Production plan	**2-3 GWh by 2024** Giga factory planned in India by Reliance	**30GWh Market size by 2030.**	**5 GWh by 2025**	Expected 1 GWh by cathode material production (dates are yet to be announced)	600 MWh production by the end of year (2023)	**6 GWh by 2030**	NA

LiB energy density: 200-300 Wh/kg

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NOTE:
*Based on shape of cell
**(90% DoD,1C)
*** (83% DoD, 2C)
****based on chemistry
Prussian blue has low energy density due to higher density of PB

Source: Company product Information in public domain.

COMPANY 1: CATL | PRUSSIAN WHITE | TRL 7-8*

About	CATL (founded in 2011, China)
Technology advancement/ chemistry	• Different combination of Prussian white as a cathode and HC as an anode. • Bulk structure material for rearranging electrons is designed for cathode & anode with good porous structure. • Cell designs used :Cylindrical/Prismatic. • Fast-charging, 15min for 80% SoC.
Applications	**Stationary Battery Storage System, batteries for UPS power back up, Electric Vehicle (EV).**

Parameters	SIB cell (PW vs HC), cylindrical)
Capacity (Ah)	NA
Energy density (Wh./kg)	160
Cycle life	>1500
Nominal voltage(V)	NA
Operating temperature range(°C)	-20 to 60

Fig . CATL cell

Cell features

- Next Generation battery chemistry focuses on 200 Wh/Kg.
- CATL to power its first SIB in Chery EV model

Plans

- Production of 20 GWh by 2030

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Source : https://www.catl.com/en/news/665.html/

Note : NA : Not available
TM : Transition Metal
* predicted values based on updates

COMPANY 2: HiNa Energy| Layered - Na-Mn-Fe-Cu-O (NMFC) | TRL 6-7 **

中科海钠 HiNa BATTERY

About	**HiNa Battery technology co ltd.** (founded in 2016 , Jiangsu, China)
Technology advancement/ chemistry	• layered cathode material and soft carbon anode material chemistry. • Cell designs used: Prismatic*, Cylindrical • Fast-charging C – rate : 2C. • Different specification of SIB - NaCR26650, NaCR32138
Investors/OEMs/partnership	• Tech partner-Institute of Physics, Chinese Academy of Sciences • Funding: $ 140 M (until 2022)
Applications	**Stationary Battery Storage System, batteries for UPS power back up**

Parameters	SIB cell (NMFC vs Soft carbon, Prismatic)
Capacity (Ah)	25
Energy density (Wh./kg)	145
Cycle life	4500 +
Nominal voltage(V)	3.2
Operating temperature range(°C)	-40 to 80

NaCP0880138 NaCR32138 NaCR26650

Fig . HINA cell

Cell features

- based on O3 phase multi-composite layered cathode material and soft carbon anode material chemistry
- NaCP08/80/138 presently available with different sizes.
- 30 Patents applied by the team

Gigafactory production timeline

- HiNa plans for 5GWh in 2025 production with its first phase having 1GWh of sodium ion battery

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Source : 1https://www.hinabattery.com/en/index.php?catid=15

Note : * based on shape of cell
** predicted values based on updates

COMPANY 3: Natron Energy| Prussian Blue | TRL 5-7**

Natron Energy

About	**Natron Energy** (founded in 2012 , California, USA)
Technology advancement/ chemistry	• They using and built cathode material with different three different combination of PB • Anthracite based anode material. Porous structure is found which makes intercalation/deintercalation easy Cell designs used : Prismatic* (Blue battery pack) • Fast-charging C – rate : 6C • Charging range- 1 C – 6 C .
Investors/OEMs/partnership	• Financing partners: Khosla ventures, Fluxus ventures, ABB, Catalus. • United airlines invested to increase electrifying ground operations • Total Funding: $ 175 M (until 2022)
Applications	**Stationary Battery Storage System, batteries for UPS power back up EV**

Parameters	SIB cell (PB vs PB, prismatic*)
Capacity (Ah)	26.5
Energy density (Wh./kg)	17.3
Cycle life	>1,00,000 (1 C)
Nominal voltage(V)	1.8
Operating temperature range(°C)	-20 to 45

Fig . Natron cell

Cell features

- Full recharge capability in 15 minutes or less, ready immediately
- No BMS as battery assures safety

Plans

- High power and thicker cells are coming out shortly
- 5 GWh production by 2030

Cost of the per kilo watt hour is almost 2.5-time other sodium ion batteries and 2 times the lithium-ion battery, as an advantage the cycle life is higher than any other battery.

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Source :https://natron.energy/product/

Note : * Speculated shape
** predicted values based on updates

COMPANY 4: Tiamat SAS |Layered- N(TM*)P | TRL 5-6**

TIAMAT

About	Tiamat SAS (founded in 2017 , France)
Technology advancement/ chemistry	• Cathode is built with different dopants of transition metals(vanadium, Titanium) with different compositions • Cell designs used :Cylindrical. • Fast-charging (5 min),. • Cell performance validated with HC as anode & N(TM)P as cathode using proprietary electrolyte. • Fast Charging rate: 12 C (0-99% in 5 min)
Investors/OEMs/partnership	• Technology Partnership with Zenergy • Funding : > $70M (until 2022)
Applications	**Stationary Battery Storage System, batteries for UPS power back up**

Parameters	SIB cell (N(TM)P) vs HC, cylindrical)
Capacity (Ah)	NA
Energy density (Wh./kg)	90 - 120
Cycle life	>5000
Nominal voltage(V)	3.7 - 4
Operating temperature range(°C)	-20 to 60

Fig . Tiamat cylindrical cell

Cell features

- 48-volt automotive cell pack

Plans:

- 6 GWh by 2030 in France

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Source : http://www.tiamat-energy.com/#apropos/

Note : NA : Not available
*TM : Transition Metal
** predicted values based on updates

COMPANY 5: AMTE Power plc | Polyanion based | TRL 5-6**

About	ATME Power plc (founded in 2013 , Oxford, UK)
Technology advancement/ chemistry	• Selecting Polyanion based Cathode material. Cell designs used : prismatic* • 135 - 140 Wh/kg Gravimetric energy density • Validated with HC with Polyanion based cathode material • 215 - 280 Wh/l Volumetric energy density • C/10- 2.5C charging range, capable of fast charge (Sub 22 min charge)
Investors/OEMs/partnership	• Manufacturing in Thurso, Scotland. • MoU signed with 5 companies, Cosworth, Viritec, MAHLE Powertrain, Sprint Power and BMW. • Funding : > $ 3-5 M (until 2022).
Applications	**Battery energy storage for renewable power, including for residential use and in remote locations without grid access.**

Parameters	SIB cell (Polyanion based cathode vs HC, Prismatic*)
Capacity (Ah)	30
Energy density (Wh./kg)	>140
Cycle life	1000+
Nominal voltage(V)	3.1
Operating temperature range(°C)	-40 to 80

Note : * based on shape
**predicted values based on updates

Source : https://amtepower.com/our-products/

Fig . AMTE cell

Cell features

- Single pouch cell size (L*B*H) = 22.8 x 16.7 x 1.16 (±5%)
- HC as an Anode

Gigafactory production timeline

- 1 GWh by 2026.
- Full production targets of >8m cells generating >£200m p.a.

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COMPANY 6: Faradion | Layered | TRL 5-6 *

faradion

About	**Faradion Limited** (founded in 2011 , United Kingdom(UK))
Technology advancement/ chemistry	• Pouch cells of SIB, using layered cathode with hard carbon with expecting energy density up to 160 Wh/kg • Nickel is doped in cathode material to increase the energy density and to retain the capacity over cycling • Hard Carbon with 88% active material, 6% super carbon. Cell design used : Pouch cell, prismatic, cylindrical • C/10- 2C charging range, capable of fast charge (Sub 20 min charge)
Investors/OEMs/partnership	• Tech Partnership with University of (Uo) Sheffield, Uo Oxford. • **Wholly own subsidiary purchased by Reliance New Energy Solar Limited (RNESL)** Funding : > $ 160M (until 2022)
Applications	**Stationary energy storage**

Note: Super carbon is usually known as graphene.

Parameters	SIB cell (Layered vs HC, pouch)
Capacity (Ah)	32
Energy density (Wh./kg)	160
Cycle life	4000+
Nominal voltage(V)	4.2
Operating temperature range(°C)	-20 to 60

Fig . Faradion cell

Gigafactory production timeline

- 1.9 GWh production by 2025 and 35GWh production by 2040 planned

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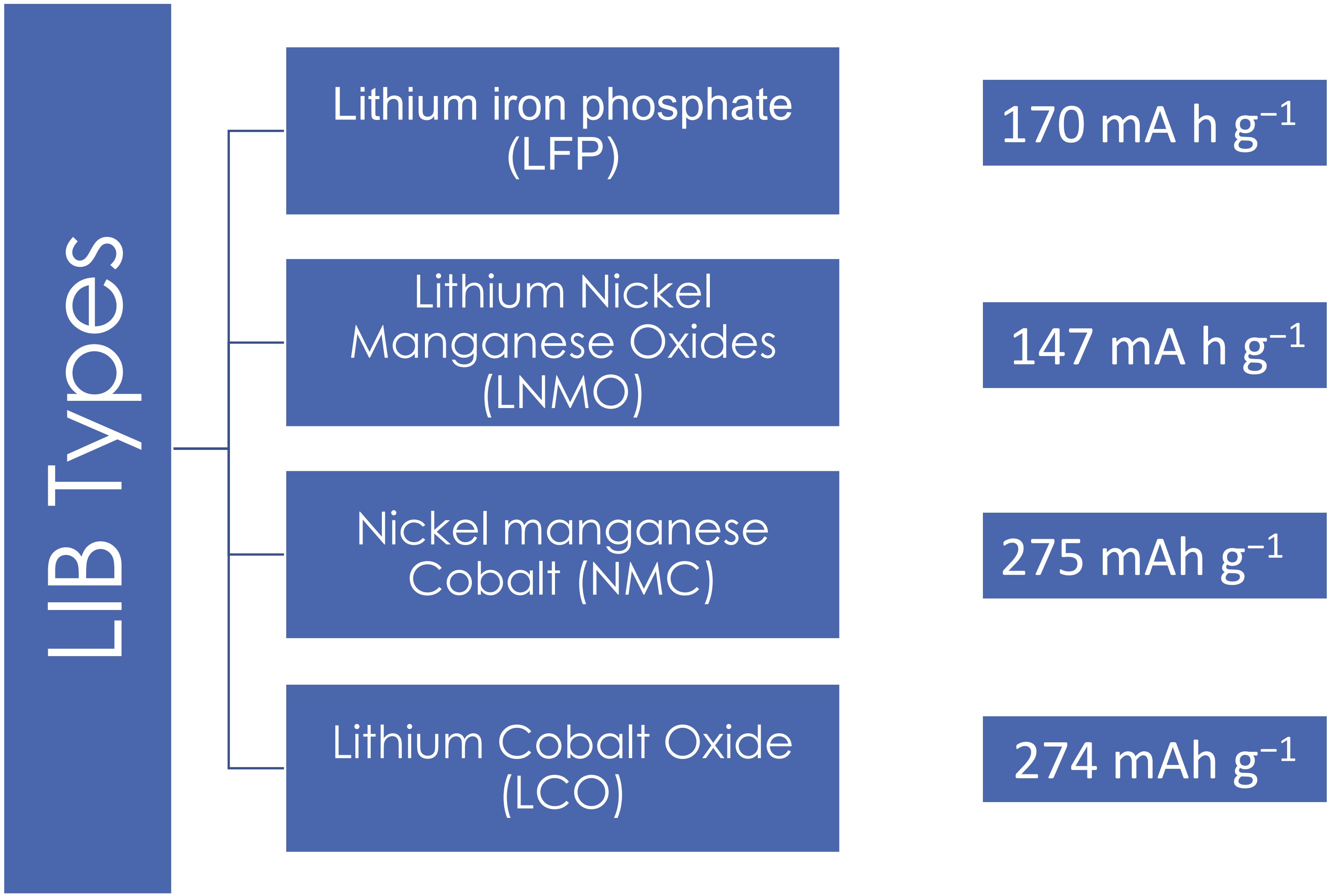
Source : 1. https://faradion.co.uk/faradion-welcomes-nissan-gigafactory-announcement/
*predicted values based on updates

Different chemistries of LIB with their theoretical capacity



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Source : CES analysis and research