

#### NACHHALTIGKEITSBEWERTUNG VON NATRIUM-IONEN BATTERIEN IN DER FRÜHEN ENTWICKLUNGSPHASE – USECASE KATHODENSCREENING

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# Why is the topic sustainability important?



Global installed stationary battery energy storage capacity by scenario,2020–2050 (Source: IEA).



Schönfisch, M., Dasgupta, A., Wanner, B. (2024). Projected Global Demand for Energy Storage. In: Passerini, S., Barelli, L., Baumann, M., Peters, J., Weil, M. (eds) Emerging Battery Technologies to Boost the Clean Energy Transition. The Materials Research Society Series. Springer, Cham. https://doi.org/10.1007/978-3-031-48359-2\_3

Sodium-Ion batteries (SiBs) are considered as an alternative to overcome some sustainability challenges related to Lithium-Ion batteries (LiB)

NEWS

#### 'World-first' grid-scale sodium-ion battery project in China launched





# Introduction

- SIB are based on essentially the same principle like LIB
- Sodium instead of lithium in the cathode active material and electrolyte salt
- Aluminium instead of copper for the current collector
- Use of several cathode materials





http://www.renewablesdaily.com/sodium-ion-batteries-are-improving



Goodenough, J.B. How we made the Li-ion rechargeable battery. Nat Electron 1, 204 (2018). https://doi.org/10.1038/s41928-018-0048-6 J. F. Peters, A. Peña Cruz, und M. Weil, "Exploring the Economic Potential of Sodium-Ion Batteries", *Batteries*, Bd. 5, Nr. 1, S. 10, März 2019, doi: 10.3390/batteries5010010.



# **Background – Sustainability assessment**



In early technology readiness levels (TRL) opportunities to steer are plentiful, but hard to choose from, while at later stages this is reversed



D. Collingridge, The social control of technology. New York: St. Martin's Press, 1980.





Baumann, M.; Häringer, M.; Schmidt, M.; Schmidt, M.; Schmidt, M.; Schmidt, J. R.; Weil, M. Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials 2022. Advanced energy materials, 12 (46), Artkl.Nr.: 2202636. doi:10.1002/aenm.202202636



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# **Use Case #1 Material Screening**



- Sustainability screening SiB Cathode Materials
- Very high uncertainty TRL<6</p>

### ADVANCED ENERGY MATERIALS

Research Article 🖞 Open Access 💿 🔅 😂

Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials

Manuel Baumann 🔀, Marcel Häringer, Marius Schmidt, Luca Schneider, Jens F. Peters, Werner Bauer, Joachim R. Binder, Marcel Weil

First published: 10 October 2022 | https://doi.org/10.1002/aenm.202202636

### Cell level not considered



### Scope: Only Materials





- Screening of 42 cathode active materials (CAM)
- Three indicators: Cost, Carbon Footprint, Criticality
- Theoretical data
  - Literature and electrochemical calculations

### Separation of cathode materials into:

- Oxidic Materials (NMC622 Benchmark)
- Polyanionic Materials (LFP Benchmark)





- Results for Carbon Footprint
- Carbon footprint global warming potential (GWP) (kg CO2 eq. / kWh)
- Cobalt, Nickel and Vanadium as key drivers for carbon footprint
- Energy density
- Surprisingly good correlation between carbon footprint, costs and criticality
- High uncertainty due to early stage
  assessment



- Results for Criticality
- Supply Risk (SR<sup>EU</sup>) → composite index descr. the risk of a disruption in supply of a specific material<sup>1</sup>
- Cobalt, Nickel and Vanadium as key drivers for carbon footprint
- Energy density
- Surprisingly good correlation between carbon footprint, costs and criticality
- High uncertainty due to early stage assessment

1; e.g. global supply and sourcing countries mixes (described by the Herfindahl-Hirschman Index HHI), import reliance, supplier countries' governance performance (World Governance Index (WGI) [53]), trade restrictions and agreements, availability and criticality of substitutes as well as end-of-life recycling input rate (EOL RIR).

Energy Density Supply risk total share Supply risk relative share w/o Wh/kg 4 0% 40% 60% 80% 100% avered oxide materia LiCoO<sub>2</sub> 585 LINI0.8C00.15Al0.05O2 (NCA) 696 NMC LiNi0.5Mn0.5O2 585 LiNi0.33Mn0.33Co0.33O2 (NMC111 592 LiNi0.6Mn0.2Co0.2O2 (NMC622 629 LiMn<sub>2</sub>O<sub>4</sub> (LMO) 472 LiNi0.5Mn1.504 (LNMO) 644 P2-Na<sub>0.67</sub>CoO<sub>2</sub> 369 a-NaMnO<sub>2</sub> 509 ß-NaMnO 523 Na0.44MnO 336 P2-Na<sub>0 67</sub>MnO<sub>2</sub> 490 P2-Na0 57Mn0 72Mg0 280 572 P2-Na0 67 Mn0 95 Mg0 050 455 Li 📕 Ni P2-Na0 67 Mn0 5 Fe0 50 O3-NaMn<sub>0.5</sub>Fe<sub>0.5</sub>O<sub>2</sub> P2-Na0.67Ni0.33Mn0.67O2 ■ Mg Co P2-Na0.8Li0.12Ni0.22Mn0.66O 415 P2-Na0.83Li0.07Ni0.31Mn0.62O2 490 P2-Na0.83Li0.25Mn0.75O2 500 AI V O3-NaFe0.5Co0.5O2 502 O3-NaNi0.33Co0.33Fe0.33O2 487 O3-NaNi0.5Mn0.5O2 377 🛛 Mn 📕 Fe Na[Mn<sub>0.4</sub>Fe<sub>0.5</sub>Ti<sub>0.1</sub>]O<sub>2</sub> NaMn<sub>0.33</sub>Fe<sub>0.33</sub>Ni<sub>0.33</sub>O<sub>2</sub> Na0.6Fe0.11Mn0.66Ni0.22O 🛛 P 🛛 🗖 Si NaMno 3Feo 4Nio 3O2 P2-Na0.6Fe0.2Mn0.65Ni0.15O Na0.6Ni0.22Al0.11Mn0.66O 675 ∎Na ∎Ti polyanionic materials LiFePO₄ (LFP 569 F F C Na-V-(PO.) Na<sub>4</sub>MnV(PO<sub>4</sub>) Na<sub>3</sub>MnTi(PO<sub>4</sub>)<sub>3</sub> Na<sub>3</sub>MnTi(PO<sub>4</sub>)<sub>3</sub> \*' LFP Na<sub>3</sub>MnZr(PO<sub>4</sub>) NaFePO/ Na1.702Fe3(PO4) Na4Fe3(PO4)P2O7 \*\* Na<sub>2</sub>MnPO<sub>4</sub>F \* NaV(PO₄)F Na1.5VPO4.8F0.7 Na<sub>2</sub>Fe(PO<sub>4</sub>)F Na<sub>3</sub>MnPO<sub>4</sub>CO<sub>3</sub> Na<sub>2</sub>MnFe(CN)<sub>6</sub> 490 Na0.61Fe[Fe(CN)6]0.94 493 Na<sub>0.81</sub>Fe[Fe(CN)<sub>6</sub>]<sub>0</sub> 447 Na<sub>2</sub>FeSiO<sub>4</sub> \* 724 Na<sub>2</sub>MnSiO<sub>4</sub> 630 Na<sub>2</sub>Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> 418 - 21 institute ioi Technology Assessment

and Systems Analysis

**10** February 12, 2024 Manuel Baumann

- Results for Cost
- €/kWh for active materials & preparation of precursors
- Cobalt, Nickel and Vanadium as key drivers for carbon footprint
- Energy density
- Surprisingly good correlation between carbon footprint, costs and criticality
- High uncertainty due to early stage
  assessment

M. Baumann, M. Häringer, M. Schmidt, L. Schneider, J. Peters, W.Bauer, J. R. Binder, and M. Weil, "Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials, Advanced Energy Materials, 2022, doi: 10.1002/aenm.202202636



Technology Assessment and Systems Analysis

- Tentative ranking based on simple weighted sum method (WSM)
- Good results for several SIB materials, above all Prussian Blue Analogues and silicate or sulphate based CAM.

Re

- Cobalt and Vanadium-containing CAM are ranked lower
- Weights of different criteria are varied for robustness check
- High uncertainty, but robust regarding varying weights of individual criteria

						Var	iatio	n of <b>\</b>	Weights	5		Varia	ation	of C	riteria	
		Equal		En	viron			Sup	ply		Cost		+ Sp	bec. E	n.	
		335	%		50%	6		259	6	1	25%		25%		25%	
		CF			C			CF			CF		CF		SE	
	Weights	33%	33%	25%		25%	25%		50%	50%		25%	25%	2	25%	
	Weights	€∠	SR	€		SR	€		SR	€		SR	£	$\Delta$	SR	
_	Year	Score	Rank		Score	Rank		Score	Rank		Score	Rank	Š	core	Rank	
	LiCoO <sub>2</sub>	0.22	48		0.24	48		0.24	48		0.20	48		0.34	47	
	LiNi <sub>0.8</sub> Co <sub>0.15</sub> Al <sub>0.05</sub> O <sub>2</sub> (NCA)	0.70	41		0.71	41		0.75	40		0.67	42		0.77	25	
	LiNi <sub>0.5</sub> Mn <sub>0.5</sub> O <sub>2</sub>	0.77	39		0.79	39		0.79	38		0.74	39		0.75	28	
ference	LiNi <sub>0.33</sub> Mn <sub>0.33</sub> Co <sub>0.33</sub> O <sub>2</sub> (NMC111)	0.59	46		0.61	46		0.61	46		0.56	46		0.62	44	
	LiNi <sub>0.6</sub> Mn <sub>0.2</sub> Co <sub>0.2</sub> O <sub>2</sub> (NMC622)	0.66	43		0.68	43		0.70	43		0.63	45		0.70	35	
	LiMn <sub>2</sub> O <sub>4</sub> (LMO)	0.83	35		0.86	35		0.81	35		0.83	35		0.73	31	
	LiNi <sub>0.5</sub> Mn <sub>1.5</sub> O <sub>4</sub> (LNMO)	0.85	32		0.87	34		0.88	26		0.84	34		0.85	7	
	P2-Na <sub>0.67</sub> CoO <sub>2</sub>	0.00	49		0.00	49		0.00	49		0.00	49		0.04	49	
	a-NaMnO <sub>2</sub>	0.92	15		0.94	14		0.91	14		0.94	13		0.82	15	
	ß-NaMnO <sub>2</sub>	0.89	23		0.92	23		0.87	27		0.92	21		0.81	18	
	Na <sub>0.44</sub> MnO <sub>2</sub>	0.85	34		0.88	31		0.81	30		0.87	31		0.66	38	
	P2-Na <sub>0.67</sub> MnO <sub>2</sub>	0.91	1/		0.93	16		0.90	20		0.93	18		0.80	19	
	P2-Na <sub>0.67</sub> Mn <sub>0.72</sub> Mg <sub>0.28</sub> O <sub>2</sub>	0.89	22		0.92	21		0.87	29		0.92	20		0.84	11	
	P2-Na <sub>0.67</sub> Mn <sub>0.95</sub> Mg <sub>0.05</sub> O <sub>2</sub>	0.89	24		0.92	7		0.87	20		0.91	7		0.77	0	
	P2-Na <sub>0.67</sub> Min <sub>0.5</sub> Pe <sub>0.5</sub> O <sub>2</sub>	0.94	26		0.90	24		0.94	20		0.90	22		0.69	36	
	P2 No Ni Mp O	0.09	20		0.92	26		0.07	16		0.91	25		0.085	6	
	P2-Na Li Ni Ma O	0.90	23		0.91	33		0.91	33		0.90	33		0.05	34	
	P2-NaLi -Ni - Mp - O	0.87	30		0.89	30		0.88	23		0.87	32		0.77	22	
	P2-NaLiMoO-	0.90	19		0.92	19		0.90	19		0.91	25		0.80	20	
	O3-NaFee Coa O	0.64	44		0.65	44		0.65	44		0.65	44		0.61	45	
	O3-NaNia a Coa a Fea a Oa	0.69	42		0.69	42		0.71	42		0.68	41		0.63	42	
	O3-NaNia Mna Oa	0.81	37		0.82	37		0.82	34		0.80	37		0.66	40	
	Na[Mno Feo Tio 1]O2	0.87	29		0.90	29		0.85	32		0.90	27		0.67	37	
	NaMno 33Feo 33Nio 33O3	0.89	25		0.90	28		0.91	17		0.89	28		0.78	21	
	Na <sub>0.6</sub> Fe <sub>0.11</sub> Mn <sub>0.66</sub> Ni <sub>0.22</sub> O <sub>2</sub>	0.81	36		0.84	36		0.80	37		0.82	36		0.63	43	
	NaMno3Feo4Nio3O2	0.87	31		0.88	32		0.88	24		0.87	30		0.71	33	
	P2-Na0.6Fe0.2Mn0.65Ni0.15O2	0.93	12		0.94	13		0.93	11		0.94	14		0.89	5	
	Na <sub>0.6</sub> Ni <sub>0.22</sub> Al <sub>0.11</sub> Mn <sub>0.66</sub> O <sub>2</sub>	0.92	14		0.94	15		0.93	10		0.93	17		0.92	2	
	polyanionic materials					1000						• 1 occur			a location of	•
eference	LiFePO <sub>4</sub> (LFP)	0.89	27		0.91	25		0.89	21		0.89	29		0.83	13	
	Na <sub>3</sub> V <sub>2</sub> (PO <sub>4</sub> ) <sub>3</sub>	0.64	45		0.65	45		0.65	45		0.65	43		0.53	46	•
	Na <sub>4</sub> MnV(PO <sub>4</sub> ) <sub>3</sub>	0.78	38		0.79	38		0.77	39		0.79	38		0.64	41	
	Na <sub>3</sub> MnTi(PO <sub>4</sub> ) <sub>3</sub> *	0.88	28		0.91	27		0.87	31		0.91	24		0.74	30	
	Na <sub>3</sub> MnTi(PO <sub>4</sub> ) <sub>3</sub> **	0.91	16		0.93	1/		0.90	18		0.93	15		0.81	16	
	Na <sub>3</sub> MnZr(PO <sub>4</sub> ) <sub>3</sub>	0.90	20		0.92	20		0.88	25		0.92	19		0.74	29	
	NaFePO4	0.93	10		0.95	10		0.92	12		0.95	17		0.77	23	
	Na <sub>1.7</sub> 0 <sub>2</sub> Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>3</sub>	0.92	15		0.94	11		0.91	12		0.95	10		0.70	27	
	Na MpBO E *	0.95	8		0.94	2		0.92	0		0.95	8		0.07	20	
	NaV/PO )E	0.43	47		0.45	47		0.42	47		0.45	47		0.32	48	
	Na VPO Fee	0.71	40		0.72	40		0.72	41		0.72	40		0.66	39	
г	Na-Fe(PO4)F	0.90	18		0.93	18		0.88	22		0.93	16		0.72	32	•
	Na <sub>2</sub> MnPO <sub>4</sub> CO <sub>2</sub> *	0.95	6		0.96	6		0.96	6		0.96	6		0.83	12	
	Na-MnFe(CN) *	0.96	4		0.97	4		0.97	4		0.97	5		0.84	9	
	Nager Fe[Fe(CN)] and 1)	0.96	5		0.97	5		0.96	5		0.97	4		0.84	10	
	Na <sub>0.81</sub> Fe[Fe(CN) <sub>6</sub> ] <sub>0.70</sub> <sup>1)</sup>	0.97	2		0.98	2		0.98	2		0.98	2		0.82	14	
ty	Na <sub>2</sub> FeSiO <sub>4</sub> *	0.97	3		0.98	3		0.98	3		0.98	3		0.98	1	
-	Na <sub>2</sub> MnSiO <sub>4</sub> *	0.94	9		0.95	9		0.94	8		0.95	11		0.90	4	
	Na <sub>2</sub> Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> *	0.98	1		0.99	1		0.99	1		0.99	1		0.81	17	



### **Material (screening) – Level Cost Comparison**



164

**NMC811** 

Anode material

Pack materials

#### Material Level

### Sodium-ion (Na-ion) battery chemistries contain lower-value materials than lithium-ion (Li-ion) ones

Metal intensity and 2022 cost of Na-ion and Li-ion cathodes

#### Cell Level

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

2022 battery pack costs by chemistry



Source: https://www.woodmac.com/news/opinion/sodium-ion-batteries-disrupt/

https://www.nextbigfuture.com/2023/09/future-sodium-ion-batteries-could-be-ten-timescheaper-for-energy-storage.html



# **Use Case #2 Cell production**

- Primary data collection for lab scale Cell production
- Role of upscaling
- Very high uncertainty



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#### Not considered



**Scope:** Only Materials





Journal of Cleaner Production 384 (2023) 135510

# Cell Production: lab vs. Industrial scale (Energy demand)





15 Februa

Erakca, M.; Pinto Bautista, S.; Moghaddas, S.; Baumann, M.; Bauer, W.; Leuthner, L.; Weil, M. Closing gaps in LCA of lithium-ion batteries: LCA of lab-scale cell production with new primary data 2023. Journal of Cleaner Production, 384, Art.-Nr.: 135510. doi:10.1001/0009/pAssessment

itute for

# Cell Production: lab vs. Industrial scale (Energy demand)





Global Warming Potential

2023. Journal of Cleaner Production, 384, Art.-Nr.: 135510. doi:10.1016/j.jclepro.2022.135510



# Use Case #3 Cell - Level 3 (7)



**ROYAL SOCIETY** 

OF CHEMISTRY

- Prospective LCA of Sodium-Ion cells
- Theoretical values
- High uncertainty





Scope:

#### System Periphery / BoP not considered



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# **Cell – Level – Comparison with material level results**

# GWP of a theoretical SIB vs

- Good GWP results for LIB and MMO and NMMT – type SIB (high energy density)
- Main drivers:
  - Cathode active material
  - Manufacturing energy
  - Energy density

# Results to screening very different\* w/o anode

Peters, J. F.; Baumann, M.; Binder, J. R.; Weil, M. <u>On the environmental competitiveness of sodium-ion batteries</u> <u>under a full life cycle perspective – a cell-chemistry specific modelling approach</u> 2021. Sustainable energy & fuels. <u>doi:10.1039/d1se01292d</u>



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# Early TRLs – Challenges & tranfereability to other cell technologies





Results are just valid for certain material  $\rightarrow$  very different on a component of system level

High uncertainty when assessing emerging technologies (processes, upscaling...)

Considering also lifetime and other use-phase parameters crucial as it might impact overall results

Can lead to different picture, abundant materials  $\rightarrow$  primary sourcing prefereable (?)

Has to be carried out very carefully, considering all

life cycle stages



# Conclusion



- Sustainability assessment should start as early as possible (low to high TRL and Market diffusion)
- Material screening: results are just valid for certain cathode active material → very different on a cell level
- SIB getting close to LIB, but do not yet outperform. Need for considering also lifetime and other use-phase parameters with more robust data
- Use of multiple assumptions for early TRL comparison with established technology problematic (Na vs Li-Ion)
- In general, high uncertainty when assessing emerging technologies



## Thank you for your attention!





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**Research for Sustainable Energy Technologies (RESET)** 

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### Underlying data available openly on Zenodo:

- Excel-based cell dimensioning tool, allows for incorporating also other cell chemistries
- Numeric results and graphics
- Life cycle inventory data for import and direct re-use in openLCA (requires ecoinvent 3.7.1)
- Use Phase can be adopted DOI/10.5281/zenodo.4742246

https://zenodo.org/badge/DOI/10.5281/zenodo.4742246.svg

Manuel Baumann

May 7, 2021

Zenodo

On the environmental competitiveness of Sodium-Ion batteries under a full life cycle perspective – A cell-chemistry specific modelling approach

Peters, Jens F.; Baumann, Manuel; Binder, Joachim; Weil, Marcel

This upload provides the full supplementary information and the MS-Excel based cell dimenioning tool used in the underlying publication (Environmental impacts of Sodium-Ion Batteries – Advances in production, use and recyclability)

It is based on the BatPac-Tool created by Argonne National Laboratories, but with some substantial modifications

- Reduction to dimensioning on battery cell leve, with no need to define a whole vehicle battery pack
- Inclusion of a detailed and cell-chemistry specific recycling model Automatic generation of inventory tables for life cycle assessment

The tool is free to use and to update as long as the underlying original publication is cited properly

In addition, the inventory data used for calculating the results are also provided as JSON-LD files for direct import into openLCA and in ILCD format for import into other LCA software. The LCI is based on ecoinvent 3.7; use with other ecoinvent versions might require re-linking of flows.

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#### Preview SIB-LCA-Update\_2021\_ILCD-Export\_ei371\_2021-08-15.zip 41f6c41a-42b0-4ecd-808d-0600bcfadb14.xml C4597934-ecac-422c-b431-382e85fdcb83.xml flowproperties 01846770-4cfe-4a25-8ad9-919d8d378345.xml 838aaa20-0117-11db-92e3-0800200c9a66.xml • 193a60a56-a3c8-11da-a746-0800200b9a66.xm 93a60a56-a3c8-19da-a746-0800200c9a66.xml • 193a60a56-a3c8-21da-a746-0800200c9a66.xml 93a60a56-a3c8-22da-a746-0800200c9a66.xml

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- 04b06043-ab0b-4125-9982-dec1687edda5.xml • 10639ab9a-43bd-48b8-b8d9-99c50aa022fd.xml • • • 06440ac0-a1f5-4ba5-a0f7-727570bfbfff.xml • 081e318e-b5f5-4f93-8c48-ab0bf5c43f2a xml





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1.6 kB

1.6 kB

2.2 kB

3.3 kB

3.0 kB

3.4 kB

3.3 kB

3.4 kB

sment; cell layout; recycling model; inv oning tool, lithium-ion; sodium-ion

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### Sensitivity analysis

#### Anode

C) Cost €/kWh

	w/o an	ode	н	C/G	raphite	Na/Li	anod	le	
	- 20 4	0 60	8 -	20	40 60 80	- 20	40	60	80
layered oxide materials						1			
LICOU2			18						
LINI <sub>0.8</sub> Co <sub>0.15</sub> Al <sub>0.05</sub> O <sub>2</sub> (NCA)		-	18		<b>-</b>		-		
LINI <sub>0.5</sub> Mn <sub>0.5</sub> O <sub>2</sub>			18	H		-	-		
LiNi <sub>0.33</sub> Mn <sub>0.33</sub> Co <sub>0.33</sub> O <sub>2</sub> (NMC111)		-	11		H - 1	-	-		
LiNi <sub>0.6</sub> Mn <sub>0.2</sub> Co <sub>0.2</sub> O <sub>2</sub> (NMC622)		4	11		H		<b>-</b>		
LiMn <sub>2</sub> O <sub>4</sub> (LMO)			11	E I	-		-		
LiNi <sub>0.5</sub> Mn <sub>1.5</sub> O <sub>4</sub> (LNMO)			11		4				
P2-Na <sub>0.67</sub> CoO <sub>2</sub>		-	11		F			-	_
a-NaMnO <sub>2</sub>			11	•					
ß-NaMnO <sub>2</sub>			11	•					
Na <sub>0.44</sub> MnO <sub>2</sub>	<b>B</b>		11						
P2-Na <sub>0.67</sub> MnO <sub>2</sub>	<b>D</b> 11		11	н					
P2-Na <sub>0.67</sub> Mn <sub>0.72</sub> Mg <sub>0.28</sub> O <sub>2</sub>	<b>S</b> 11		16						
P2-Na <sub>0.67</sub> Mn <sub>0.95</sub> Mg <sub>0.05</sub> O <sub>2</sub>	<b>1</b> 11		16	H					
P2-Na <sub>0.67</sub> Mn <sub>0.5</sub> Fe <sub>0.5</sub> O <sub>2</sub>	<b>5</b> H		16						
O3-NaMn <sub>0.5</sub> Fe <sub>0.5</sub> O <sub>2</sub>			19						
P2-Na <sub>0.67</sub> Ni <sub>0.33</sub> Mn <sub>0.67</sub> O <sub>2</sub>	<b>5</b> 11		16			<b>1 1</b>			
P2-Na <sub>0.8</sub> Li <sub>0.12</sub> Ni <sub>0.22</sub> Mn <sub>0.66</sub> O <sub>2</sub>	<b>6.</b> H		19						
P2-Na <sub>0.83</sub> Li <sub>0.07</sub> Ni <sub>0.31</sub> Mn <sub>0.62</sub> O <sub>2</sub>			18						
P2-Na <sub>0.83</sub> Li <sub>0.25</sub> Mn <sub>0.75</sub> O <sub>2</sub>			18						
O3-NaFe <sub>0.5</sub> Co <sub>0.5</sub> O <sub>2</sub>			1.6	_	1	- 1			
O3-NaNi <sub>0.33</sub> Co <sub>0.33</sub> Fe <sub>0.33</sub> O <sub>2</sub>			18						
O3-NaNi <sub>0.5</sub> Mn <sub>0.5</sub> O <sub>2</sub>	<b></b>		18		-	- 22	-		
Na[Mn <sub>0.4</sub> Fe <sub>0.5</sub> Ti <sub>0.1</sub> ]O <sub>2</sub>			18		1				
NaMn <sub>0.33</sub> Fe <sub>0.33</sub> Ni <sub>0.33</sub> O <sub>2</sub>	-44		18						
Na <sub>0.6</sub> Fe <sub>0.11</sub> Mn <sub>0.66</sub> Ni <sub>0.22</sub> O <sub>2</sub>	<u> </u>		11	•					
NaMn <sub>0.3</sub> Fe <sub>0.4</sub> Ni <sub>0.3</sub> O <sub>2</sub>	<b>_</b>		11	-					
P2-Na0.6Fe0.2Mn0.65Ni0.15O2	<b>- 1</b>								
Na <sub>0.6</sub> Ni <sub>0.22</sub> Al <sub>0.11</sub> Mn <sub>0.66</sub> O <sub>2</sub>	P 11								
	P 11		11						
polyanionic materials									
LiFePO <sub>4</sub> (LFP)			11						
Na <sub>3</sub> V <sub>2</sub> (PO <sub>4</sub> ) <sub>3</sub>	<b>H</b>		11				-		
Na MnV(PO <sub>4</sub> )			11		<b>H</b>		-		
Na <sub>3</sub> MnTi(PO <sub>4</sub> ) <sub>3</sub> *		4	11		-		-		
Na <sub>2</sub> MnTi(PO <sub>4</sub> ) <sub>2</sub> **			16				T.		
Na <sub>2</sub> MnZr(PO <sub>4</sub> ) <sub>2</sub>			16						
NaFePO			16						
Na1 202Fe2(PO4)2			16						
Na <sub>4</sub> Fe <sub>2</sub> (PO <sub>4</sub> )P <sub>2</sub> O <sub>7</sub> **			16				1		
Na MnPO F *			16				1		
NaV(PO <sub>4</sub> )F			18						
Na VPO For			18	- 1				_	_
Na <sub>2</sub> Fe(PO <sub>4</sub> )F			18	_					
Na <sub>2</sub> MnPO <sub>4</sub> CO <sub>2</sub> *			18						
Na <sub>2</sub> MnFe(CN), *			18						
Naca FelFe(CN) close 1)			18						
Nacos FelFe(CN) close 1)			18						
Na-FeSiO. *			18						
Na-MnSiQ. *			18						
Na_Fe_(SO_)_ *	24		11						
1021 02100413			1.						
			10						

#### Material cost Scale effects

#### A) CAM Cost 2021 -2030 €/kWh w/o anode

lavarad oxida matarials	0 20	4	0	60	5	30 10
				299	%	
$LINI_{0.8}CO_{0.15}AI_{0.05}O_2$ (NCA)				375	%	
$LINI_{0.5} MI_{0.5} O_2$						
		-			312%	
$LINI_{0.6}MIn_{0.2}CO_{0.2}O_2$ (NMC622)			475%			
LIMn <sub>2</sub> O <sub>4</sub> (LMO)			372%			
LINI <sub>0.5</sub> Mn <sub>1.5</sub> O <sub>4</sub> (LNMO)				-		188%
P2-Na <sub>0.67</sub> CoO <sub>2</sub>	-219%	-		-		10070
a-NaMnO <sub>2</sub>	219%					
ß-NaMnO <sub>2</sub>	219%					
Na <sub>0.44</sub> MnO <sub>2</sub>	0199/					
P2-Na <sub>0.67</sub> MnO <sub>2</sub>	21070					
P2-Na <sub>0.67</sub> Mn <sub>0.72</sub> Mg <sub>0.28</sub> O <sub>2</sub>	525%					
P2-Na <sub>0.67</sub> Mn <sub>0.95</sub> Mg <sub>0.05</sub> O <sub>2</sub>	218%					
P2-Na <sub>0.67</sub> Mn <sub>0.5</sub> Fe <sub>0.5</sub> O <sub>2</sub>	F 198%					
O3-NaMn <sub>0.5</sub> Fe <sub>0.5</sub> O <sub>2</sub>	<b>1</b> 200%				Vee	2021
P2-Na <sub>0.67</sub> Ni <sub>0.33</sub> Mn <sub>0.67</sub> O <sub>2</sub>	146%				rear	2031
P2-Na <sub>0.8</sub> Li <sub>0.12</sub> Ni <sub>0.22</sub> Mn <sub>0.66</sub> O <sub>2</sub>	236%	1			Year	2021
P2-Na <sub>0.83</sub> Li <sub>0.07</sub> Ni <sub>0.31</sub> Mn <sub>0.62</sub> O <sub>2</sub>	192%		Potenti	al pric	e char	ges
P2-Na <sub>0.83</sub> Li <sub>0.25</sub> Mn <sub>0.75</sub> O <sub>2</sub>	430%		(average	e valu	es)	
O3-NaFeo Coo O2		187	(		,	
03-NaNio 33C00 33Feo 33O3		0%				
O3-NaNio = Mno = O2	188%					
Na[Mno 4Feo FTio 1]O2	<b>P</b> +186%		Element	2021	2031	Change Unit
NaMno as Feo as Nio as Os	137%		Al	1,670 31.033	2,066	124% €/(t 176% €/t
Nao (Feo 44 Mno (cNio 23 Oc	153%		F	271	272	100% €/t
NaMna - Fea - Nia - Oa	137%		Li	92 15,567	90 76,049	98% €/t 489% €/t
P2-Na - Fe - Mn - Ni - O	<b>160%</b>		Mg	2,231	4,047	181% €/t
	<b>1</b> 52%		Na	162	389	240% €/t
140.61410.22410.1114110.66			P	12,765 100	15,628 182	122% €/t 182% €/t
nolvanionic matorials			s	108	266	245% €/t
		558	SI KE TI	2,289 2,526	3,691 3,685	161% €/t 146% €/t
	106%	4	- V 7r	26	27	104% €/kg
$Na_3 V_2 (PO_4)_3$	116%		21	1,200	1,713	14376 671
$Na_4MnV(PO_4)_3$	H 180%					
$N_{a_{3}} V(\Pi \Pi (PO_{4})_{3}$	180%					
$Na_3 N n \Pi (PO_4)_3 T^*$	H232%					
	149%					
	120%					
$Na_{1.7}U_2Fe_3(PO_4)_3$	153%					
$Na_4Fe_3(PO_4)P_2O_7 **$	104%					
Na <sub>2</sub> MnPO <sub>4</sub> F *	209%	50/				
NaV(PO <sub>4</sub> )F	10	0%				
Na <sub>1.5</sub> VPO <sub>4.8</sub> F <sub>0.7</sub>	106%					
Na <sub>2</sub> Fe(PO <sub>4</sub> )F	153%					
Na <sub>3</sub> MnPO <sub>4</sub> CO <sub>3</sub> *	P 215%					
Na2MnFe(CN)6 *	<b>H</b> 187%					
Na <sub>0.61</sub> Fe[Fe(CN) <sub>6</sub> ] <sub>0.94</sub> <sup>1)</sup>	<b>h</b> 193%					
Na <sub>0.81</sub> Fe[Fe(CN) <sub>6</sub> ] <sub>0.79</sub> <sup>1)</sup>	138%					
Na <sub>2</sub> FeSiO <sub>4</sub> *	h 166%					
Na₂MnSiO₄ *	<b>P</b> + 200%					
Na <sub>2</sub> Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> *	· 152%					

CF	%			
33%				itive
€∠	SR 🗌		rar	IK
2021	2031		2021	2031
0.27	0.23		48	48
0.70	0.67		38	40
0.70	0.44		47	47
0.67	0.62		41	42
0.81	0.76		31	37
0.84	0.80		27	29
0.01	0.07		49	49
0.91	0.91		15	17
0.88	0.89		23	26
0.77	0.77		42	45
0.90	0.90		20	20
0.89	0.88		37	35
0.88	0.89		28	28
0.93	0.93		7	7
0.88	0.88		25	27
0.88	0.90		19	16
0.84	0.84		30	30
0.80	0.87		18	24
0.65	0.68		10	42
0.69	0.72		40	30
0.79	0.82		32	31
0.74	0.75		43	44
0.79	0.82		35	32
0.81	0.83		33	33
0.86	0.88		26	19
0.91	0.92		12	13
0.91	0.92		13	12
0.88	0.83		17	25
0.65	0.71		45	41
0.78	0.81		36	34
0.88	0.88		24	22
0.90	0.90		16	15
0.89	0.89		21	21
0.92	0.92		11	11
0.91	0.91		14	14
0.92	0.92		10	10
0.92	0.92		9	9
0.47	0.50		46	40
0.72	0.89		39	19
0.00	0.89		22	10
0.94	0.94		4	5
0.94	0.94		5	4
0.05	0.95		3	2
0.55	0.00			the second se
0.95	0.95		1	1
0.95	0.95		1	1
	33 2021 0.27 0.70 0.76 0.60 0.67 0.81 0.91 0.84 0.90 0.88 0.93 0.88 0.93 0.88 0.93 0.88 0.93 0.88 0.65 0.69 0.79 0.84 0.86 0.69 0.79 0.84 0.86 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.88 0.88 0.99 0.77 0.84 0.88 0.99 0.77 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.79 0.84 0.85 0.69 0.77 0.79 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.84 0.85 0.69 0.77 0.81 0.79 0.88 0.88 0.99 0.77 0.88 0.88 0.99 0.77 0.88 0.88 0.99 0.77 0.88 0.77 0.79 0.88 0.79 0.77 0.79 0.88 0.77 0.79 0.88 0.77 0.79 0.88 0.77 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.79 0.74 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.78 0.77 0.72 0.72 0.72 0.72 0.72 0.72 0.94 0.94	33%        CF        33%        2021      2031        0.27      0.23        0.70      0.67        0.76      0.70        0.60      0.44        0.67      0.76        0.78      0.70        0.61      0.76        0.81      0.70        0.91      0.91        0.88      0.89        0.77      0.90        0.93      0.93        0.88      0.89        0.93      0.93        0.88      0.89        0.93      0.93        0.88      0.89        0.93      0.81        0.84      0.84        0.85      0.72        0.79      0.82        0.74      0.72        0.77      0.92        0.91      0.92        0.91      0.92        0.91      0.92        0.92      0.92        0.93      0.93        0.86      0.88        0.99	33%      33%        CF      33%        2021      2031        0.77      0.67        0.76      0.70        0.67      0.67        0.76      0.70        0.60      0.44        0.67      0.62        0.81      0.76        0.81      0.76        0.91      0.91        0.93      0.93        0.94      0.80        0.90      0.90        0.89      0.88        0.88      0.89        0.93      0.93        0.88      0.89        0.88      0.89        0.88      0.89        0.88      0.89        0.79      0.82        0.79      0.82        0.79      0.82        0.79      0.82        0.79      0.82        0.79      0.82        0.79      0.82        0.79      0.82        0.88      0.88        0.91      0.92        0.92	33%      Indica        CF      33%      Indica        SR      rar        2021      2031      2021        0.27      0.23      48        0.70      0.67      38        0.60      0.44      47        0.67      0.62      41        0.81      0.76      31        0.60      0.44      0.80      2.7        0.61      0.07      49        0.91      0.91      15        0.88      0.89      2.23        0.77      77      42        0.90      0.90      20        0.88      0.89      2.23        0.77      0.77      7        0.88      0.89      2.0        0.88      0.89      2.0        0.88      0.89      2.0        0.88      0.89      2.1        0.88      0.86      18        0.55      0.68      44        0.69      0.72      40        0.79      0.82 <t< td=""></t<>



Institute for Technology Assessment and Systems Analysis

CAMP Cost CAM

### Cost can change drastically

- Price development until 2031
- Clear impact for some materials
- Economy of scale effects
- SiB might offer high advantage









# Why is the topic sustainability important?

- Climate Change, Planetary limits....
- Sustainability development goals (SDG)
- European Green Deal
- Sustainable Finance & Taxonomy Regulation
- A new Circular Economy Action Plan
- EU Battery directive
- Critical raw material act



Source: https://www.unep.org/interactive/measuring-progress-environment-sdgs/



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