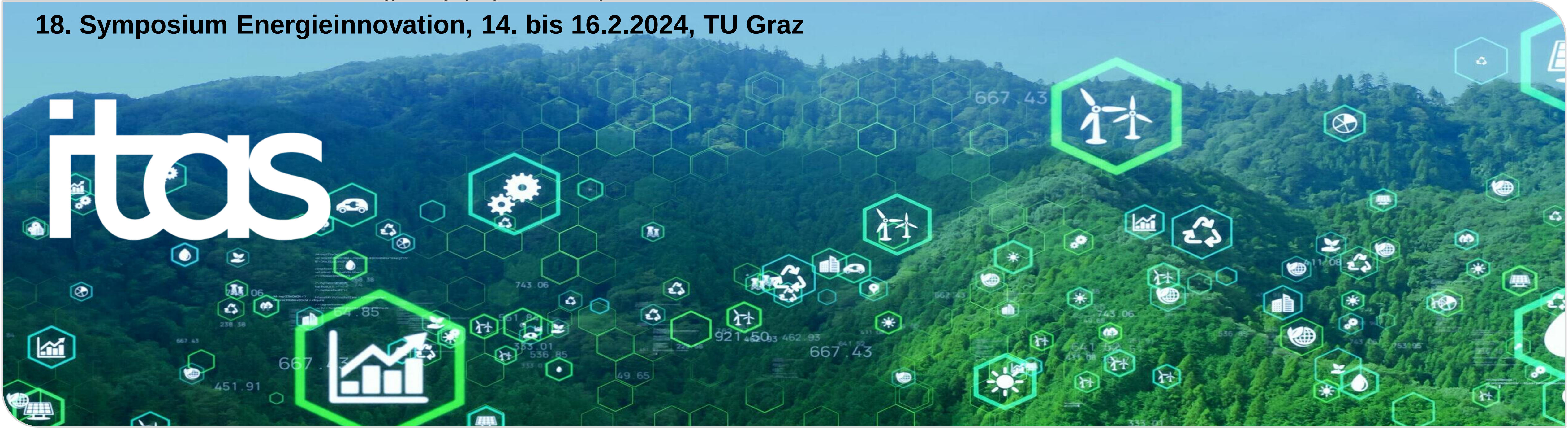
NACHHALTIGKEITSBEWERTUNG VON NATRIUM-IONEN BATTERIEN IN DER FRÜHEN ENTWICKLUNGSPHASE – USECASE KATHODENSCREENING

Manuel Baumann[1] , Jens Peters[2] , Friedrich Jasper[1], Merve Erakca[1], Hüseyin Ersoy[1], Sebastian Pinto-Bautista[1], Bismark Raza Haruna[1], Marcel Weil[1],

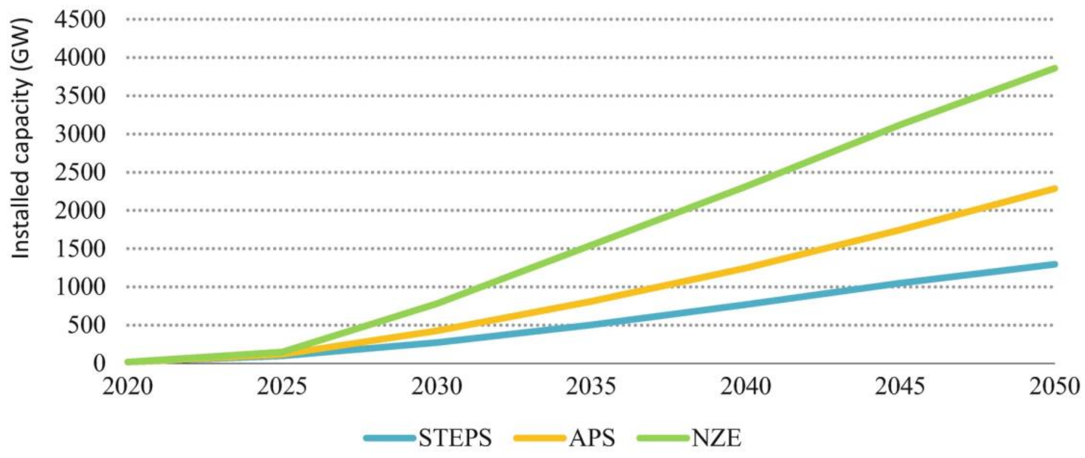
Institute for Technology Assessment and System Analysis (ITAS), Karlsruhe Institute of Technology (KIT), Germany. manuel.baumann@kit.edu
University of Alcalá (UAH), Department of Economics, Alcalá de Henares, Madrid, Spain
Helmholtz Institute Ulm for Electrochemical Energy Storage (HIU), Ulm, Germany

18. Symposium Energieinnovation, 14. bis 16.2.2024, TU Graz

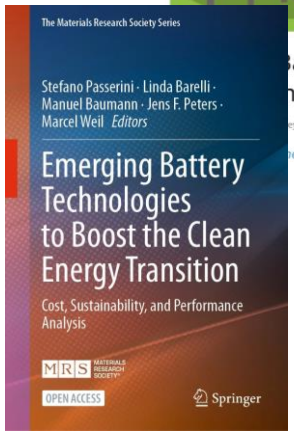


Why is the topic sustainability important?

- 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



Open Access: https://link.springer.com/book/10.1007/978-3-031-48359-2

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

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

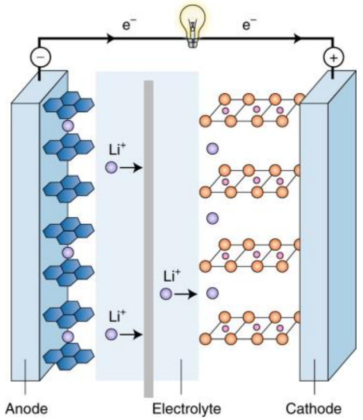
http://www.renewablesdaily.com/sodium-ion-batteries-are-improving

Li-Ion Batteries

„Same, same but different „

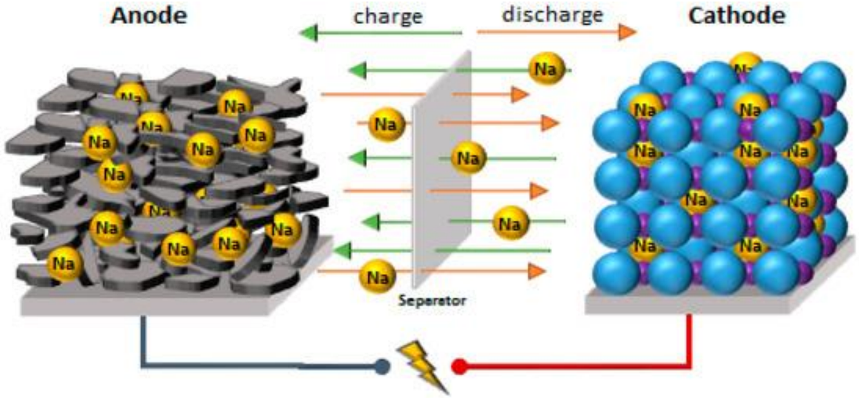
Na-Ion Batteries

Anode Materials:
Graphite
Metallic Li



Li-Cathode Materials:
Ni
Co
Mn
FePO4
Al
…

Anode Materials:
Hard Cabon
Metallic Na



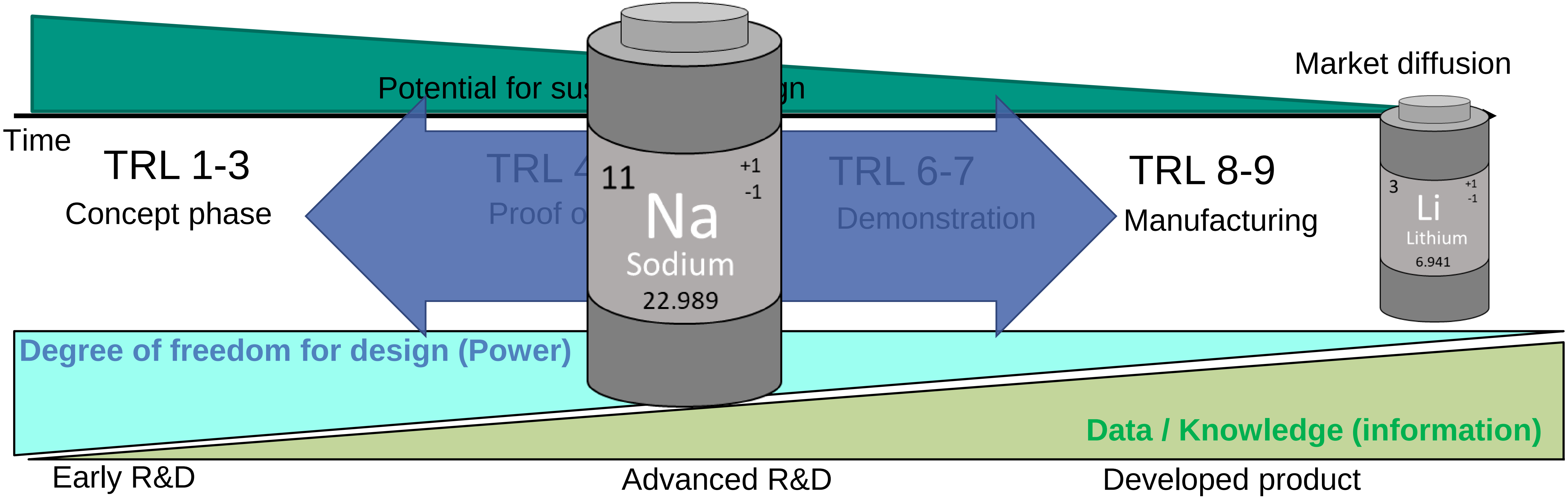
Na-Cath. Materials:
Ni
Mn
FePO4
Ti
Al
…

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.

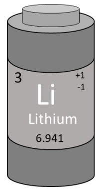
Which method?

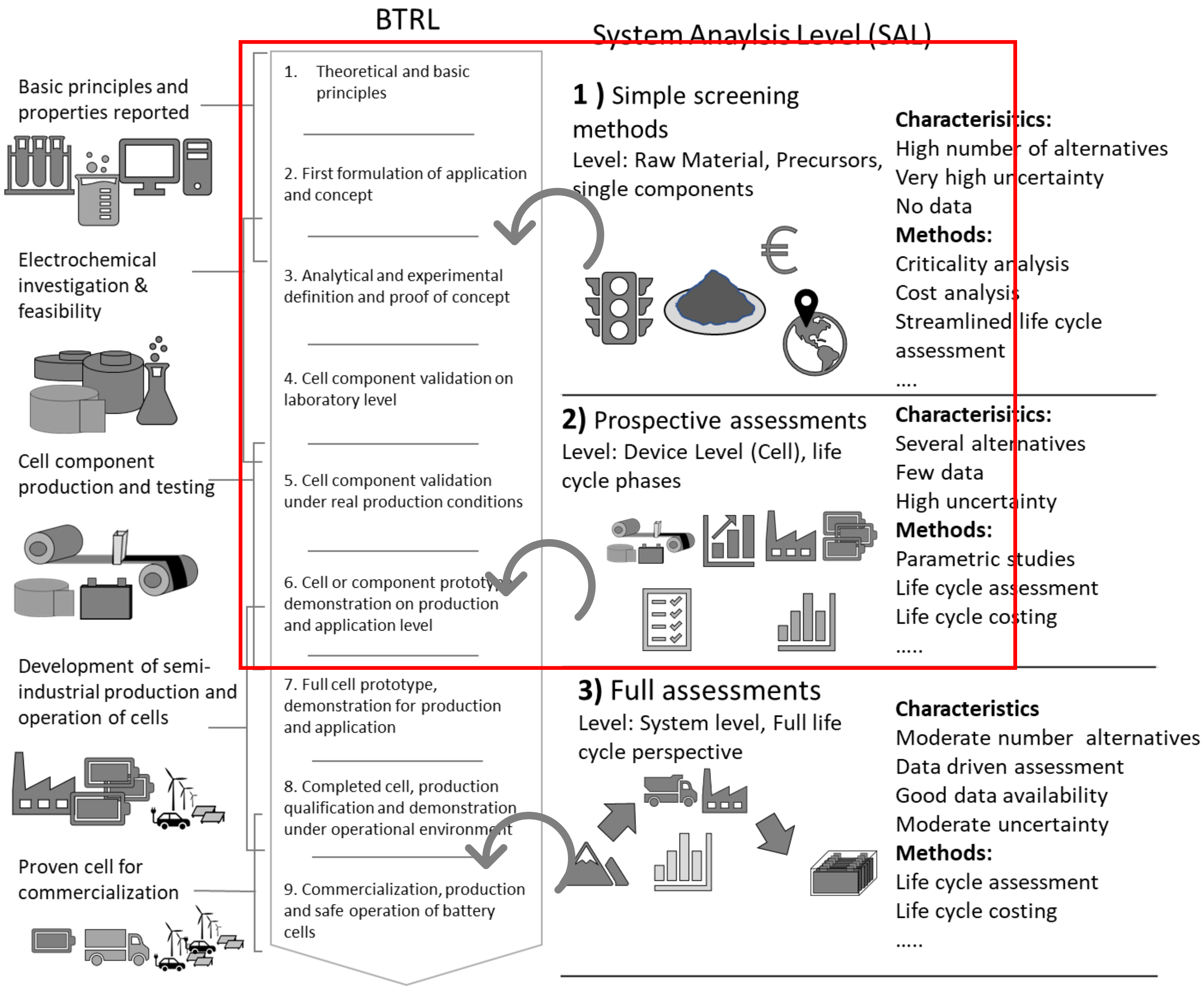
Where to start?

How to compare?

Data availability?

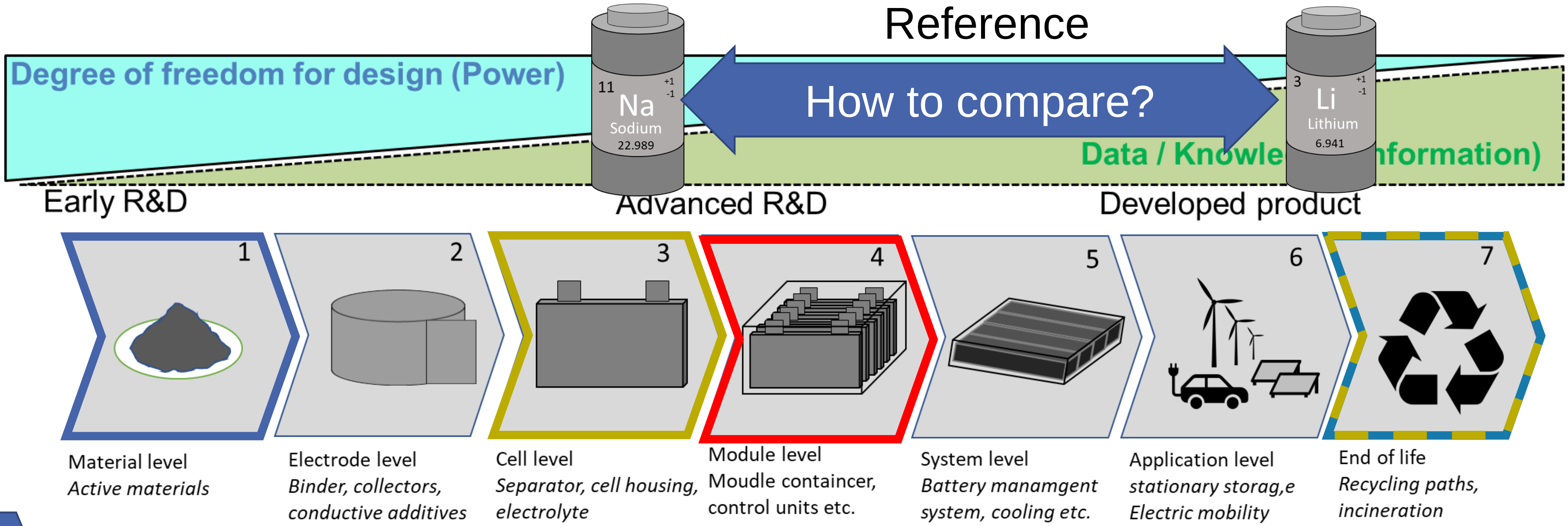
Who is my target group?





Baumann, M.; Häringer, M.; Schmidt, M.; Schneider, L.; Peters, J. F.; Bauer, W.; Binder, 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

Use Cases



Use Cases

Material (screening) – Level 1

Cell production 1-4 (upscaling challenges)

Cell level- Level 3 (Cell vs. material screening)

Use Case #1 Material Screening

- Sustainability screening
  SiB Cathode Materials

- Very high uncertainty TRL<6

ADVANCED ENERGY MATERIALS

Research Article | Open Access

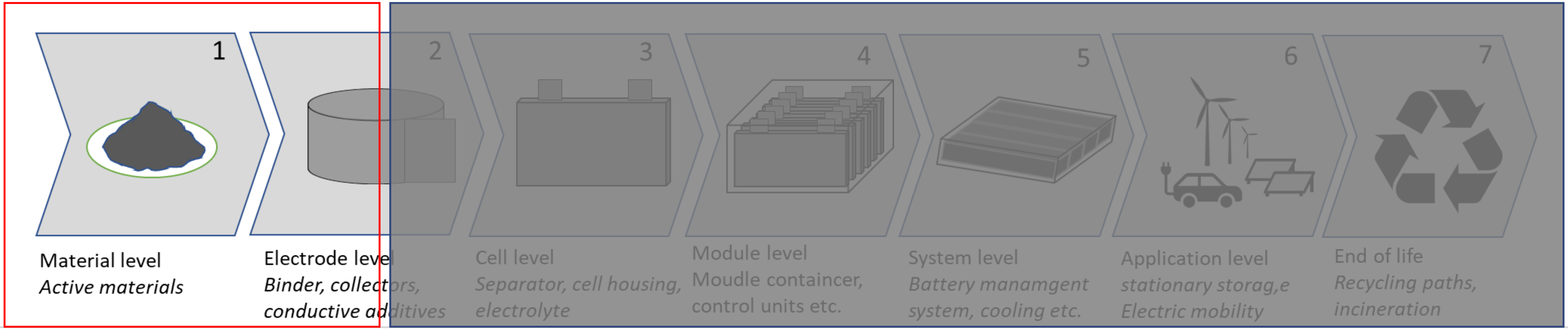
Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials

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

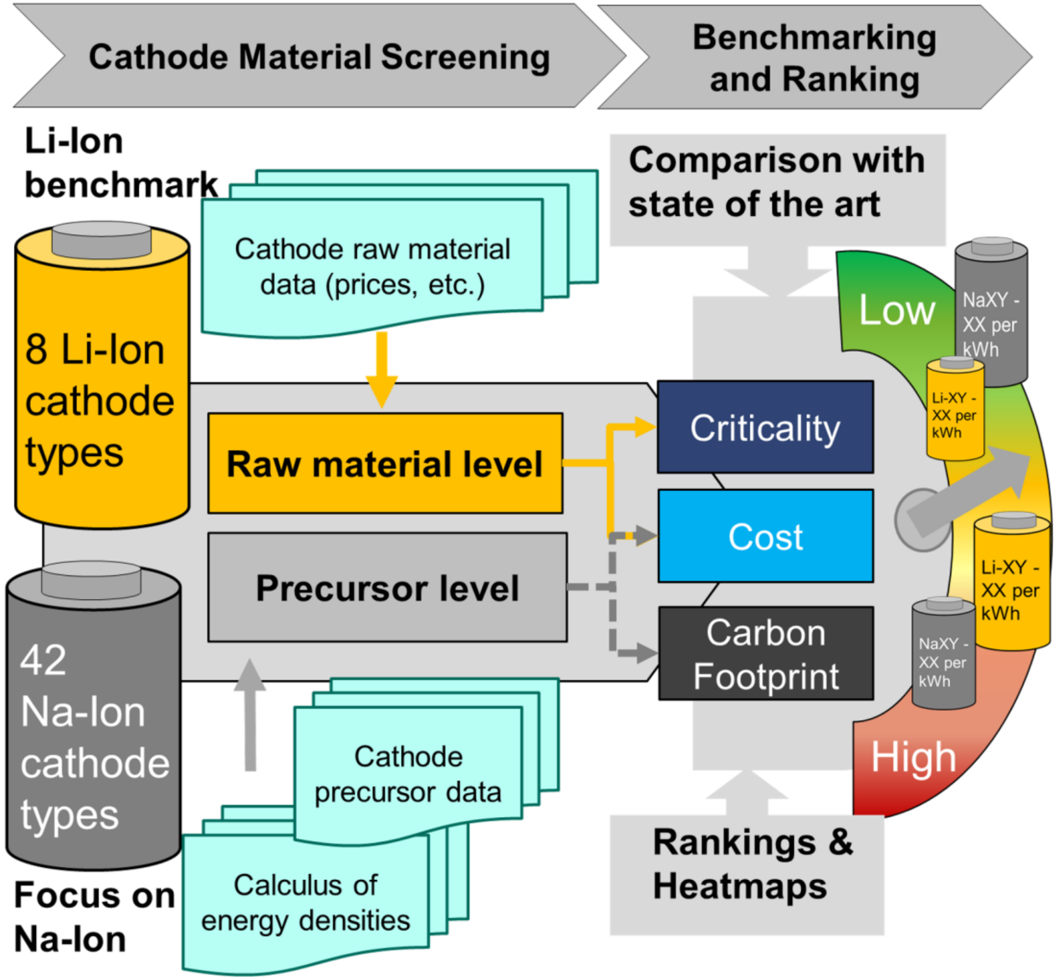
Cell level not considered

Scope: Only Materials



Material (screening) – Level

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



Separation of cathode materials into:

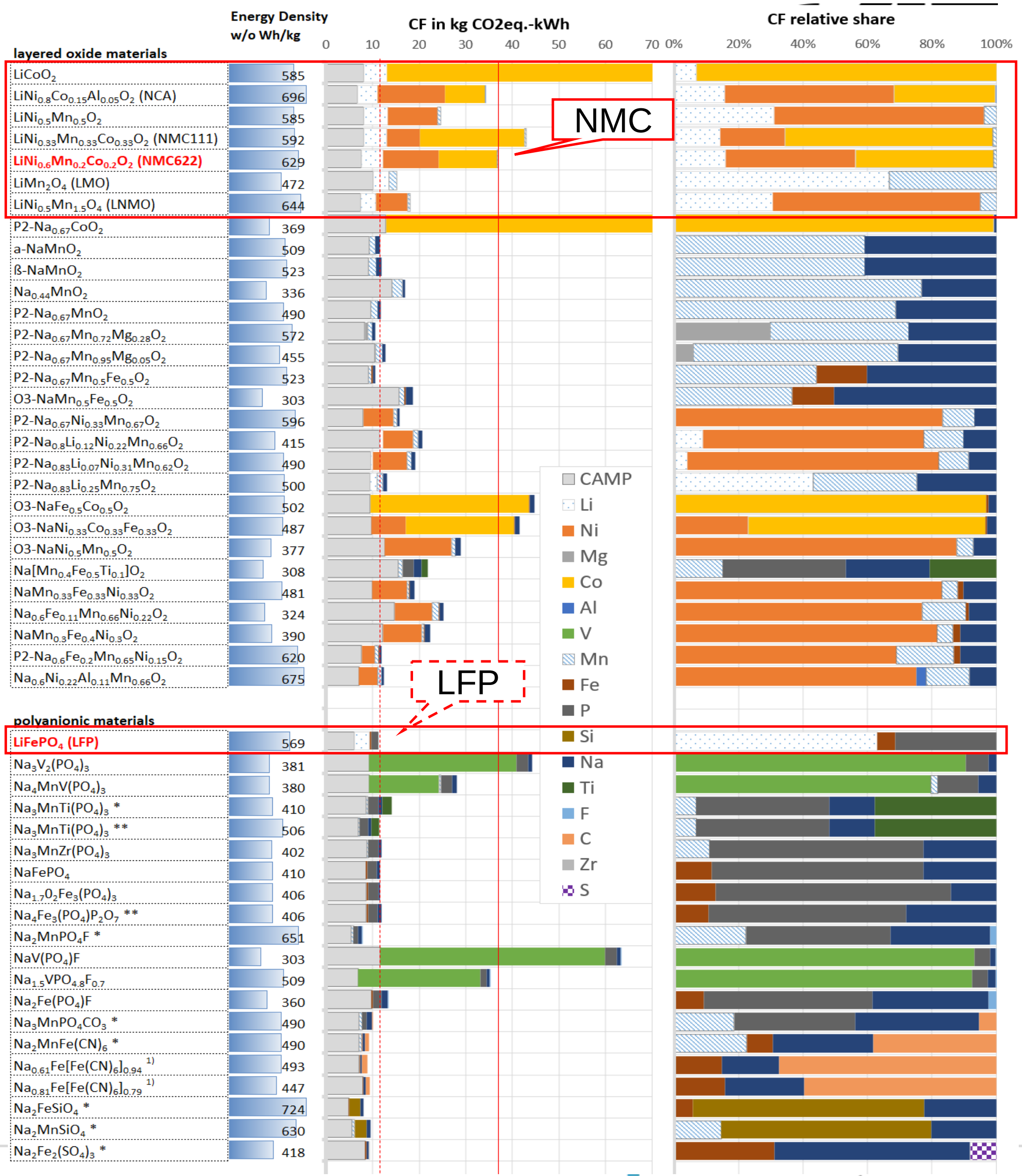
- Oxidic Materials (NMC622 Benchmark)
- Polyanionic Materials (LFP Benchmark)

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

Material (screening) – Level

- **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

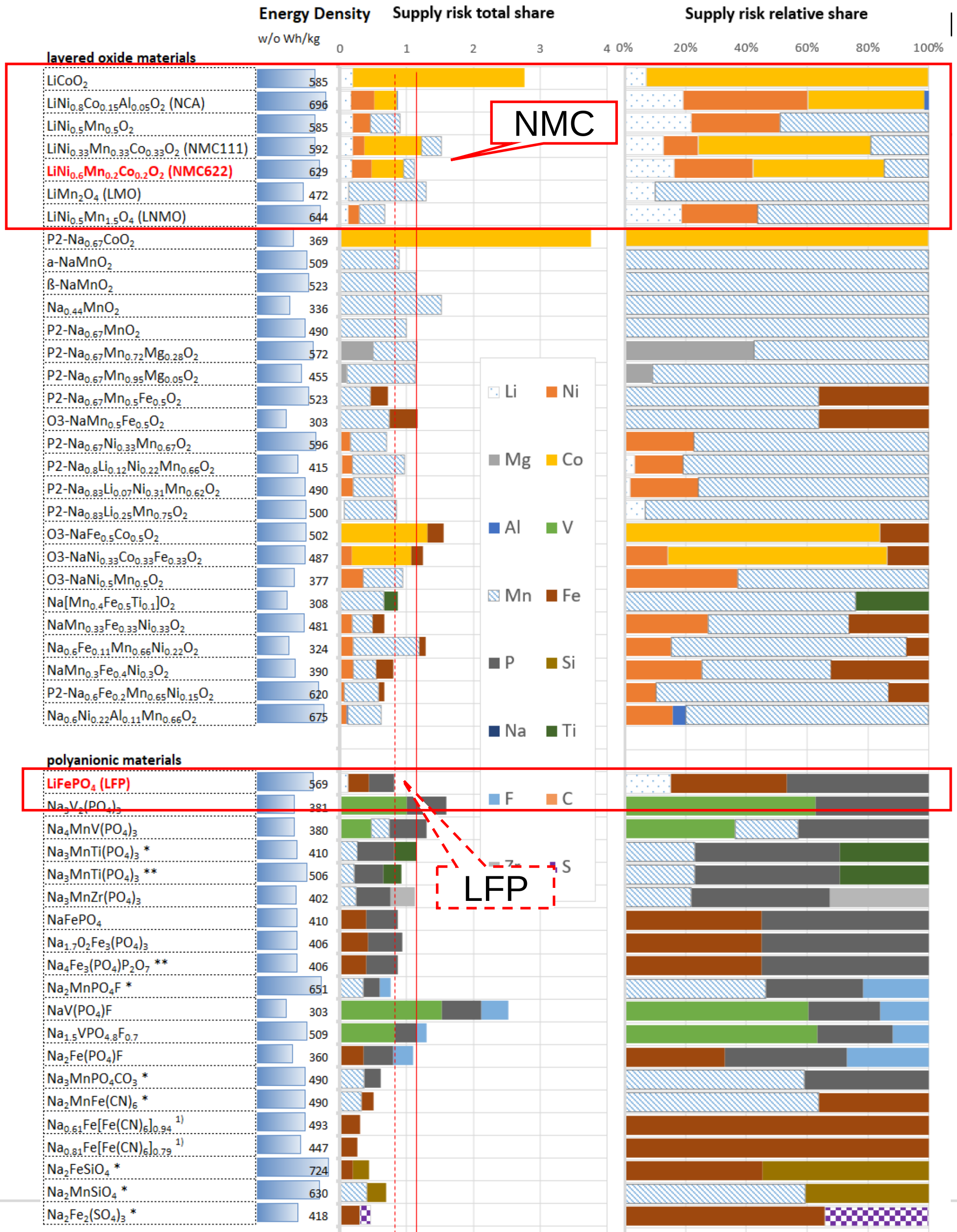


M. Baumann, M. Häringer, M. Schmidt, L. Schneider, J. Peters, W.Bauer, J. R. Binder, and M. Weil, „Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials, Advanced Energy Materials, 2022, doi: 10.1002/aenm.202202636

Material (screening) – Level

- **Results for Criticality**
- Supply Risk (SR^{EU}) → composite index descr. the risk of a disruption in supply of a specific material[1]

- 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



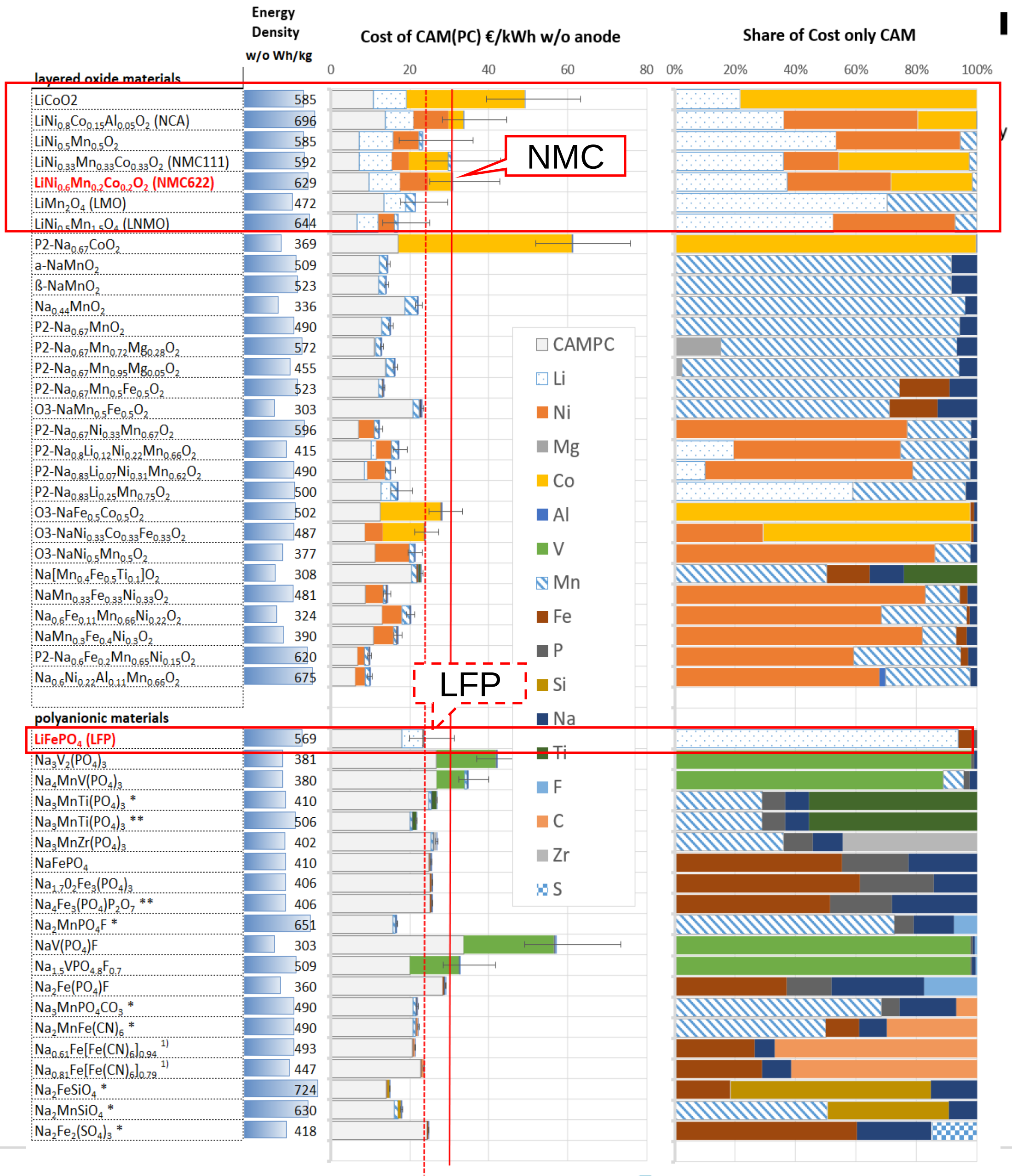
1; e.g. global supply and sourcing countries mixes (described by the Herfindahl-Hirschman Index HHI), import reliance, supplier countries' governance performance (World Governance Index (WGI) [53]), trade restrictions and agreements, availability and criticality of substitutes as well as end-of-life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

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

Material (screening) – Level

- **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

Material (screening) – Level

- 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.
- 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

Reference

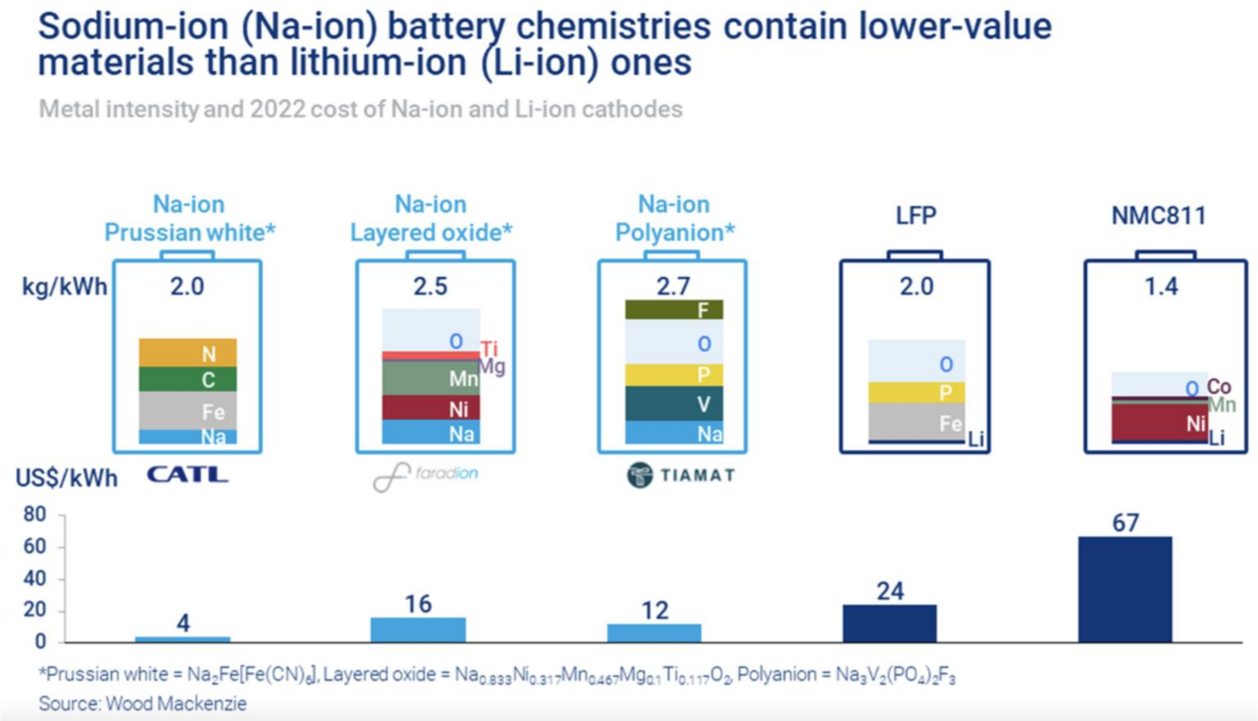
Reference

	Variation of Weights								Variation of Criteria + Spec. En.	
	Equal		Environ.		Supply		Cost			
Weights	33% CF, 33% €, 33% SR		50% CF, 25% €, 25% SR		25% CF, 25% €, 50% SR		25% CF, 50% €, 25% SR		25% CF, 25% SE, 25% €, 25% SR	
Year	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
$LiCoO_2$	0.22	48	0.24	48	0.24	48	0.20	48	0.34	47
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)	0.70	41	0.71	41	0.75	40	0.67	42	0.77	25
$LiNi_{0.5}Mn_{0.5}O_2$	0.77	39	0.79	39	0.79	38	0.74	39	0.75	28
$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC111)	0.59	46	0.61	46	0.61	46	0.56	46	0.62	44
$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622)	0.66	43	0.68	43	0.70	43	0.63	45	0.70	35
$LiMn_2O_4$ (LMO)	0.83	35	0.86	35	0.81	35	0.83	35	0.73	31
$LiNi_{0.5}Mn_{1.5}O_4$ (LNMO)	0.85	32	0.87	34	0.88	26	0.84	34	0.85	7
P2-$Na_{0.67}CoO_2$	0.00	49	0.00	49	0.00	49	0.00	49	0.04	49
a-$NaMnO_2$	0.92	15	0.94	14	0.91	14	0.94	13	0.82	15
ß-$NaMnO_2$	0.89	23	0.92	23	0.87	27	0.92	21	0.81	18
$Na_{0.44}MnO_2$	0.85	34	0.88	31	0.81	36	0.87	31	0.66	38
P2-$Na_{0.67}MnO_2$	0.91	17	0.93	16	0.90	20	0.93	18	0.80	19
P2-$Na_{0.67}Mn_{0.72}Mg_{0.28}O_2$	0.89	22	0.92	21	0.87	29	0.92	20	0.84	11
P2-$Na_{0.67}Mn_{0.95}Mg_{0.05}O_2$	0.89	24	0.92	22	0.87	28	0.91	22	0.77	24
P2-$Na_{0.67}Mn_{0.5}Fe_{0.5}O_2$	0.94	7	0.96	7	0.94	7	0.96	7	0.85	8
O3-$NaMn_{0.5}Fe_{0.5}O_2$	0.89	26	0.92	24	0.87	30	0.91	23	0.68	36
P2-$Na_{0.67}Ni_{0.33}Mn_{0.67}O_2$	0.90	21	0.91	26	0.91	16	0.90	26	0.85	6
P2-$Na_{0.8}Li_{0.12}Ni_{0.22}Mn_{0.66}O_2$	0.85	33	0.87	33	0.85	33	0.85	33	0.71	34
P2-$Na_{0.83}Li_{0.07}Ni_{0.31}Mn_{0.62}O_2$	0.87	30	0.89	30	0.88	23	0.87	32	0.77	22
P2-$Na_{0.83}Li_{0.25}Mn_{0.75}O_2$	0.90	19	0.92	19	0.90	19	0.91	25	0.80	20
O3-$NaFe_{0.5}Co_{0.5}O_2$	0.64	44	0.65	44	0.65	44	0.65	44	0.61	45
O3-$NaNi_{0.33}Co_{0.33}Fe_{0.33}O_2$	0.69	42	0.69	42	0.71	42	0.68	41	0.63	42
O3-$NaNi_{0.5}Mn_{0.5}O_2$	0.81	37	0.82	37	0.82	34	0.80	37	0.66	40
$Na[Mn_{0.4}Fe_{0.5}Ti_{0.1}]O_2$	0.87	29	0.90	29	0.85	32	0.90	27	0.67	37
$NaMn_{0.33}Fe_{0.33}Ni_{0.33}O_2$	0.89	25	0.90	28	0.91	17	0.89	28	0.78	21
$Na_{0.6}Fe_{0.11}Mn_{0.66}Ni_{0.22}O_2$	0.81	36	0.84	36	0.80	37	0.82	36	0.63	43
$NaMn_{0.3}Fe_{0.4}Ni_{0.3}O_2$	0.87	31	0.88	32	0.88	24	0.87	30	0.71	33
P2-$Na_{0.6}Fe_{0.2}Mn_{0.65}Ni_{0.15}O_2$	0.93	12	0.94	13	0.93	11	0.94	14	0.89	5
$Na_{0.6}Ni_{0.22}Al_{0.11}Mn_{0.66}O_2$	0.92	14	0.94	15	0.93	10	0.93	17	0.92	2
polyanionic materials										
$LiFePO_4$ (LFP)	0.89	27	0.91	25	0.89	21	0.89	29	0.83	13
$Na_3V_2(PO_4)_3$	0.64	45	0.65	45	0.65	45	0.65	43	0.53	46
$Na_4MnV(PO_4)_3$	0.78	38	0.79	38	0.77	39	0.79	38	0.64	41
$Na_3MnTi(PO_4)_3$ *	0.88	28	0.91	27	0.87	31	0.91	24	0.74	30
$Na_3MnTi(PO_4)_3$ **	0.91	16	0.93	17	0.90	18	0.93	15	0.81	16
$Na_3MnZr(PO_4)_3$	0.90	20	0.92	20	0.88	25	0.92	19	0.74	29
$NaFePO_4$	0.93	10	0.95	10	0.92	12	0.95	9	0.77	23
$Na_{1.7}O_2Fe_3(PO_4)_3$	0.92	13	0.94	12	0.91	15	0.95	12	0.76	27
$Na_4Fe_3(PO_4)P_2O_7$ **	0.93	11	0.94	11	0.92	13	0.95	10	0.77	26
Na_2MnPO_4F *	0.94	8	0.96	8	0.94	9	0.96	8	0.92	3
$NaV(PO_4)F$	0.43	47	0.45	47	0.42	47	0.45	47	0.33	48
$Na_{1.5}VPO_{4.8}F_{0.7}$	0.71	40	0.72	40	0.72	41	0.72	40	0.66	39
$Na_2Fe(PO_4)F$	0.90	18	0.93	18	0.88	22	0.93	16	0.72	32
$Na_3MnPO_4CO_3$ *	0.95	6	0.96	6	0.96	6	0.96	6	0.83	12
$Na_2MnFe(CN)_6$ *	0.96	4	0.97	4	0.97	4	0.97	5	0.84	9
$Na_{0.61}Fe[Fe(CN)_6]_{0.94}$ 1)	0.96	5	0.97	5	0.96	5	0.97	4	0.84	10
$Na_{0.81}Fe[Fe(CN)_6]_{0.79}$ 1)	0.97	2	0.98	2	0.98	2	0.98	2	0.82	14
Na_2FeSiO_4 *	0.97	3	0.98	3	0.98	3	0.98	3	0.98	1
Na_2MnSiO_4 *	0.94	9	0.95	9	0.94	8	0.95	11	0.90	4
$Na_2Fe_2(SO_4)_3$ *	0.98	1	0.99	1	0.99	1	0.99	1	0.81	17

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

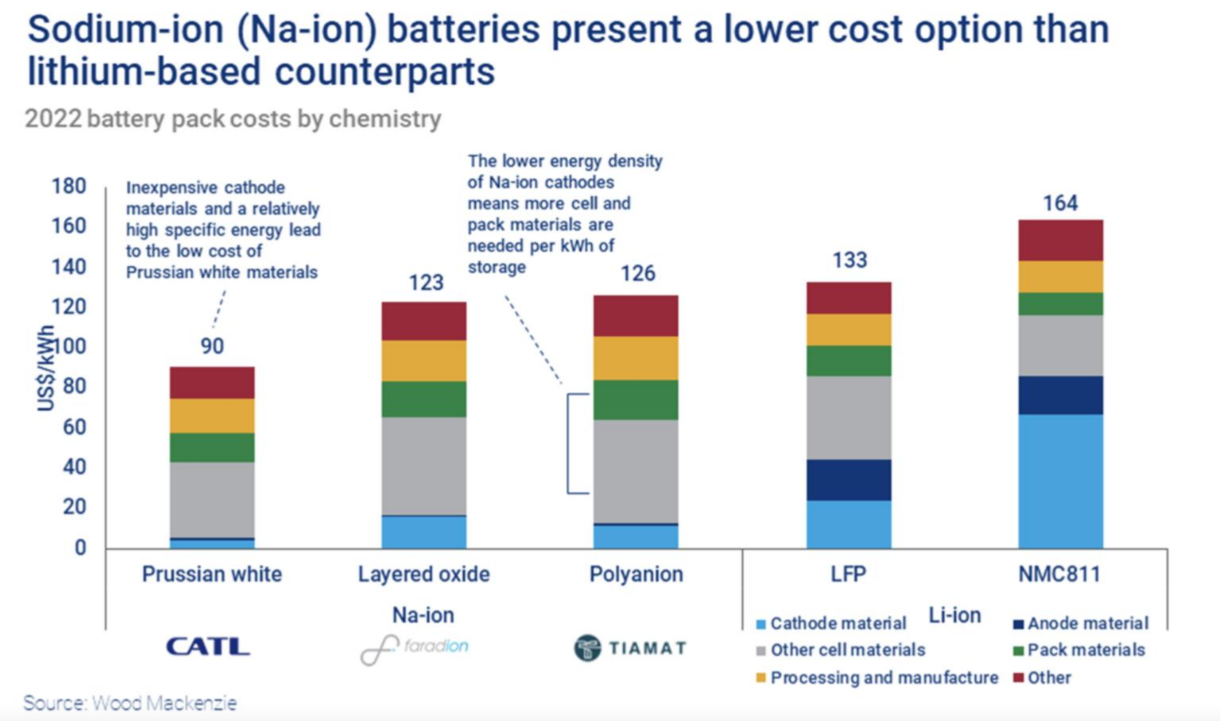
Material (screening) – Level
Cost Comparison

Material Level



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

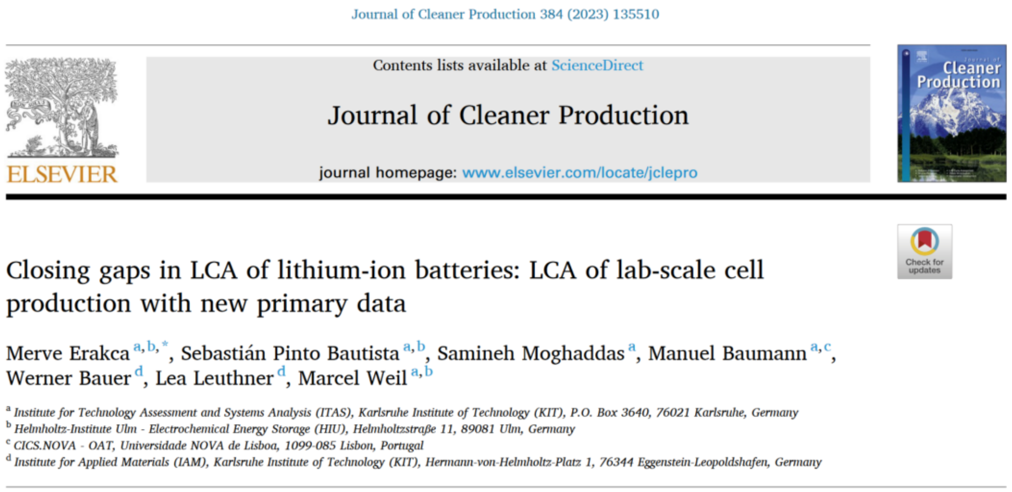
Cell Level



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

Use Case #2 Cell production

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


Journal of Cleaner Production 384 (2023) 135510

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

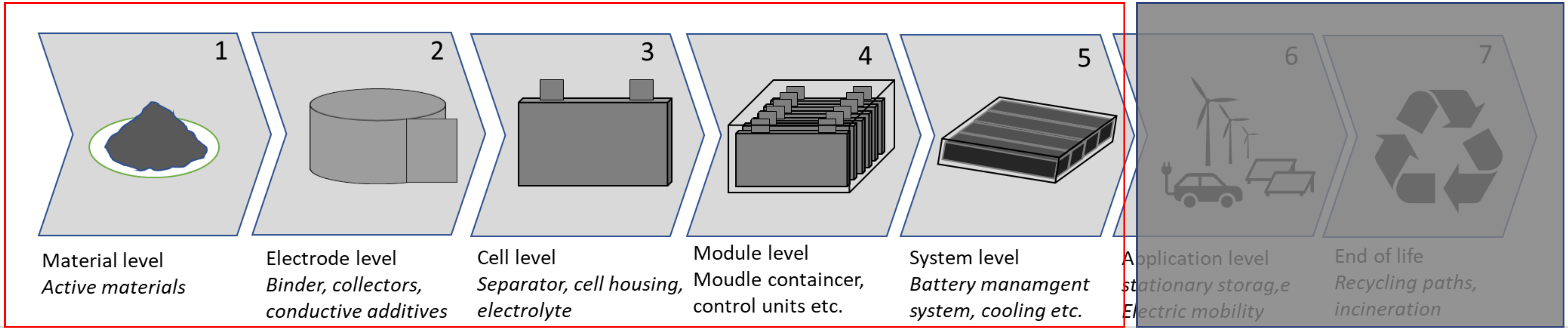
ELSEVIER

Closing gaps in LCA of lithium-ion batteries: LCA of lab-scale cell production with new primary data

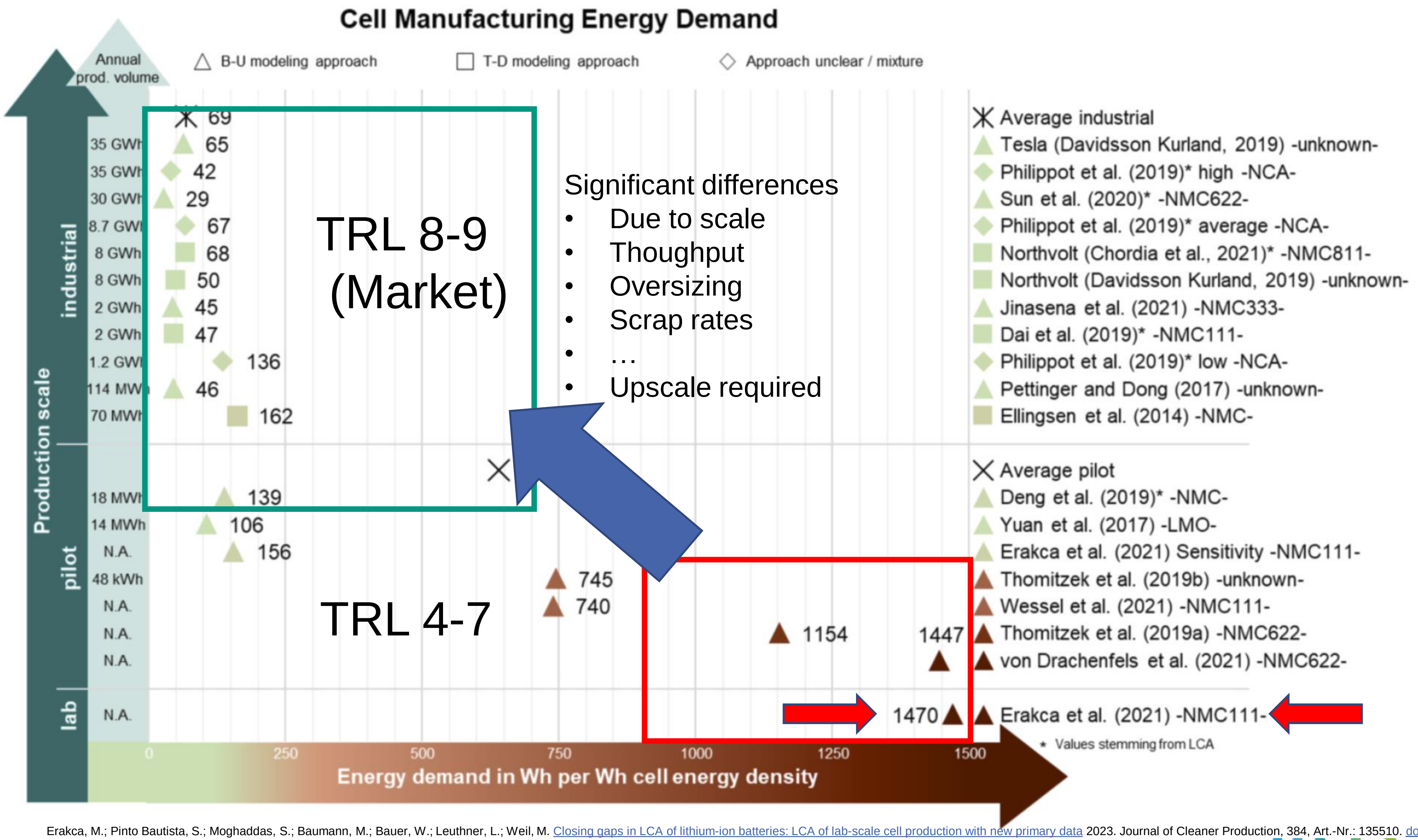
Merve Erakca[a,b,*], Sebastián Pinto Bautista[a,b], Samineh Moghaddas[a], Manuel Baumann[a,c], Werner Bauer[d], Lea Leuthner[d], Marcel Weil[a,b]

[a] Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), P.O. Box 3640, 76021 Karlsruhe, Germany
[b] Helmholtz-Institute Ulm - Electrochemical Energy Storage (HIU), Helmholtzstraße 11, 89081 Ulm, Germany
[c] CICS.NOVA - OAT, Universidade NOVA de Lisboa, 1099-085 Lisbon, Portugal
[d] Institute for Applied Materials (IAM), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

Scope: Only Materials ´Not considered



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



TRL 8-9 (Market)

TRL 4-7

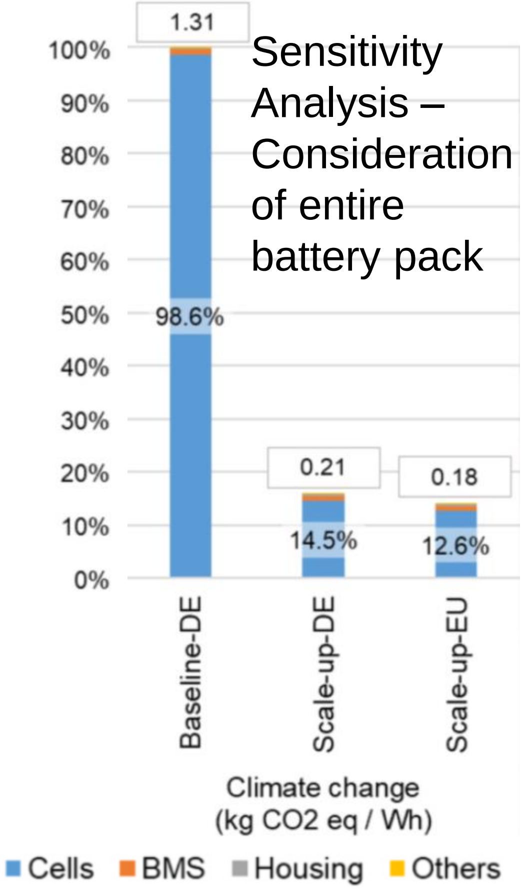
Significant differences
- Due to scale
- Thoughput
- Oversizing
- Scrap rates
- …
- Upscale required

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:10.1016/j.jclepro.2022.135510

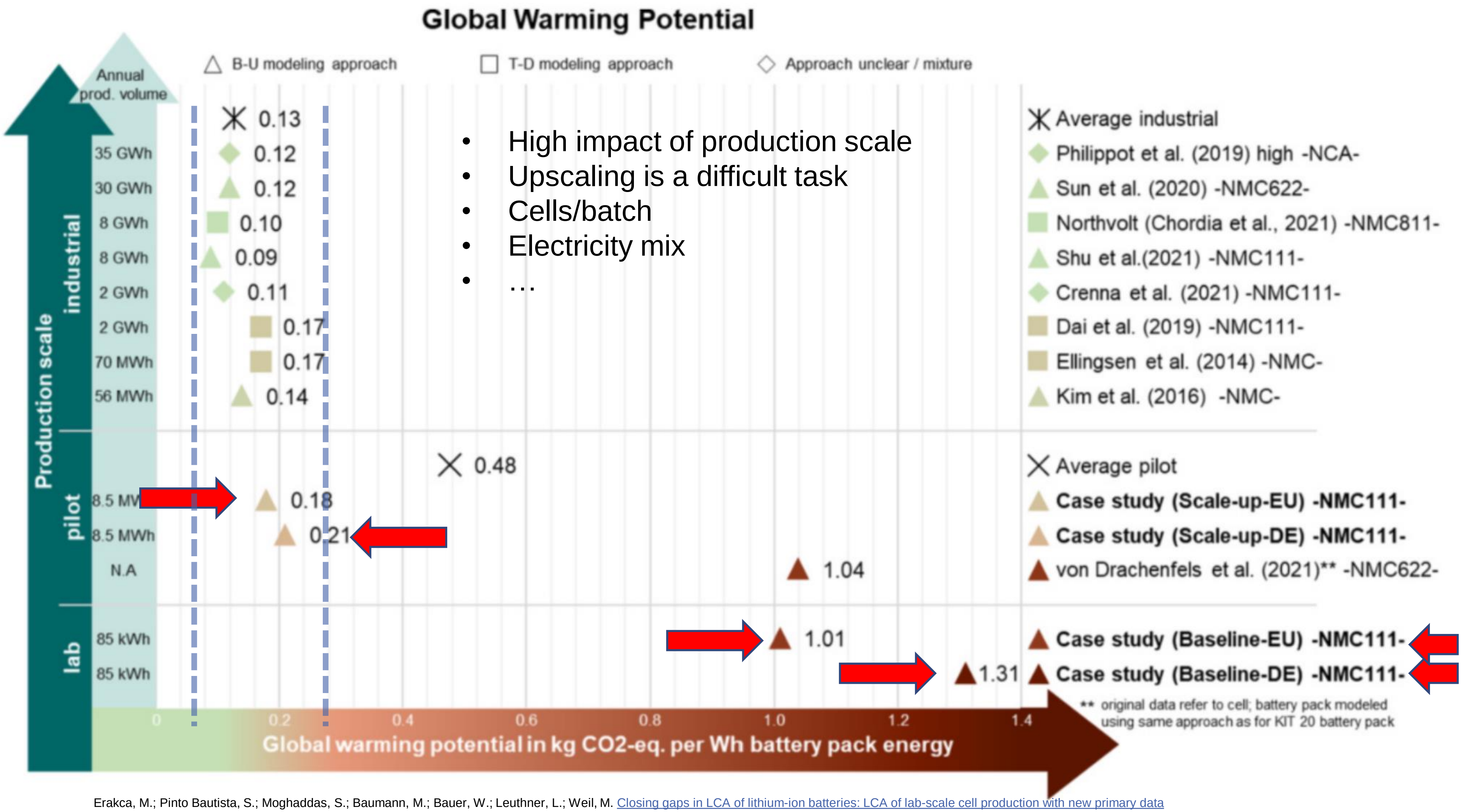
Karlsruhe Institute of Technology
…itute for …nology Assessment and Systems Analysis

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

Sensitivity Analysis – Consideration of entire battery pack



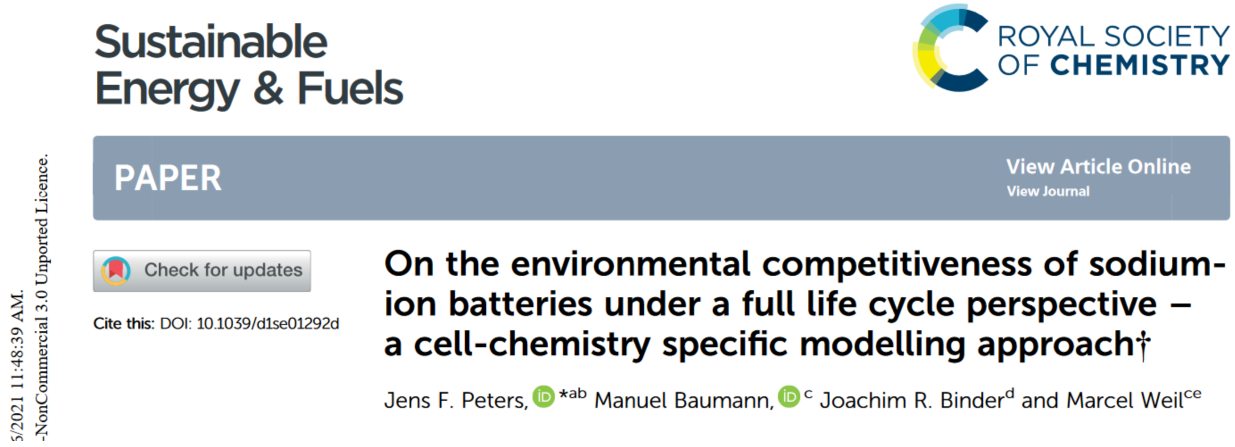
- High impact of production scale
- Upscaling is a difficult task
- Cells/batch
- Electricity mix
- …



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:10.1016/j.jclepro.2022.135510

Use Case #3 Cell - Level 3 (7)

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


Sustainable Energy & Fuels

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal

Check for updates

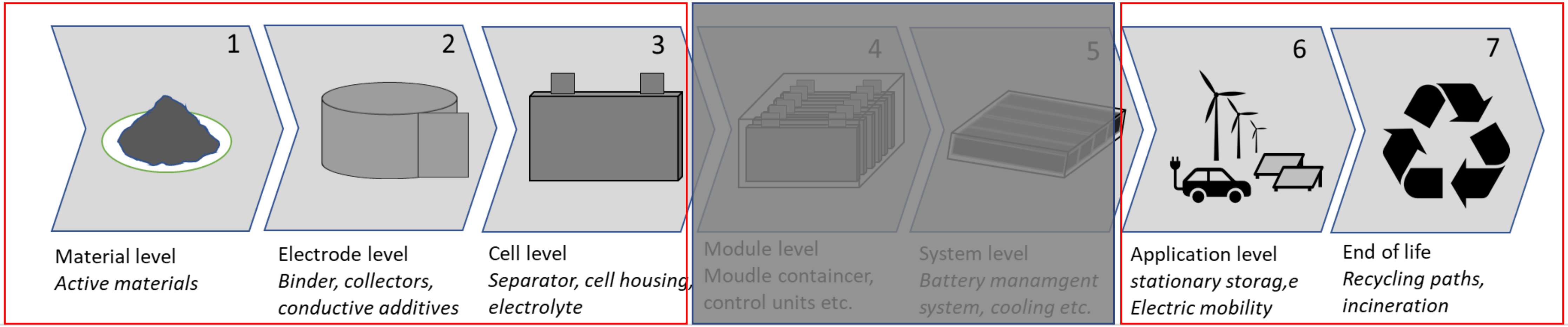
Cite this: DOI: 10.1039/d1se01292d

On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective – a cell-chemistry specific modelling approach†

Jens F. Peters, *ab Manuel Baumann, c Joachim R. Binder[d] and Marcel Weil[ce]

Scope:

System Periphery / BoP not considered



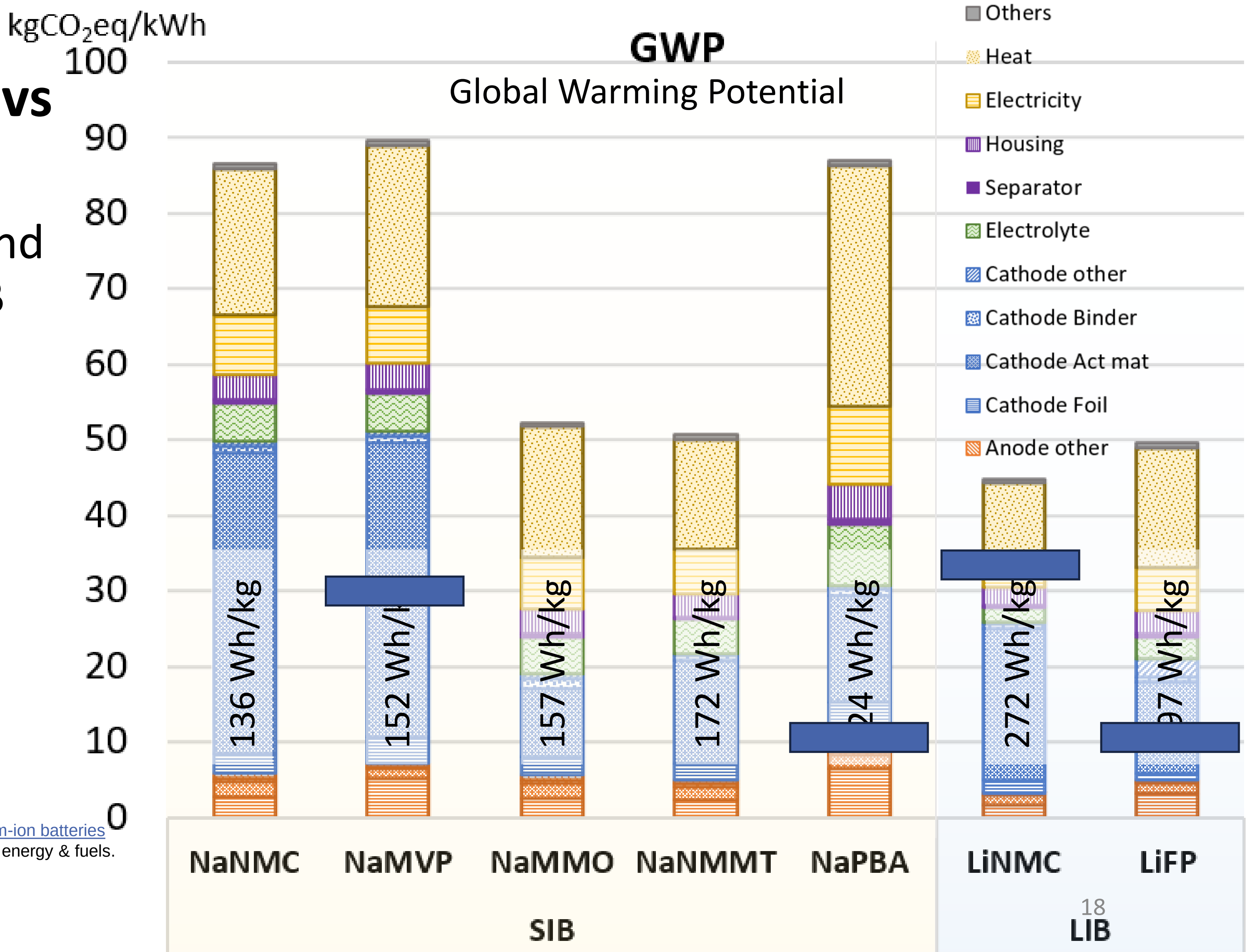
Institute for Technology Assessment and Systems Analysis

Cell – Level – Comparison with material level results

GWP of a theoretical SIB vs LIB

- 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. On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective – a cell-chemistry specific modelling approach 2021. Sustainable energy & fuels. doi:10.1039/d1se01292d

Early TRLs – Challenges & tranfereability to other cell technologies

- Materials
  - Properties
  - System level (BoP)
- Manufacturing
  - Energy demand
  - ….
- Performance
  - Life time
  - …
- Recycling
  - Energy demand
  - …

→ Result interpretation

→ Results are just valid for certain material → 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 → 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!

Karlsruher Institut für Technologie

ITAS
Institute for Technology Analysis and System Analysis
Karlstraße 11, Karlsruhe
Germany
http://www.itas.kit.edu/

StoRIES
Storage Research Infrastructure Eco-System

Research for Sustainable Energy Technologies (RESET)

Manuel Baumann
Manuel.baumann@kit.edu

POLiS
Post Lithium Storage Cluster of Excellence

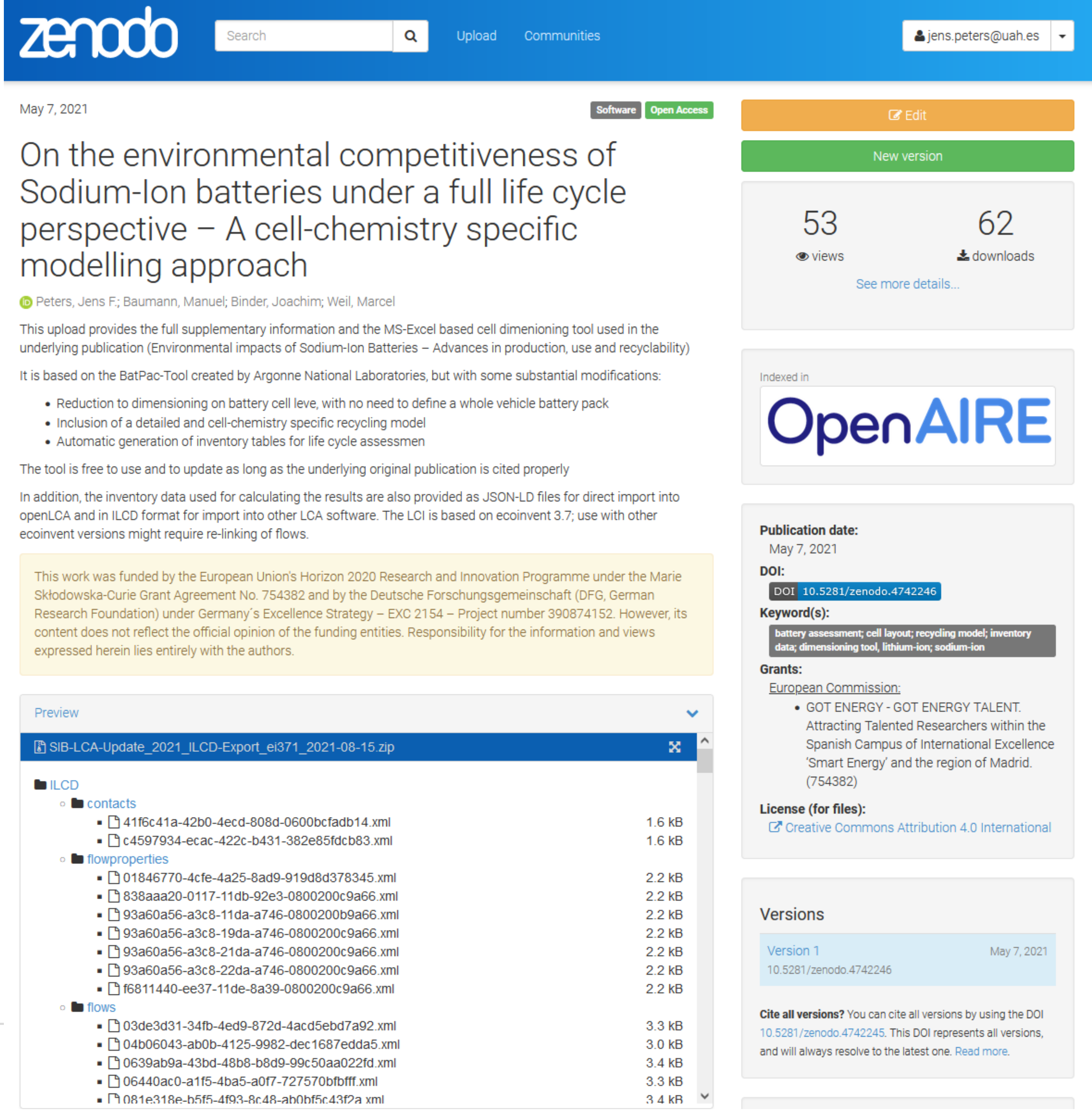
Acknowledgement: his work contributes to the research performed at CELEST (Center for Electrochemical Energy Storage Ulm-Karlsruhe) and was funded by the German Research Foundation (DFG) under Project ID 390874152 (POLiS Cluster of Excellence, EXC 2154). M.B. and M.W. acknowledge the funding by the European Union's Horizon 2020 Research and Innovation Program under Grant Agreement No. 875126 (StoRIES).

Literature

- D. Collingridge, *The social control of technology*. New York: St. Martin's Press, 1980.
- Jens Peters, Manuel Baumann, Marcel Weil, Stefano Passerini, On the environmental competitiveness of Sodium-Ion Batteries – Current state of the art in Life Cycle Assessment, 2021, Sodium-Ion Batteries: Materials, Characterization, and Technology. Ed. Philipp Adelhelm, Magdalena Titirici, Yong Sheng Hu, Wiley 2022(Forthcoming)
- Jasper, F. B.; Späthe, J.; Baumann, M.; Peters, J. F.; Ruhland, J.; Weil, M. Life cycle assessment (LCA) of a battery home storage system based on primary data 2022. Journal of Cleaner Production, 366, Article: 132899. doi:10.1016/j.jclepro.2022.132899
- Peters, J. F.; Baumann, M.; Binder, J. R.; Weil, M. On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective – a cell-chemistry specific modelling approach 2021. Sustainable energy & fuels. doi:10.1039/d1se01292d
- 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:10.1016/j.jclepro.2022.135510
- 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.
- 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
- Baumann, M.; Peters, J.; Weil, M. Exploratory multi-criteria decision analysis of utility-scale battery storage technologies for multiple grid services based on life cycle approaches 2020. Energy technology, 8 (11), Art.Nr. 1901019. doi:10.1002/ente.201901019
- Baumann, M.; Peters, J. F.; Weil, M.; Grunwald, A. CO_2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications 2017. Energy technology, 5 (7), 1071–1083. doi:10.1002/ente.201600622

Underlying data available openly on Zenodo:

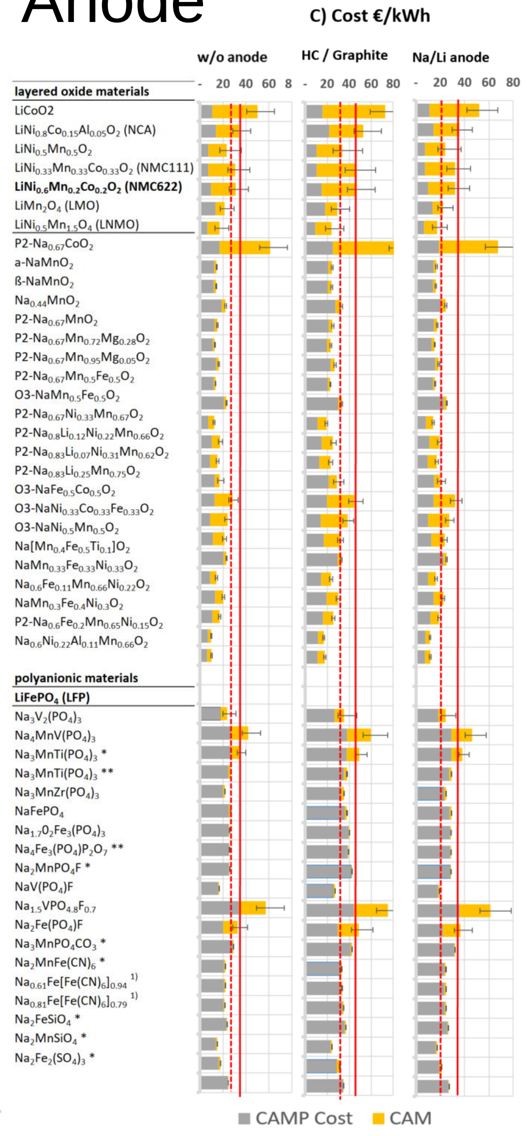
- Excel-based cell dimensioning tool, allows for incorporating also other cell chemistries
- Numeric results and graphics
- Life cycle inventory data for import and direct re-use in openLCA (requires ecoinvent 3.7.1)
- Use Phase can be adopted
- DOI/10.5281/zenodo.4742246



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

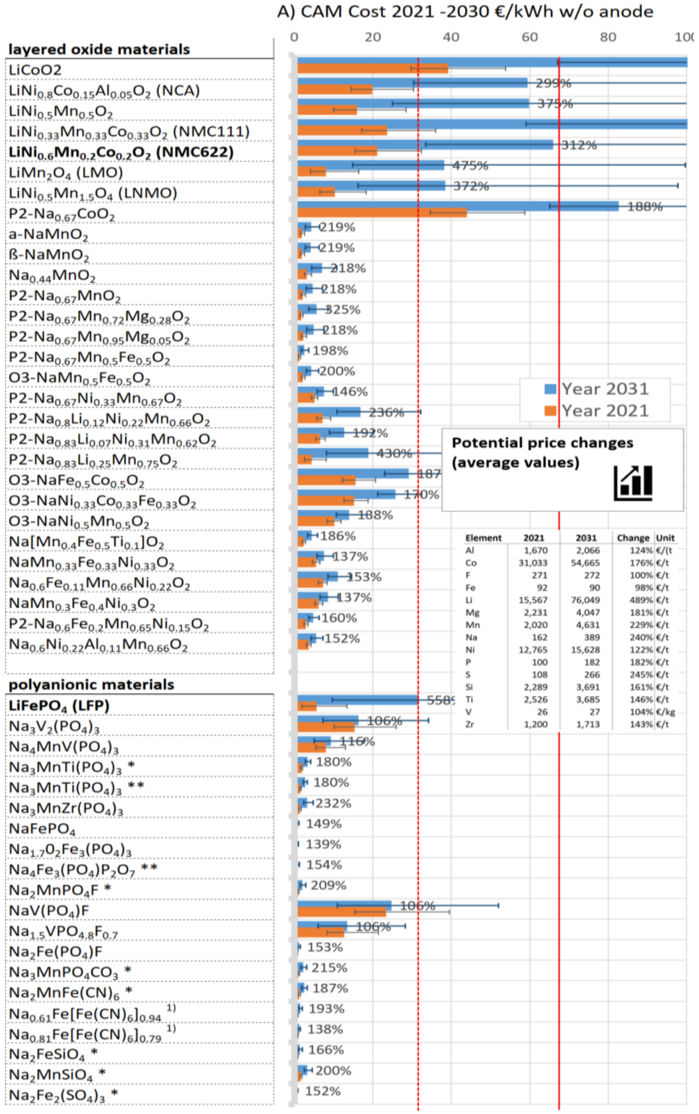
Sensitivity analysis

Anode



Material cost

Scale effects



Element	2021	2031	Change	Unit
Al	1,670	2,066	124%	€/(t
Co	31,033	54,665	176%	€/t
F	271	272	100%	€/t
Fe	92	90	98%	€/t
Li	15,567	76,049	489%	€/t
Mg	2,231	4,047	181%	€/t
Mn	2,020	4,631	229%	€/t
Na	162	389	240%	€/t
Ni	12,765	15,628	122%	€/t
P	100	182	182%	€/t
S	108	266	245%	€/t
Si	2,289	3,691	161%	€/t
Ti	2,526	3,685	146%	€/t
V	26	27	104%	€/kg
Zr	1,200	1,713	143%	€/t

Ranking

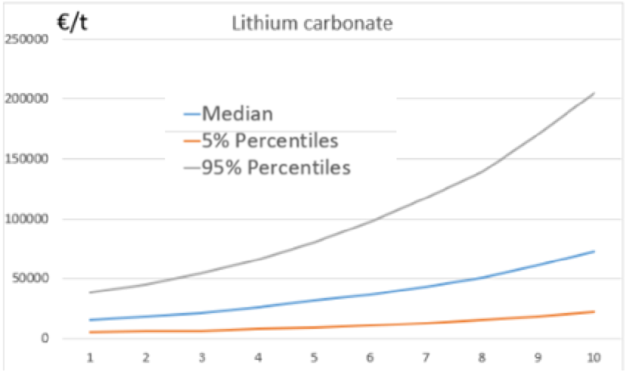
Equal: 33% CF, 33% €, 33% SR

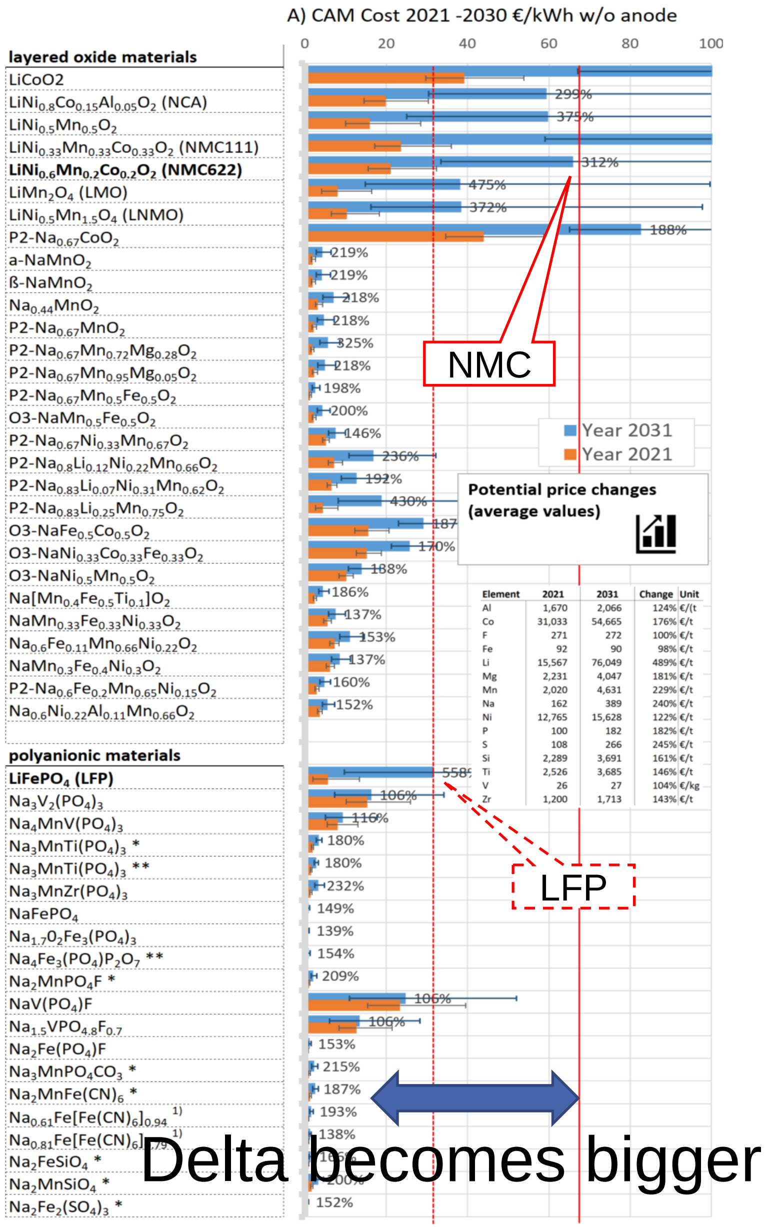
Weights			Indicative rank	
Year	2021	2031	2021	2031
$LiCoO_2$	0.27	0.23	48	48
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)	0.70	0.67	38	40
$LiNi_{0.5}Mn_{0.5}O_2$	0.76	0.70	34	38
$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC111)	0.60	0.44	47	47
$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622)	0.67	0.62	41	43
$LiMn_2O_4$ (LMO)	0.81	0.76	31	37
$LiNi_{0.5}Mn_{1.5}O_4$ (LNMO)	0.84	0.80	27	29
P2-$Na_{0.67}CoO_2$	0.01	0.07	49	49
a-$NaMnO_2$	0.91	0.91	15	17
ß-$NaMnO_2$	0.88	0.89	23	26
$Na_{0.44}MnO_2$	0.77	0.77	42	45
P2-$Na_{0.67}MnO_2$	0.90	0.90	20	20
P2-$Na_{0.67}Mn_{0.72}Mg_{0.28}O_2$	0.89	0.88	37	35
P2-$Na_{0.67}Mn_{0.95}Mg_{0.05}O_2$	0.88	0.89	28	28
P2-$Na_{0.67}Mn_{0.5}Fe_{0.5}O_2$	0.93	0.93	7	7
O3-$NaMn_{0.5}Fe_{0.5}O_2$	0.88	0.88	25	27
P2-$Na_{0.67}Ni_{0.33}Mn_{0.67}O_2$	0.88	0.90	19	16
P2-$Na_{0.8}Li_{0.12}Ni_{0.22}Mn_{0.66}O_2$	0.84	0.84	30	30
P2-$Na_{0.83}Li_{0.07}Ni_{0.31}Mn_{0.62}O_2$	0.86	0.87	29	24
P2-$Na_{0.83}Li_{0.25}Mn_{0.75}O_2$	0.89	0.86	18	23
O3-$NaFe_{0.5}Co_{0.5}O_2$	0.65	0.68	44	42
O3-$NaNi_{0.33}Co_{0.33}Fe_{0.33}O_2$	0.69	0.72	40	39
O3-$NaNi_{0.5}Mn_{0.5}O_2$	0.79	0.82	32	31
$Na[Mn_{0.4}Fe_{0.5}Ti_{0.1}]O_2$	0.74	0.75	43	44
$NaMn_{0.33}Fe_{0.33}Ni_{0.33}O_2$	0.79	0.82	35	32
$Na_{0.6}Fe_{0.11}Mn_{0.66}Ni_{0.22}O_2$	0.81	0.83	33	33
$NaMn_{0.3}Fe_{0.4}Ni_{0.3}O_2$	0.86	0.88	26	19
P2-$Na_{0.6}Fe_{0.2}Mn_{0.65}Ni_{0.15}O_2$	0.91	0.92	12	13
$Na_{0.6}Ni_{0.22}Al_{0.11}Mn_{0.66}O_2$	0.91	0.92	13	12
polyanionic materials				
$LiFePO_4$ (LFP)	0.88	0.83	17	25
$Na_3V_2(PO_4)_3$	0.65	0.71	45	41
$Na_4MnV(PO_4)_3$	0.78	0.81	36	34
$Na_3MnTi(PO_4)_3$ *	0.88	0.88	24	22
$Na_3MnTi(PO_4)_3$ **	0.90	0.90	16	15
$Na_3MnZr(PO_4)_3$	0.89	0.89	21	21
$NaFePO_4$	0.92	0.92	11	11
$Na_{1.7}O_2Fe_3(PO_4)_3$	0.91	0.91	14	14
$Na_4Fe_3(PO_4)P_2O_7$ **	0.92	0.92	10	10
Na_2MnPO_4F *	0.92	0.92	9	9
$NaV(PO_4)F$	0.47	0.56	46	46
$Na_{1.5}VPO_{4.8}F_{0.7}$	0.72	0.77	39	36
$Na_2Fe(PO_4)F$	0.88	0.89	22	18
$Na_3MnPO_4CO_3$ *	0.93	0.93	6	6
$Na_2MnFe(CN)_6$ *	0.94	0.94	4	5
$Na_{0.61}Fe[Fe(CN)_6]_{0.94}$ [1)]	0.94	0.94	5	4
$Na_{0.81}Fe[Fe(CN)_6]_{0.79}$ [1)]	0.95	0.95	3	2
Na_2FeSiO_4 *	0.95	0.95	1	1
Na_2MnSiO_4 *	0.92	0.92	8	8
$Na_2Fe_2(SO_4)_3$ *	0.95	0.95	2	3

Institute for Technology Assessment and Systems Analysis

Material (screening) – Level

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





Element	2021	2031	Change	Unit
Al	1,670	2,066	124%	€/(t
Co	31,033	54,665	176%	€/t
F	271	272	100%	€/t
Fe	92	90	98%	€/t
Li	15,567	76,049	489%	€/t
Mg	2,231	4,047	181%	€/t
Mn	2,020	4,631	229%	€/t
Na	162	389	240%	€/t
Ni	12,765	15,628	122%	€/t
P	100	182	182%	€/t
S	108	266	245%	€/t
Si	2,289	3,691	161%	€/t
Ti	2,526	3,685	146%	€/t
V	26	27	104%	€/kg
Zr	1,200	1,713	143%	€/t

Delta becomes bigger

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

Why is the topic sustainability important?

Karlsruhe Institute of Technology

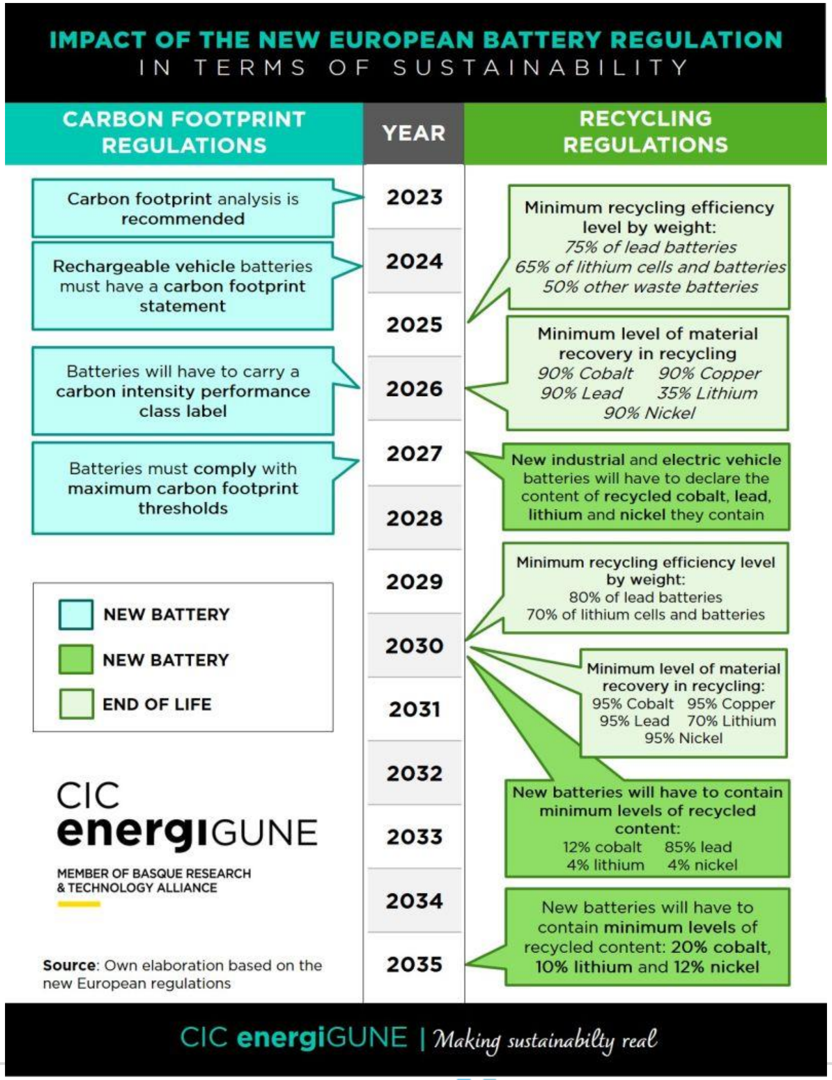
- Climate Change, Planetary limits….
- Sustainability development goals (SDG)
- European Green Deal
- Sustainable Finance & Taxonomy Regulation
- A new Circular Economy Action Plan
- EU Battery directive
- Critical raw material act
- ….

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

European Commission

Green Deal: Sustainable batteries for a circular and climate neutral economy

Source: https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_20_2312/IP_20_2312_EN.pdf



Institute for Technology Assessment and Systems Analysis