Recycling of Co and Ni Free Batteries

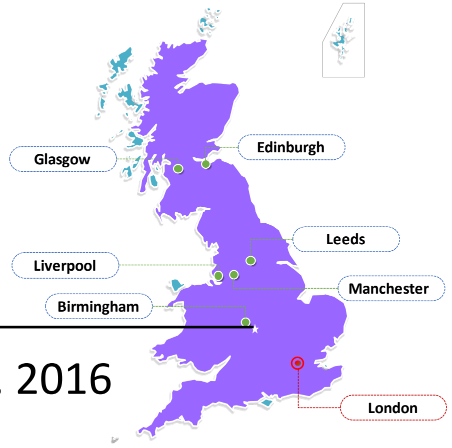
Dr Michelle Lynch, CChem FRSC

ACI Battery Recycling Europe

1st & 2nd March 2023

Enabled Future

Inc. 2016



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Key Clients

MENNTA ENERGY SOLUTIONS
exacer catalyst support
hensel recycling
Gefn
TCG The Catalyst Group Assessment Knowledge Impact
GLG
European Commission
PRIMARY INSIGHT
NexantECA
ECONIC TURNING CO_2 INTO ENDLESS POTENTIAL
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Enabled Future Limited Business Proposition

Optimising Technology Portfolios

Enabled Catalysts

Enabled Circular

Enabled Power

Enabled Metals

Consulting – Training – Multiclient Reporting
Thought Leadership – Industry Tracking

New Membership Programme As Of November 2022

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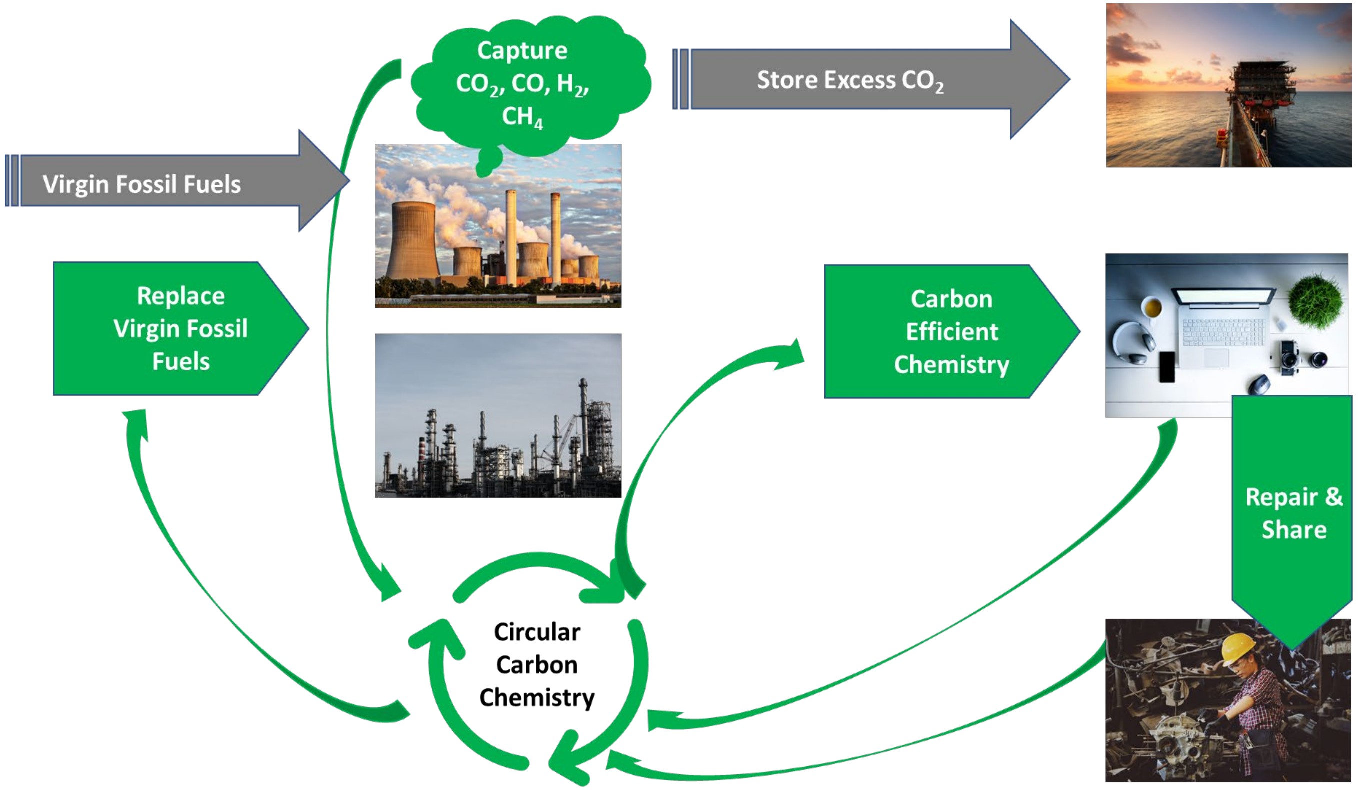
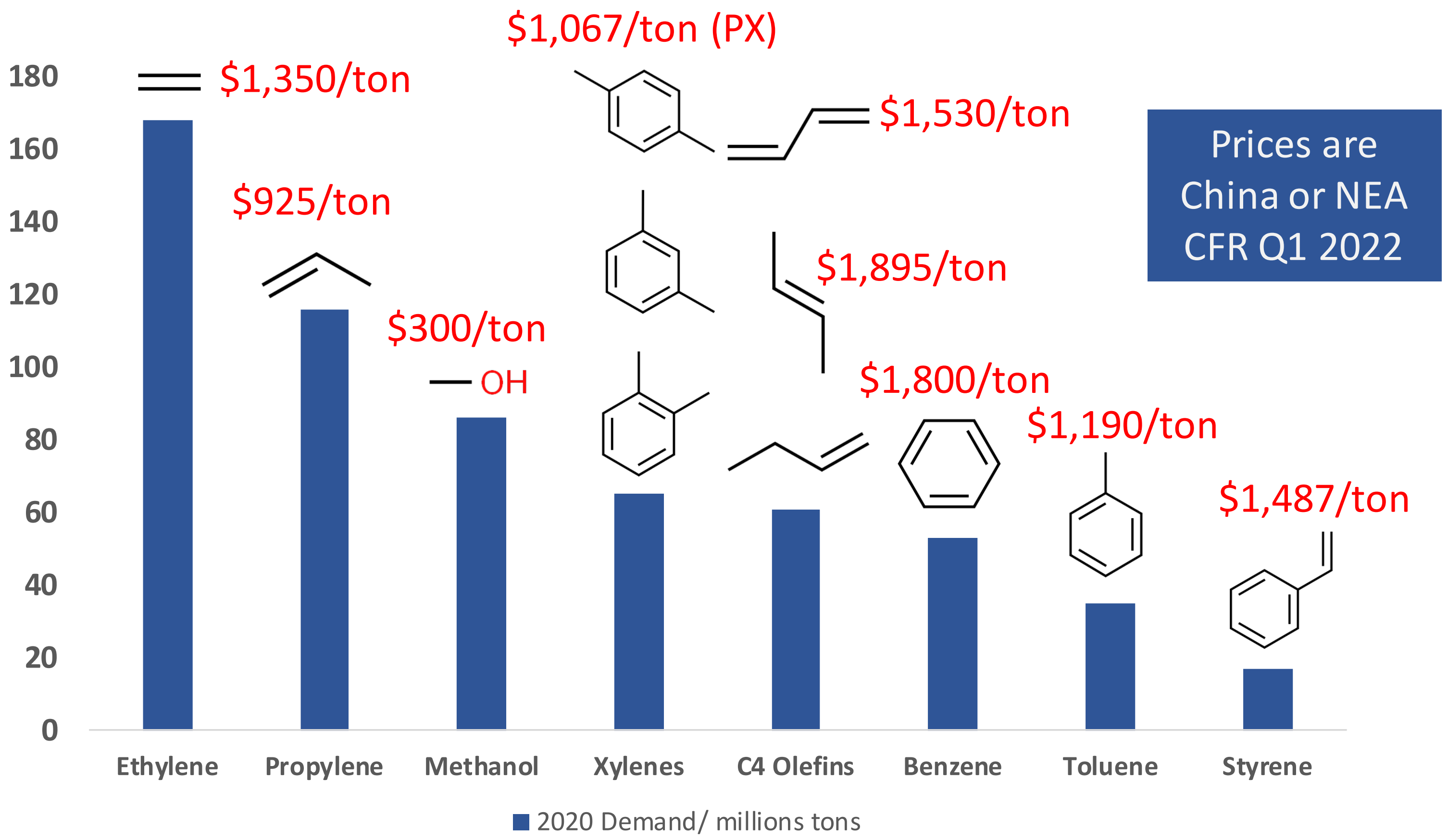
NetZero Does not Enable the Circular Economy



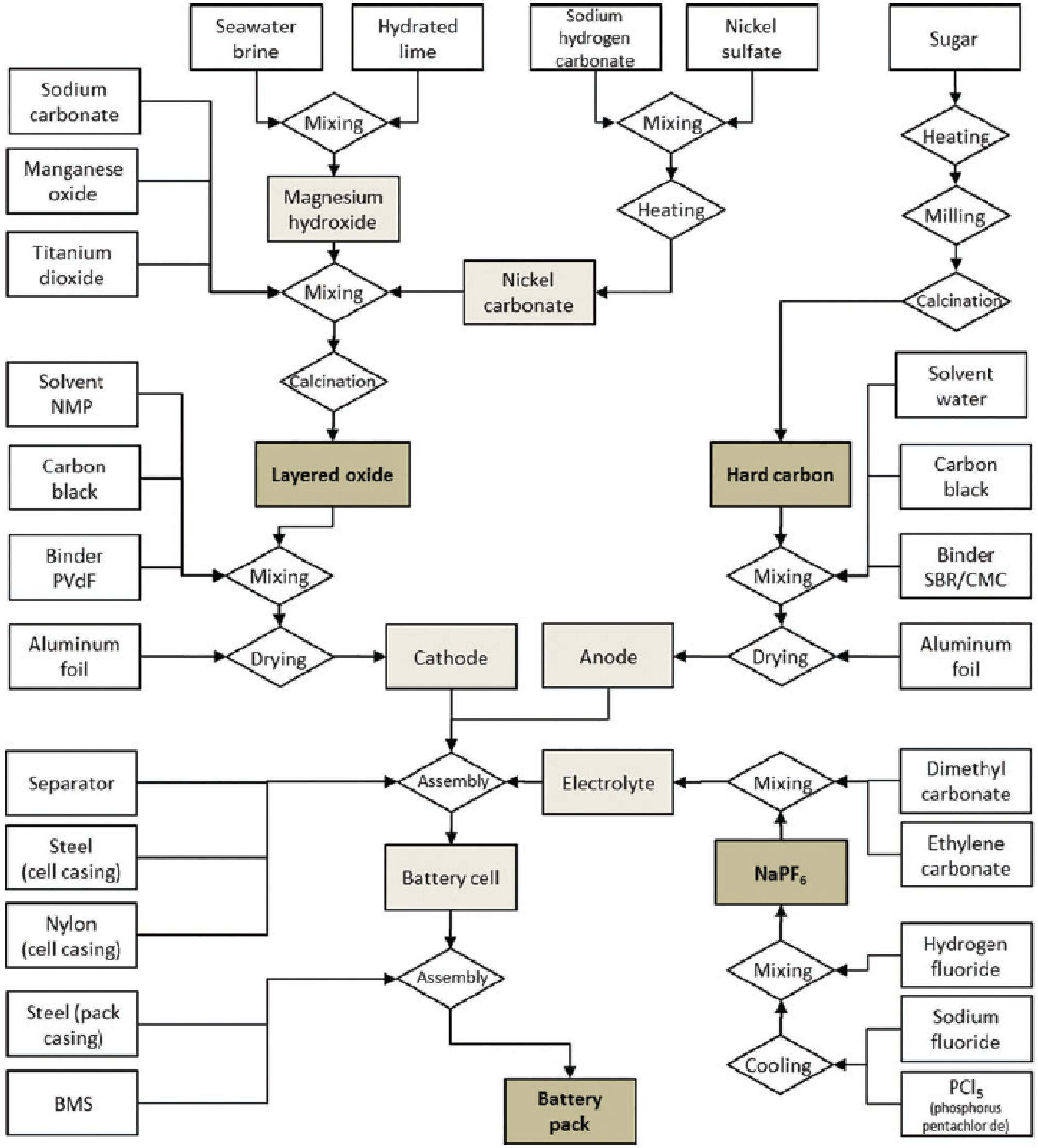
- Non-Circular Net Zero is essentially a linear economy with a massive penalty for burying CO_2
- Business as usual already has implemented many efficiency improvements using catalysis, chemical and heat engineering; replacing fossil fuels with waste CO_2 and green hydrogen drops into the same downstream
- The Circular Economy reduces virgin material dependence and waste disposal
- Sustainability 4.0 – “The repair and share economy” is a way by which we can limit the damage we do to the planet while maintaining a reasonable quality of life. It’s a quietly growing movement.

Top Key Chemical Building Blocks



- Gigascale for chemicals in planning just as much batteries in the context of the energy transition
- The two largest chemical building blocks (ethylene and propylene) extensively used in batteries.
- C4s and aromatics needed e.g., for Styrene Butadiene Rubber (SBR) binders
- Also, carbons, petroleum pitch, petcoke, graphite, ammonia, chlor-alkali, sulphuric acid, lithium chemicals, fluorine chemicals, CMC thickeners, NMP solvent, specialty solvents and additives.

Materials for a Sodium Ion Battery



The largest single contributor to the batteries GWP is the hard carbon (30%)

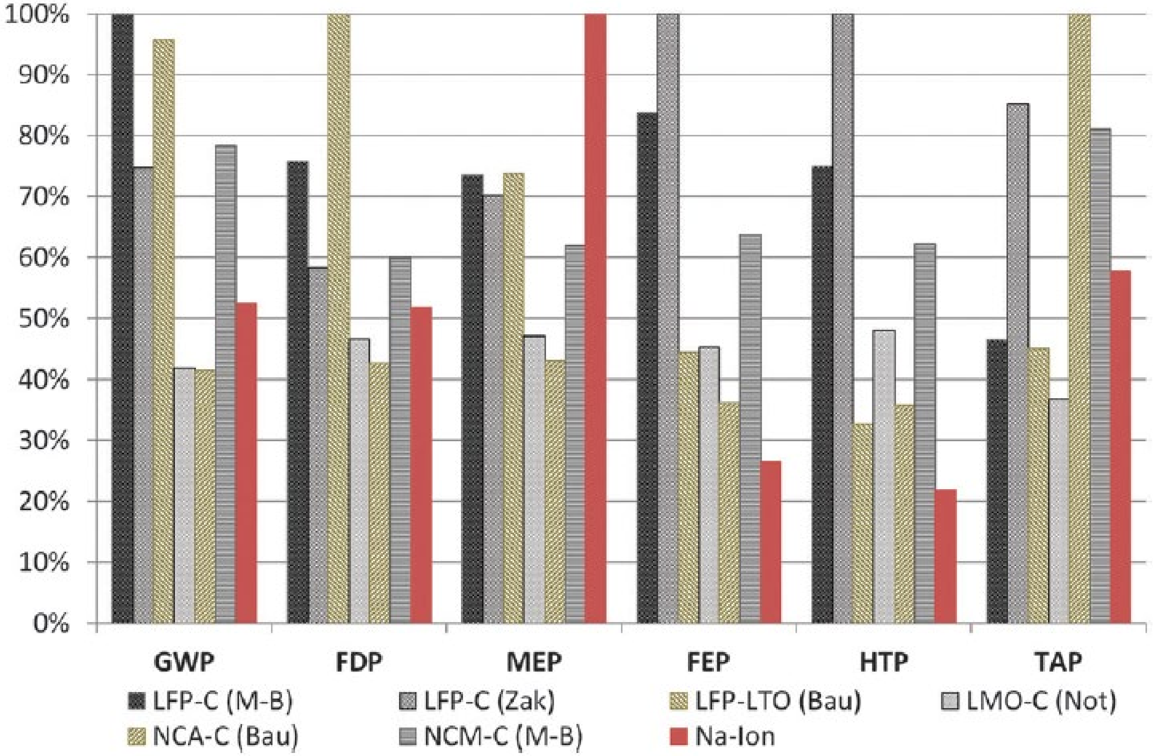
It isn't all the metals, and it's not all about the carbon footprint

A vast amount of value is added to the metals before they become a battery

Nothing is waste until it's lost all its value to anyone who would value it

Source (Peters, Buchholz, Passerini, & Weil, 2016)

The Lifecycle Analysis of Batteries



Source (Peters, Buchholz, Passerini, & Weil, 2016)

ADP	Abiotic Depletion Potential
AP	Acidification Potential
FDP	Fossil depletion potential
FEP	Freshwater Eutrophication Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
MEP	Marine Eutrophication Potential
ODP	Ozone Depletion Potential
TAP	Terrestrial Acidification Potential

GWP gCO2 eq /kWh

En. Dens. Wh/kg	NaNMC	NaMVP	NaMMO	NaNMMT	NaPBA	LiNMC622	LiFP
100	37.709	34.805	36.770	33.540	27.623	37.701	26.114
110	35.036	32.294	34.182	31.246	25.765	35.028	24.393
120	32.808	30.202	32.025	29.334	24.217	32.801	22.959
130	30.923	28.432	30.200	27.716	22.907	30.916	21.746
140	29.307	26.914	28.636	26.329	21.784	29.301	20.706
150	27.907	25.599	27.281	25.127	20.811	27.901	19.805
160	26.681	24.448	26.094	24.076	19.959	26.676	19.016
170	25.600	23.433	25.048	23.148	19.208	25.595	18.320
180	24.639	22.530	24.117	22.323	18.540	24.635	17.701
190	23.779	21.722	23.285	21.585	17.942	23.775	17.148
200	23.006	20.996	22.536	20.921	17.405	23.001	16.650
210	22.305	20.338	21.858	20.320	16.918	22.301	16.199
220	21.669	19.740	21.242	19.774	16.476	21.665	15.790
230	21.088	19.194	20.679	19.275	16.072	21.084	15.415
240	20.555	18.694	20.163	18.818	15.701	20.551	15.073
250	20.065	18.234	19.689	18.397	15.361	20.061	14.757
260	19.612	17.809	19.251	18.009	15.046	19.609	14.466
270	19.193	17.415	18.846	17.649	14.755	19.190	14.196
280	18.804	17.050	18.469	17.315	14.485	18.801	13.946

ADP gSb eq./kWh

Wh/kg	NaNMC	NaMVP	NaMMO	NaNMMT	NaPBA	LiNMC622	LiFP
100	0.0055	0.0024	0.0022	0.0033	0.0017	0.0031	0.0036
110	0.0051	0.0023	0.0021	0.0031	0.0016	0.0029	0.0034
120	0.0048	0.0022	0.0020	0.0029	0.0016	0.0028	0.0032
130	0.0045	0.0021	0.0020	0.0028	0.0015	0.0027	0.0031
140	0.0043	0.0020	0.0019	0.0027	0.0015	0.0026	0.0029
150	0.0041	0.0020	0.0019	0.0026	0.0015	0.0025	0.0028
160	0.0039	0.0019	0.0018	0.0025	0.0015	0.0024	0.0027
170	0.0038	0.0019	0.0018	0.0024	0.0014	0.0023	0.0026
180	0.0036	0.0018	0.0018	0.0024	0.0014	0.0023	0.0025
190	0.0035	0.0018	0.0017	0.0023	0.0014	0.0022	0.0024
200	0.0034	0.0018	0.0017	0.0023	0.0014	0.0022	0.0024
210	0.0033	0.0017	0.0017	0.0022	0.0014	0.0021	0.0023
220	0.0032	0.0017	0.0017	0.0022	0.0014	0.0021	0.0023
230	0.0031	0.0017	0.0016	0.0021	0.0013	0.0021	0.0022
240	0.0030	0.0016	0.0016	0.0021	0.0013	0.0020	0.0022
250	0.0030	0.0016	0.0016	0.0021	0.0013	0.0020	0.0021
260	0.0029	0.0016	0.0016	0.0020	0.0013	0.0020	0.0021
270	0.0028	0.0016	0.0016	0.0020	0.0013	0.0019	0.0020
280	0.0028	0.0016	0.0016	0.0020	0.0013	0.0019	0.0020

AP mmolc H+ eq /kWh

Wh/kg	NaNMC	NaMVP	NaMMO	NaNMMT	NaPBA	LiNMC622	LiFP
100	0.250	0.260	0.178	0.181	0.124	0.211	0.139
110	0.231	0.241	0.166	0.169	0.116	0.196	0.131
120	0.216	0.224	0.156	0.159	0.110	0.184	0.123
130	0.203	0.210	0.148	0.151	0.105	0.174	0.117
140	0.192	0.198	0.141	0.143	0.100	0.165	0.112
150	0.183	0.188	0.135	0.137	0.097	0.157	0.107
160	0.175	0.179	0.130	0.132	0.093	0.150	0.103
170	0.167	0.171	0.125	0.127	0.090	0.144	0.100
180	0.161	0.164	0.121	0.123	0.088	0.139	0.096
190	0.155	0.157	0.117	0.119	0.085	0.134	0.094
200	0.150	0.152	0.114	0.115	0.083	0.130	0.091
210	0.145	0.146	0.111	0.112	0.081	0.126	0.089
220	0.140	0.142	0.108	0.109	0.080	0.123	0.087
230	0.137	0.137	0.105	0.107	0.078	0.120	0.085
240	0.133	0.134	0.103	0.104	0.076	0.117	0.083
250	0.130	0.130	0.101	0.102	0.075	0.114	0.081
260	0.126	0.127	0.099	0.100	0.074	0.112	0.080
270	0.124	0.123	0.097	0.098	0.073	0.109	0.079
280	0.121	0.121	0.095	0.096	0.072	0.107	0.077

HTP mCTUh/kWh

Wh/kg	NaNMC	NaMVP	NaMMO	NaNMMT	NaPBA	LiNMC622	LiFP
100	0.028	0.065	0.017	0.018	0.012	0.029	0.019
110	0.026	0.060	0.016	0.017	0.012	0.027	0.018
120	0.025	0.055	0.016	0.016	0.012	0.025	0.017
130	0.023	0.052	0.015	0.016	0.011	0.024	0.016
140	0.022	0.048	0.015	0.015	0.011	0.023	0.015
150	0.021	0.046	0.014	0.015	0.011	0.022	0.015
160	0.020	0.043	0.014	0.014	0.010	0.021	0.014
170	0.020	0.041	0.013	0.014	0.010	0.020	0.014
180	0.019	0.039	0.013	0.014	0.010	0.020	0.013
190	0.019	0.037	0.013	0.013	0.010	0.019	0.013
200	0.018	0.036	0.013	0.013	0.010	0.018	0.013
210	0.018	0.035	0.012	0.013	0.010	0.018	0.013
220	0.017	0.033	0.012	0.013	0.010	0.017	0.012
230	0.017	0.032	0.012	0.012	0.009	0.017	0.012
240	0.016	0.031	0.012	0.012	0.009	0.017	0.012
250	0.016	0.030	0.012	0.012	0.009	0.016	0.012
260	0.016	0.029	0.012	0.012	0.009	0.016	0.012
270	0.015	0.028	0.011	0.012	0.009	0.016	0.011
280	0.015	0.028	0.011	0.012	0.009	0.015	0.011

Source (Peters, Baumann, Binder, & Weil, 2021)

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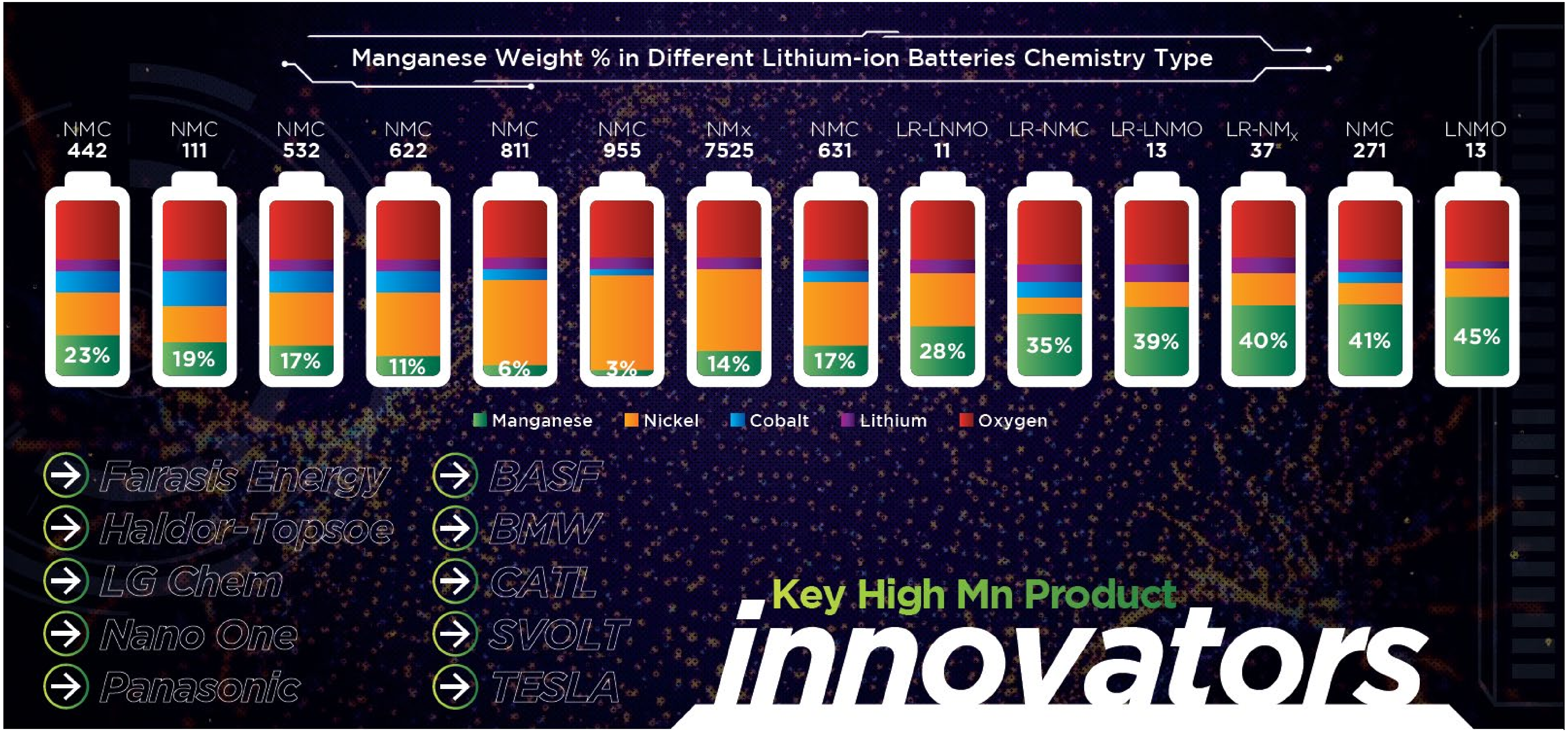
Metal Content by Battery Chemistry



Metal Content by Battery Chemistry

CODE	MOLAR MASS/G	CHEMICAL FORMULAE	WEIGHT % BATTERY METAL					
			Li	Ni	Mn	Co	O	
NMC-442	96.18	$LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$	7%	24%	23%	12%	34%	
NMC-111	96.46	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	7%	20%	19%	20%	34%	
NMC-532	96.55	$LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$	7%	30%	17%	12%	34%	Dominant current formulations
NMC-622	96.93	$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$	7%	36%	11%	12%	34%	
NMC-811	97.28	$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	7%	48%	6%	6%	33%	
NMC-955	96.69	$LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$	7%	54%	3%	3%	33%	
NMx-7525	96.69	$LiNi_{0.75}Mn_{0.25}O_2$	7%	46%	14%	0%	33%	
NMC-631	95.03	$LiNi_{0.6}Mn_{0.3}Co_{0.1}O_2$	7%	36%	17%	6%	34%	
LR-LNMO-11	96.87	$Li_{1.16}Ni_{0.5}Mn_{0.5}O_2$	8%	30%	28%	0%	34%	
LR-NMC	85.29	$Li_{1.20}Ni_{0.13}Mn_{0.54}Co_{0.13}O_2$	10%	9%	35%	9%	37%	Future formulations
LR-LNMO-13	106.29	$Li_{1.5}Ni_{0.25}Mn_{0.75}O_{2.5}$	10%	14%	39%	0%	37%	
LR-NMx-37	95.00	$Li_{1.3}Ni_{0.3}Mn_{0.7}O_2$	9%	18%	40%	0%	33%	
NMC-271	95.03	$Li_{1.0}Ni_{0.2}Mn_{0.7}Co_{0.1}O_2$	7%	12%	41%	6%	34%	
LNMO-13	182.69	$LiNi_{0.5}Mn_{1.5}O_4$	4%	16%	45%	0%	35%	

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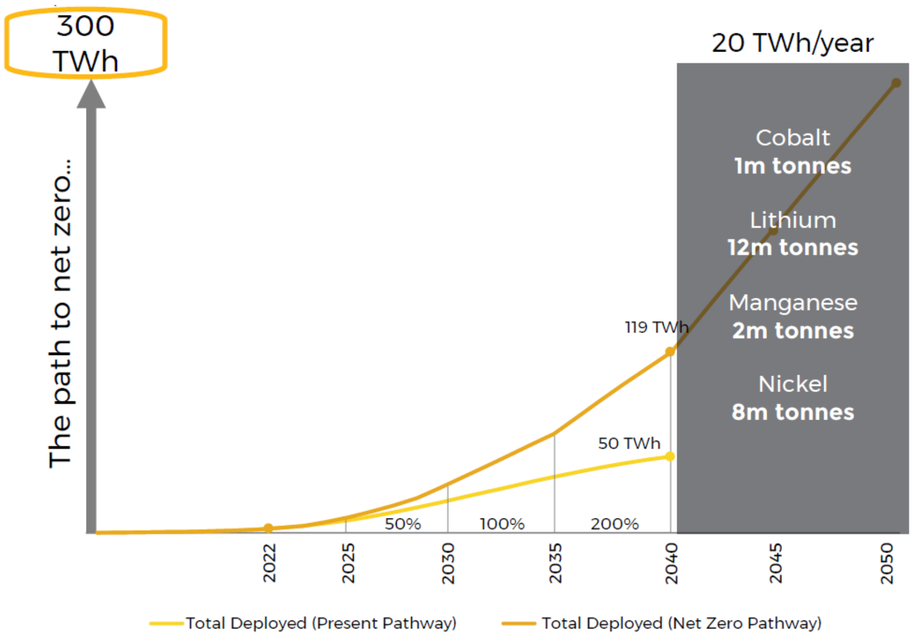
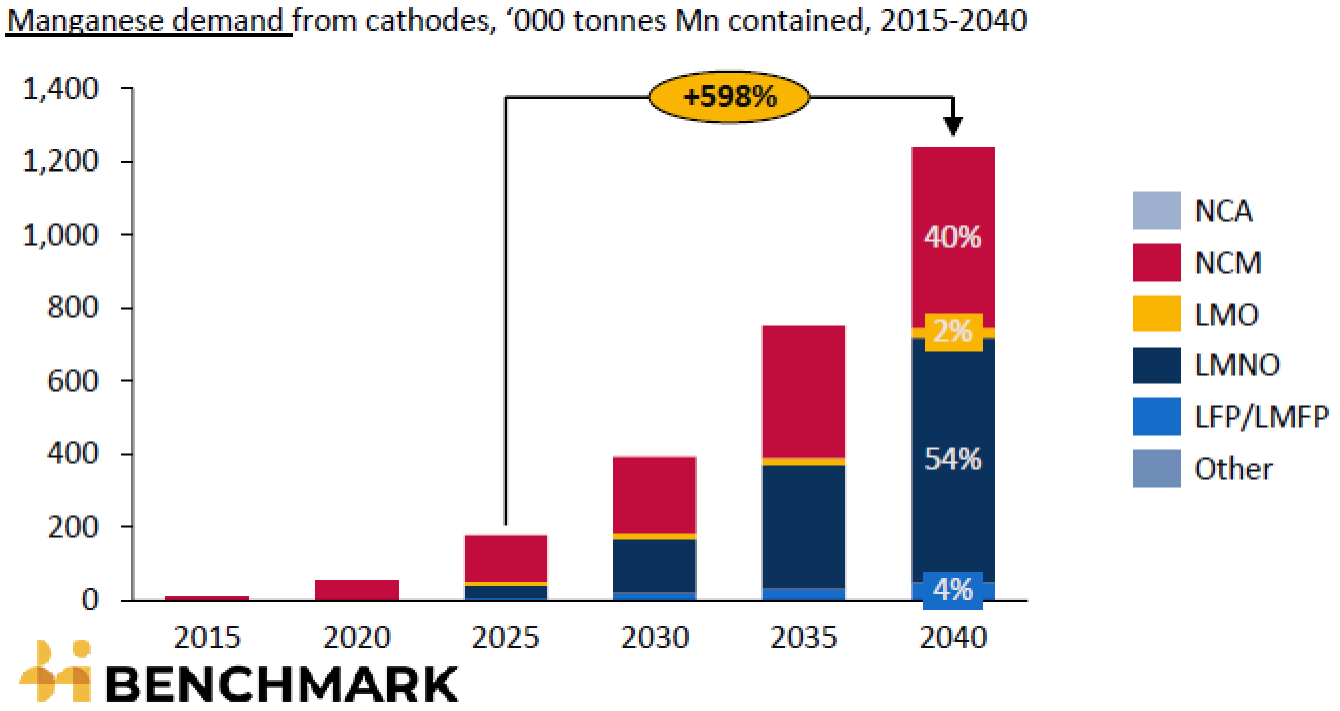
Key Critical Raw Material Needs Include Manganese





Source: Benchmark Minerals, January 2023

Meeting Demand for Mn from Secondary Sources

Secondary Sources of Mn

Recycled LIB

Advantages:
High recycling rates
Large Volumes
Known specifications for NCM/NCA

Disadvantages:
Only 3-12% Mn in majority of spent (NCM/NCA) batteries
Recycling concentrated in Asian countries

Recycled non-LIB/Other

Advantages:
Many industry players
Reasonable Volumes
Uses same refineries as LIB black mass
Suitable for LNMO

Disadvantages:
Potential for wider range of impurities
Not as suitable for high-Ni NCM/NCA

Sustainable Mine Sources

Advantages:
No need for a complex collection infrastructure
Potential for large volumes with one specification
Can also take in recycling

Disadvantages:
Lead time until fully operational
Can it meet European demand?

Achieving Recycled Content in LNMO

- ❖ Cathodes need to have recycled content in line with EU Battery Passport regulations. Also, cell makers and EVs require recycled content to meet their ESG goals.
- ❖ The refiners send metal salts and solutions that have a % of recycled content mixed with virgin content.
- ❖ Some cell OEMs would like a closed loop supply, however this could only work for the largest companies, i.e., so refineries would need a separate line just for that OEMs materials. Not enough hydromet capacity as yet.
- ❖ A key activity ongoing at cathode materials producers is validation of specifications for material provided from recyclers/refiners.
- ❖ Specifications are still being developed for LNMO – and they are based on old ones for NCM811, so they are not necessarily appropriate.
- ❖ Some impurities cause more trouble than others for LNMO. For instance, Co isn't as bad as Fe. Levels of <100 to >300 ppm are being seen. This can cause self-discharge and shelf-life issues in cells.
- ❖ The art is to go for the cheapest materials in the largest quantities – evaluate those first, then consider smaller and/or more expensive feeds. The ideal is to have a constant supply of material within a range of specifications that are being developed during qualification tests.
- ❖ It may be difficult to keep recycled materials in Europe – cars have a habit of going East, then South and the material may not be exported back.
- ❖ Not all the manganese has to come from other batteries, it could come in from the chemical industry and other sources such as sustainable mining projects e.g., Euro-Mn and others.
- ❖ Projects are only bankable if they have green electricity sources – so refiners are competing for "green-electrons". Many new wind farms in Scandinavia are attracting battery metal refining capacity.

Cathode Material Specifications NCM811 vs. LNMO

Item	Measured value	Unit	Instrument name/test method
Surface	Black or brownish yellow powder, no sundries, no lumps, uniform color		Visual inspection
Tap density	2.30±0.20	g/cm^3	Vibration density meter
D10	5.00±1.00	μm	Laser particle size meter
D50	11.00±1.00	μm	
D90	20.00±2.00	μm	
Dmax	<45	um	
Specific area	≤11.50	m^2/g	
Elemental content	Ni	51.60±1.00	wt%
	Co	7.50±0.80	wt%
	Mn	2.90±0.80	wt%
	Fe	≤50	ppm
	Na	≤300	ppm
	Ca	≤100	ppm
	Mg	≤100	ppm
	Cu	≤20	ppm
	Zn	≤20	ppm
	Pd	≤20	ppm
	Cd	≤20	ppm
	Cr	≤20	ppm
	Fe+Cr+Zn+ex.Ni	<80	ppb
	H_2O	<0.80	ppm
	S	<0.1500	ppm
Particle morphology		Spherical or quasi-spherical, with good sphericity and consistency, basically free of micropowder	
Crystal structure		No impurity peaks	

The specification for LNMO is a little easier on Fe – this is still being tested though.

Some of the headaches are Zn, Ca, Mg, P and F

Manganese Recycling Challenges

- Mn is the last priority for a hydromet after Ni, Co and Li.
- It costs as much to recycle Mn as it does Ni and Co combined.
- Mn doesn’t get recycled back to the grade needed for most batteries (NCM, NCA).
- Usually end up getting Mn(OH)x when the carbonates would be preferable.
- Need to rationalize different Mn-rich precipitates and process centrally.
- Pyro units have a Mn-containing slag which is in the form of oxides and silicates, goes into construction materials currently. With some upgrading, could be viable for LNMO/LMFP.
- As long the feeds don’t have too much Fe or fluorine, they can be viable for upgrading – companies can also choose to do an extra upgrade themselves then send for refining – needs discussion between the companies and the refiners.
- Blending of Mn salts from different recycled materials with purer feeds of Mn e.g., from the mine tailings can be a useful strategy – but need to demonstrate it.
- Cathode-to-cathode is one useful strategy but difficult for LNMO where there is no EoL scrap.
- There is competition from other industries – e.g. steel alloys and taking the feed into batteries could cause a structural deficit there.
- We still need much higher-grade recycled Mn for NCM/NCA. Not clear where it’s coming from

Key Takeaways

- Cathodes with lower Ni/Co-Free chemistries are growing rapidly e.g., LNMO, NMx and LMFP
- LNMO will be the largest user of Mn in batteries by 2040, even more than high nickel formulations
- The need to meet demand for recycled materials in line with sustainability/ESG goals will require that much more secondary Mn is available
- Recycled Mn is expensive and could be detrimental to battery price competitiveness in the EU – large need to bring down the price.
- Much of the effort needed isn't necessarily technical – it's logistical and requires cooperation between different stakeholders.
- There is a need to ensure that Mn doesn't end up in landfill and that is actually recycled – ESG practices ought to benefit the industry here.
- There are opportunities – however we must be proactive in order to realise them.


Enabled Future

www.enabledfuture.com

Enabled Future Limited
Membership Prospectus

Enabled Future Limited (EFL) is a consultancy which works to **Optimise Technology Portfolios** with stakeholders involved in the sustainable production, use and recycling of chemicals, catalysts, plastics and polymers, energy carriers and valuable metals.

Discover the range of services including included in the new EFL Company Membership Programme to be launched in November 2022.

Don't miss out on the limited time offer of 3-month's free membership which is available until 1st November 2022!

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Thank you for listening!

Catch us at Battery Tech Expo, Silverstone on 20th April 2023
Stand M12
https://www.batterytechexpo.co.uk/

Catch us at the Vehicle Electrification Expo/Advanced Material Show at the Birmingham NEC, 28th & 29th June, 2023
Visit the Vehicle Electrification Expo 2023 (ve-expo.com)

The Advanced Materials Show I NEC, Birmingham, 28th & 29th June 2023