Workshop:
How can we achieve a circular and domestic EV battery supply chain?

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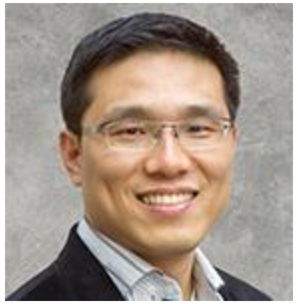
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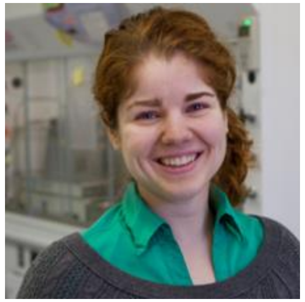
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Linear vs. circular economy

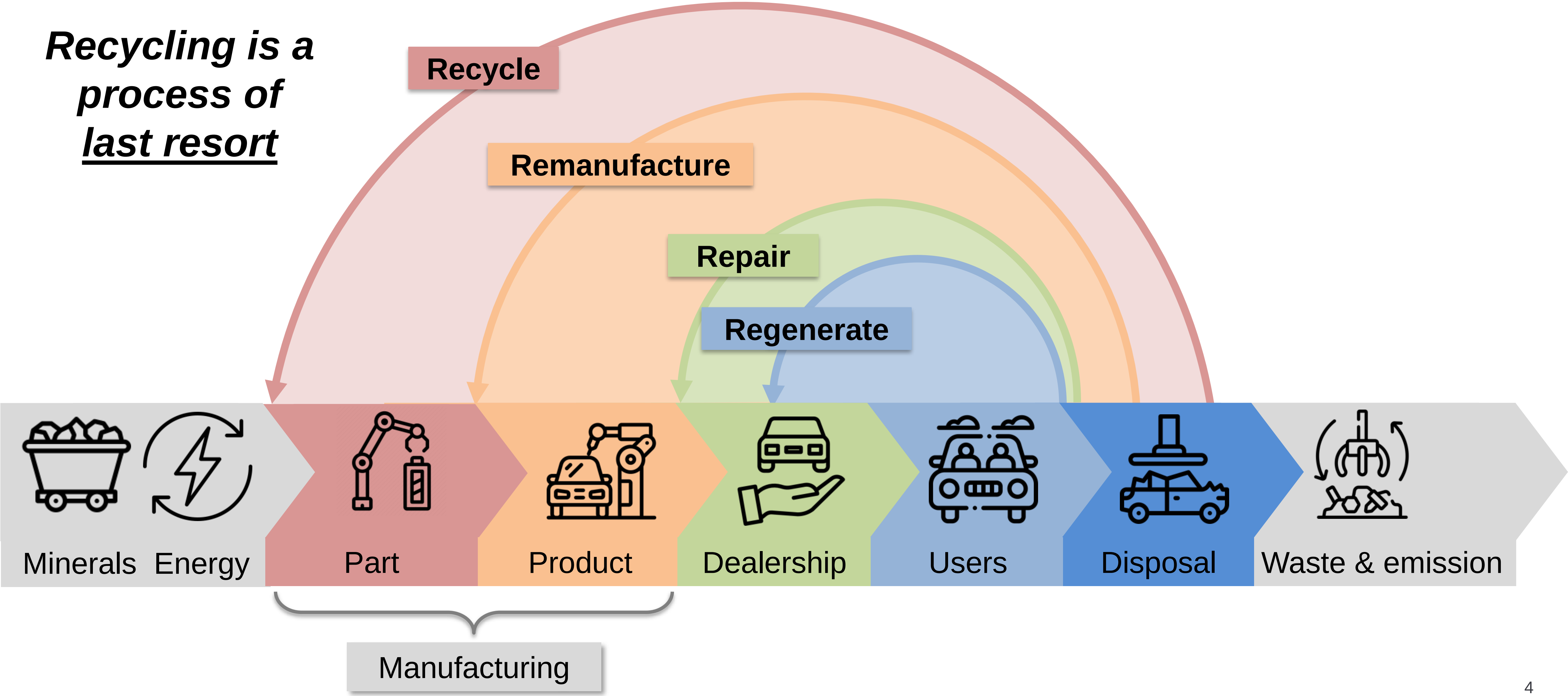
- Linear economy
  - Take, make, use, dispose
- Circular economy*
  - "An economy that uses system-level approach and involves industrial processes and economic activities that are restorative or regenerative by design."
  - "A circular economy reduces material use, redesigns materials, products, and services to be less resource intensive, and recaptures "waste" as a resource to manufacture new materials/products."
- Personal reflection and questions
  - It makes more sense to talk about **circular supply chains**
  - Limits of the linear economy are the most apparent in the EV revolution
  - Globalization of supply chains has shown its limits (COVID, War in Ukraine)

⇒ **How can we achieve a circular and domestic EV battery supply chain?**

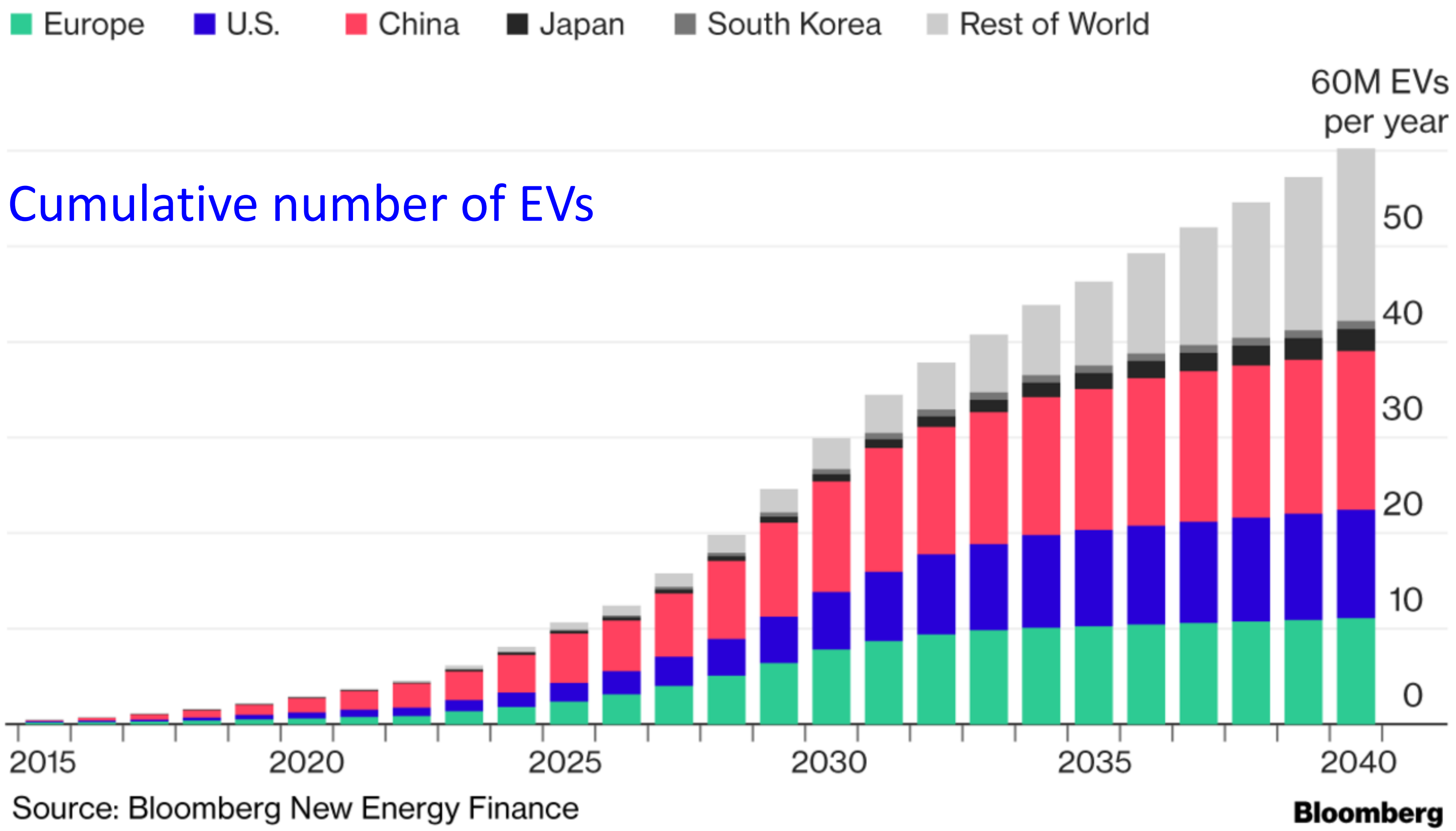
* www.epa.gov/circulareconomy/

Circularity is more than recycling…
it helps recover manufacturing value!

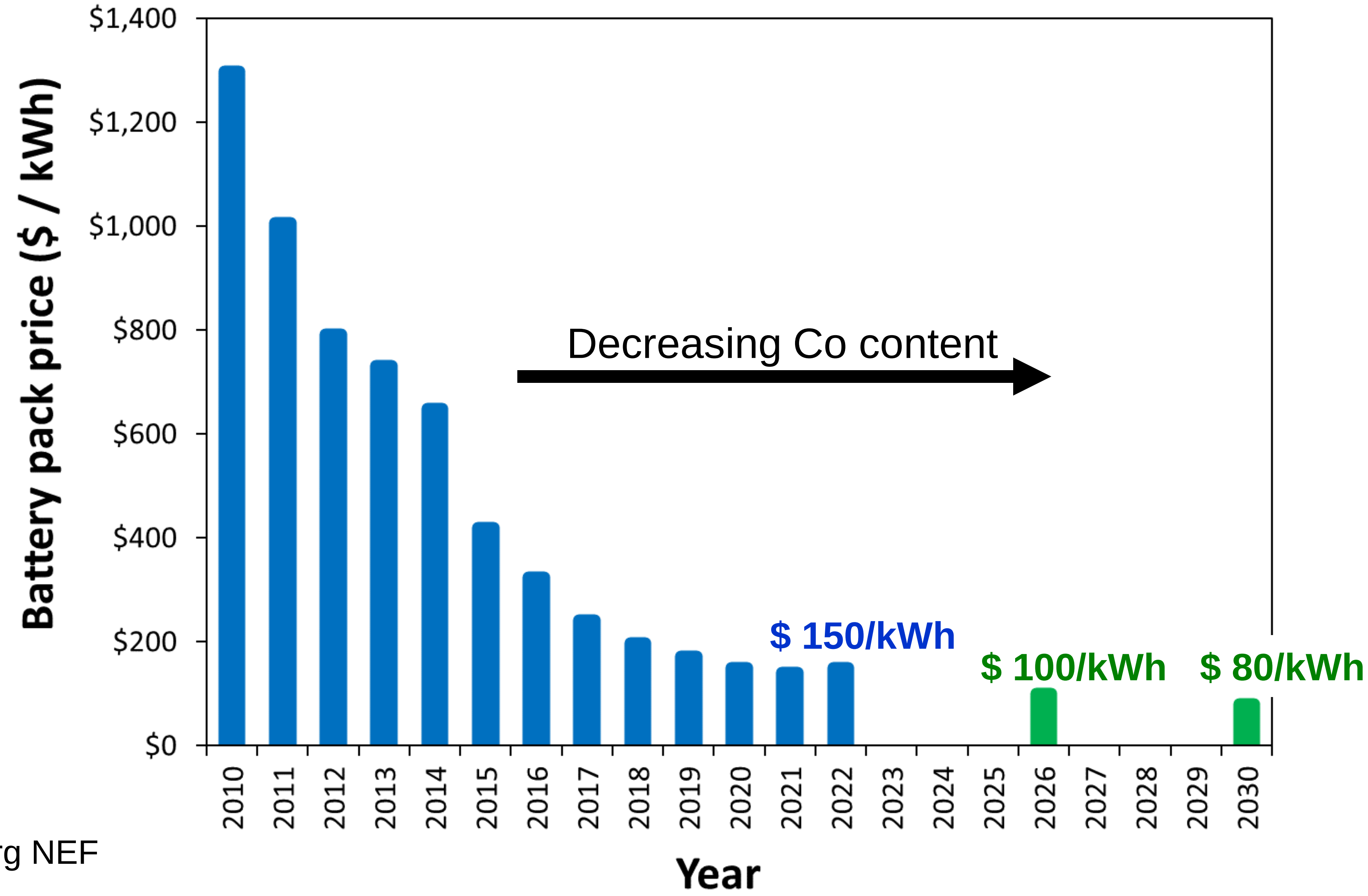
Recycling is a process of <u>last resort</u>



EV battery market is poised for substantial growth

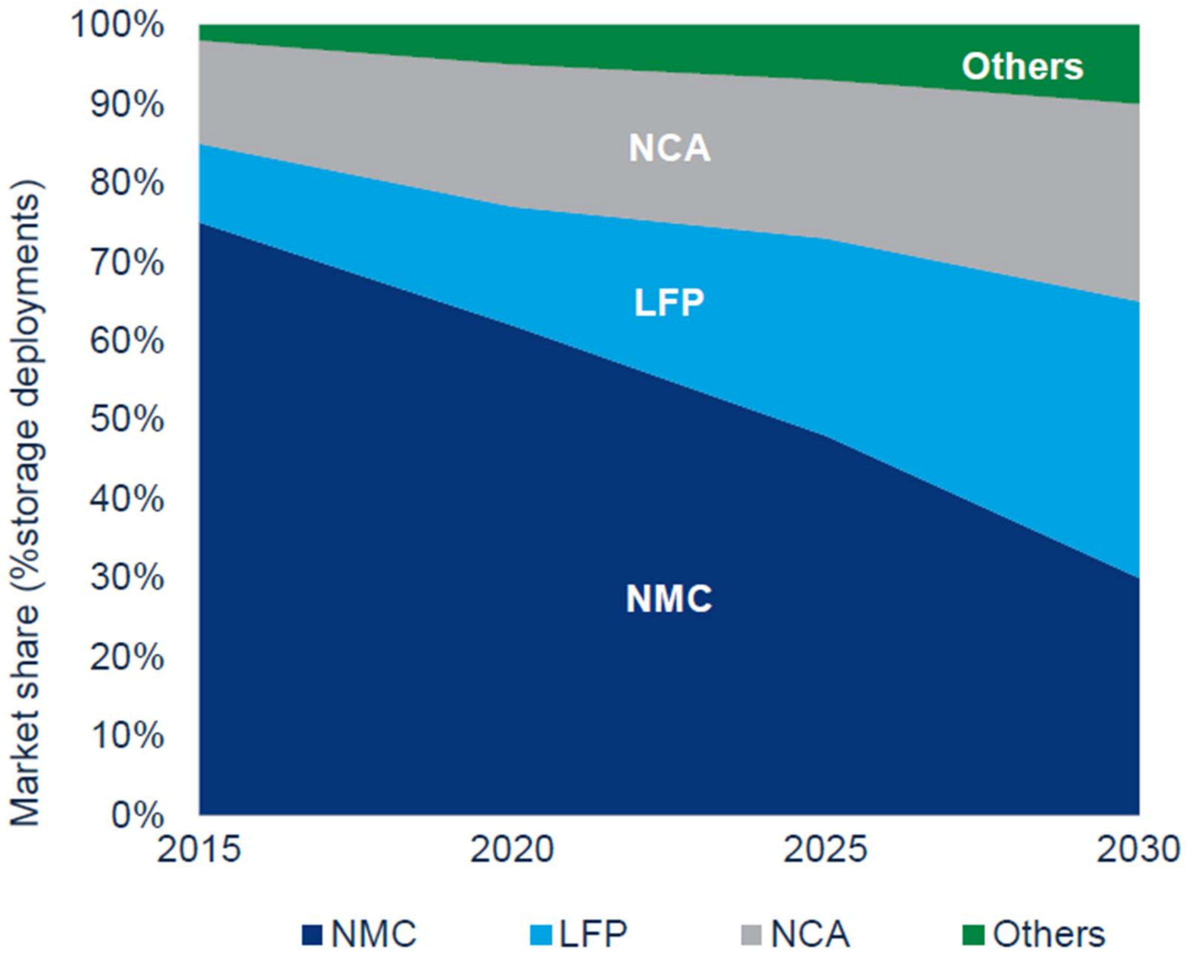


Lithium-ion battery price ($/kWh) keeps going down



Source: Bloomberg NEF

The quest for cheaper batteries



Source: Wood Mackenzie Energy Storage Service

- Price considerations
  - parity EV vs. ICE vehicles: $100/kWh
  - 2010 battery price: $1,000/kWh
  - 2022 average battery price: $152/kWh

- LFP market share is growing
  - 40% market share in 2022
  - Cheaper than NMC batteries by 20%

As the price of batteries decreases so does the value of recovered minerals

For a 60 kWh lithium-ion battery

	NMC622 Ni (60%) Mn (20%) Co (20%)	NMC811 Ni (80%) Mn (10%) Co (10%)	NCA Nickel cobalt aluminum oxide	LFP Lithium iron phosphate
Lithium	6 kg	5 kg	6 kg	6 kg
Cobalt	11 kg	5 kg	2 kg	**0 kg**
Nickel	32 kg	39 kg	43 kg	**0 kg**
Manganese	10 kg	5 kg	0 kg	0 kg
Graphite	50 kg	45 kg	44 kg	66 kg
Aluminum	33 kg	30 kg	30 kg	44 kg
Copper	19 kg	20 kg	17 kg	26 kg
Steel	19 kg	20 kg	17 kg	26 kg
Iron	0 kg	0 kg	0 kg	41 kg

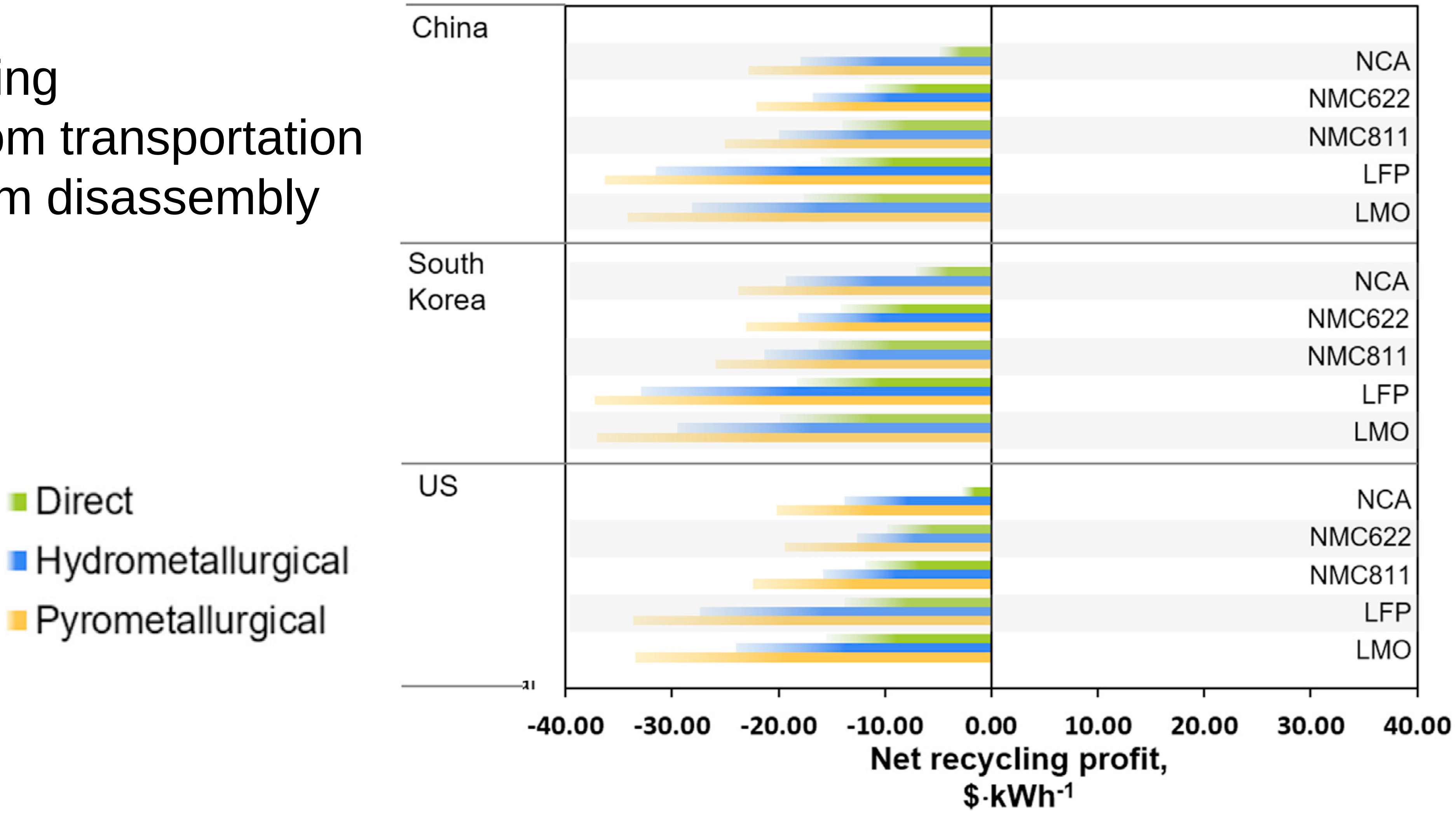
recycled (Cobalt, Nickel)

recycled (Copper)

Decreasing Co content →

Who is going to recycle EV batteries?

Cost of recycling
- 30-40% from transportation
- 20-30% from disassembly

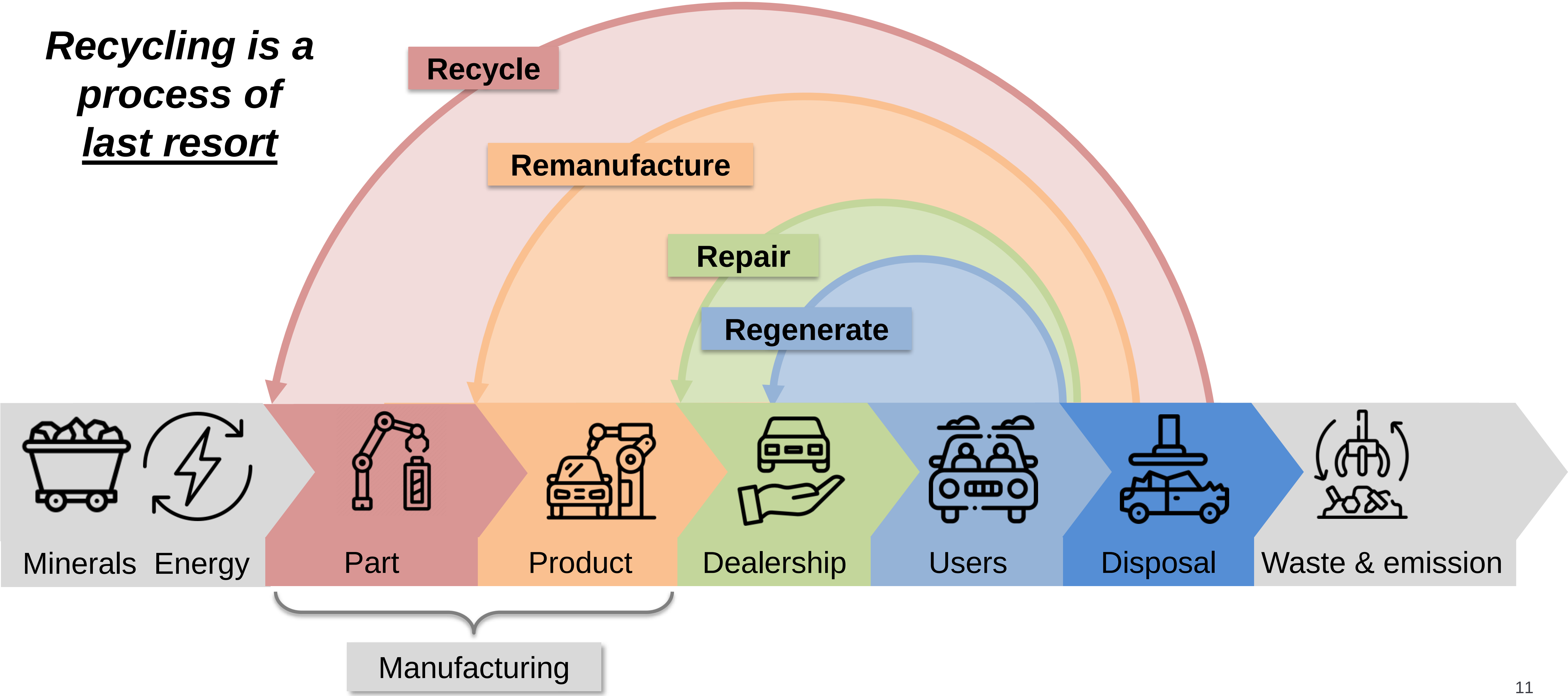


Lander et al., iScience 24, 102787 (2021). DOI: 10.1016/j.isci.2021.102787

But fast forward in 10-20 years

Circularity is more than recycling…
it helps recover manufacturing value!

Recycling is a process of <u>last resort</u>

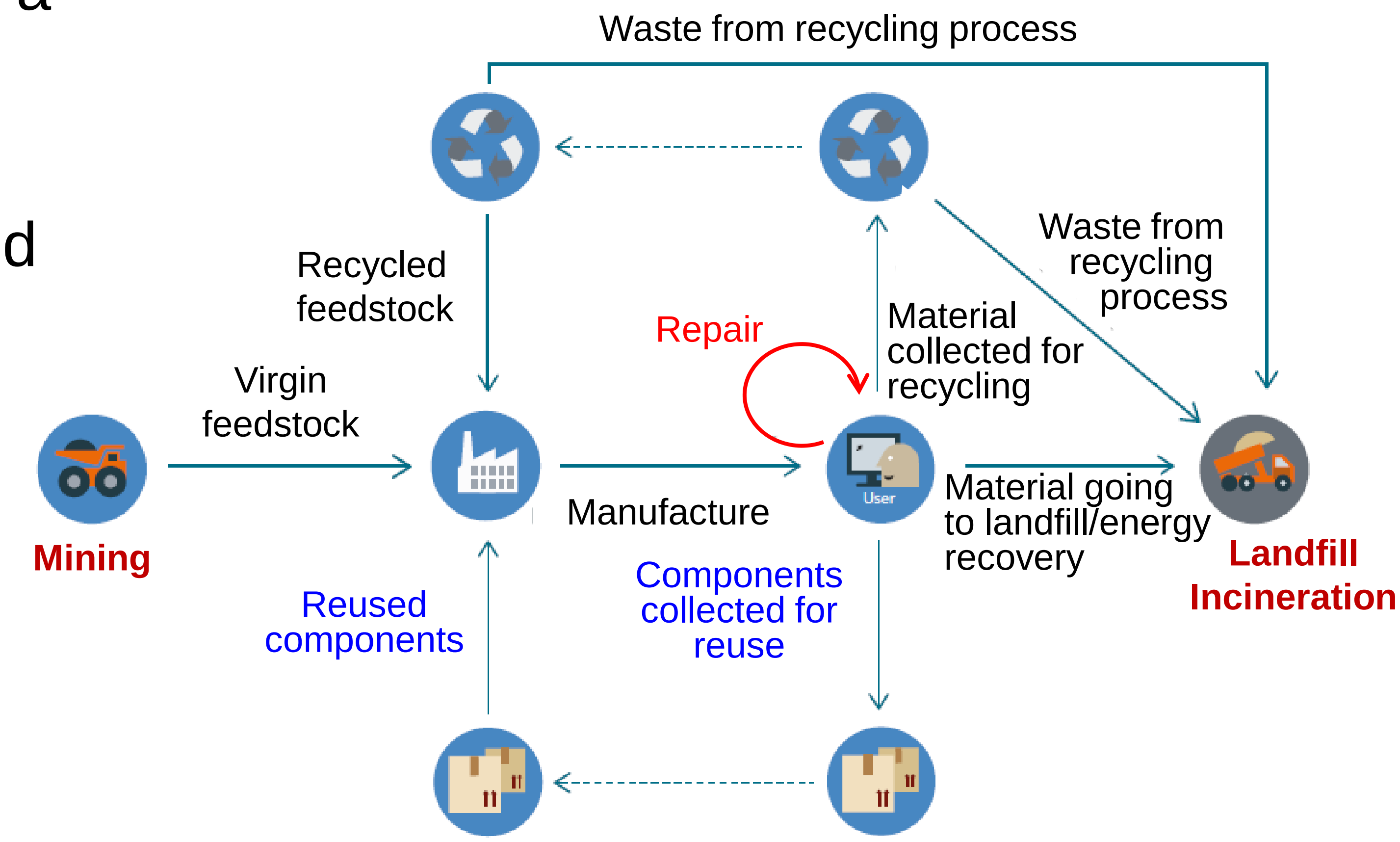


Dr. Kelly Rudman

Material circularity index (MCI) to assess the circularity of a supply chain

Metrics: Material Circularity Index (MCI)*

- Metric to evaluate the circularity of a given product(s)
- Perform a mass balance (virgin and recycled materials and waste) accounting for product lifespan
- Values range from 0 to 1
  - MCI = 0 (completely linear)
  - MCI = 1 (completely circular)



* Ellen MacArthur Foundation. Circularity Indicators: An Approach to Measuring Circularity – Methodology (2019)

Material Circularity Index (MCI)

- Inputs
  - Bill of Materials: type, amount, cost
  - Material sources: virgin, remanufactured, reused, recycled
  - Utility: how long specific product lasts as compared to similar types
  - Destination after use: landfill/incineration, recovery, remanufacture, reuse
  - Recycling: collection and efficiency
- Outputs
  - $0 \leq MCI \leq 1$

- Calculator from Thinkstep Anz

Material Circularity Indicator calculator

thinkstep anz

Utility based on (Select)	Longevity	
This product lasts:	5	Years
Typical product lasts:	5	Years
Utility of Product is	**1**	

MCI

			Input Materials			Output Materials		MCI
Component Name	**Each (kg)**	**Quantity**	**Material Type**	**Source**	**% Regenerativ**	**Collection Rate**	**Destination**	
Pen Tube	0.0040	1	Plastics	Virgin		100%	Reuse	**0.55**
Ink Tube	0.0020	1	Plastics	Virgin		100%	Reuse	**0.55**
Nib	0.0002	1	Steel	Virgin				**0.10**
Lid	0.0010	1	Plastics	Virgin				**0.10**
Product Mass (kg)	**0.0072**							**0.48**

MCI Assumptions

- General
  - Recovered materials have similar performances to new materials
  - No part of the product is consumed during use
  - All materials fall into 1 of 9 default categories and are treated the same
- Specific to battery supply chain
  - 180 kWh battery pack
  - Battery chemistry: NMC 622 or LFP
  - Collection rate: 100%
  - Recycling process: pyrometallurgy

MCI for battery packs

- 180 kWh NMC 622 battery pack

70-80 wt.%

180 kWh pack
~7776 cells
9 Modules

Per module:
864 cells
12S72P

20-30 wt.%

Electronic
+Housing

			Input Materials			Output Materials		
Component Name	**Each (kg)**	**Quantity**	**Material Type**	**Source**	**% Regenerativ**	**Collection Rate**	**Destination**	**MCI**
Active Cathode Material	231.1183	1	Composites	Reman	90%	100%	Reman	**0.96**
Graphite	149.7989	1	Natural Material	Virgin	90%	100%	Recycle	**0.83**
Carbon Black	15.6932	1	Natural Material	Virgin	90%	100%	Landfill	**0.51**
Binder: PVDF	20.6865	1	Plastics	Virgin	0%	100%	Landfill	**0.10**
Copper	114.8458	1	Natural Material	Reuse	90%	100%	Reuse	1.00
Aluminum	59.9196	1	Aluminium	Reuse	90%	100%	Reuse	1.00
Electrolyte, LiPF6	15.6932	1	Composites	Virgin	50%	100%	nergy Recove	0.10
Electrolyte, EC	44.9397	1	Composites	Virgin	50%	100%	nergy Recove	0.10
Electrolyte, DMC	44.9397	1	Composites	Virgin	50%	100%	nergy Recove	0.10
Plastic, PP	10.6999	1	Plastics	Virgin	50%	100%	Recycle	0.24
Plastic, PE	2.8533	1	Plastics	Virgin	50%	100%	Recycle	0.24
Pastic, PET	2.1400	1	Plastics	Virgin	50%	100%	Recycle	0.24
Plastic housing	23.7776	1	Plastics	Reuse	50%	100%	Reuse	1.00
Metal Housing	237.7760	1	Steel	Reuse	90%	100%	Reuse	1.00
Strap/busbar	213.9984	1	Natural Material	Reuse	90%	100%	Reuse	1.00
Product Mass (kg)	**1188.88**							**0.86**

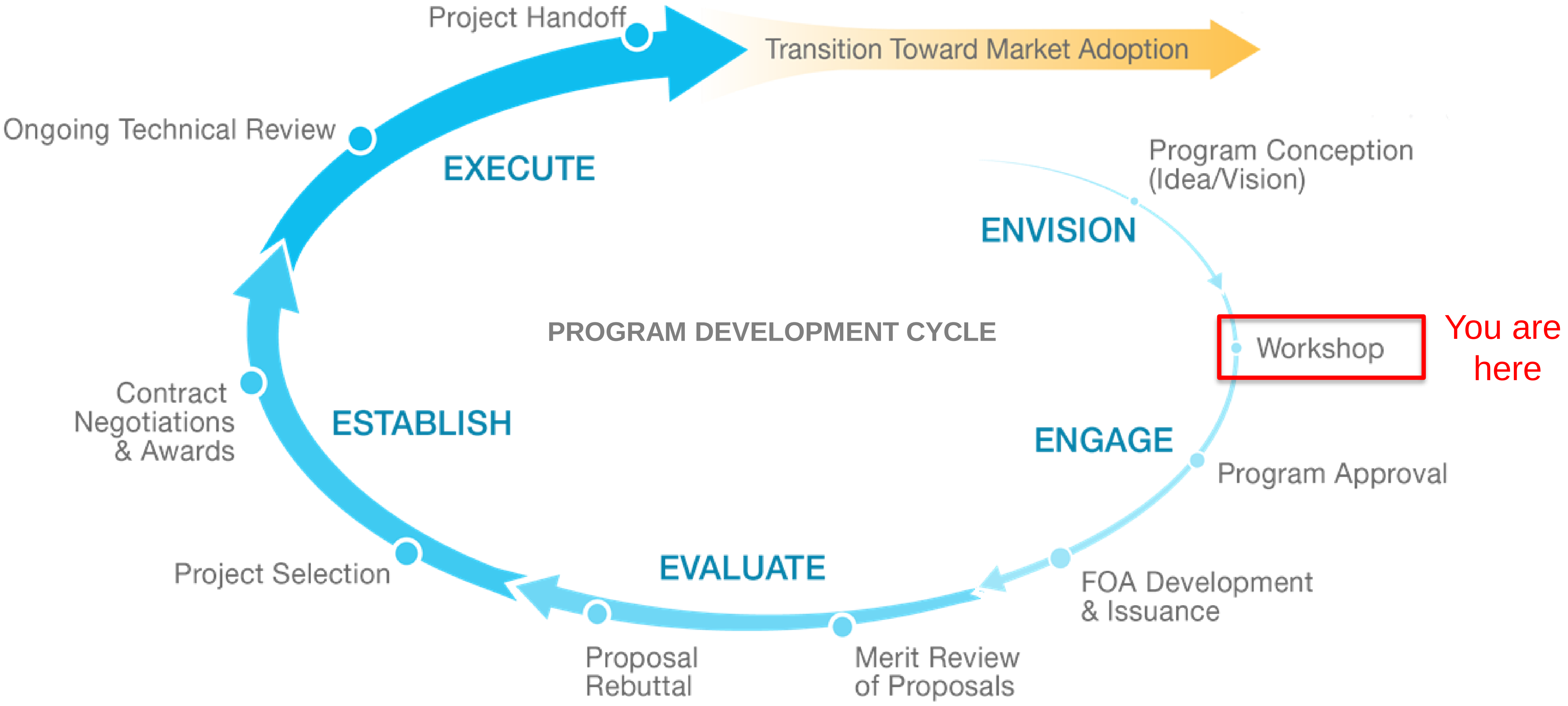
Comparison of MCI between current and ideal circular practice

MCI for NMC (622) and LFP battery pack under varying conditions			
Battery Chemistry	**Pyrometallurgical recycling**	**Hydrometallurgical recycling**	**Circular supply chain (aspirational)**
NMC (622)	0.28-0.30	0.47-0.50	0.80-0.86
LFP	0.26-0.29	0.44-0.48	0.75-0.82

Note: MCI of the lead acid battery supply chain is approximately 0.7

This workshop

Technology acceleration model



Workshop objectives

- Inform ARPA-E on technologies needed to achieve a circular battery supply chain
  - Identify the market needs, the impact, and the obstacles
  - Present existing relevant technologies
  - Identify technological opportunities and obstacles
  - Define fair, quantitative, and ambitious metrics to assess different technologies
- Start creating a community focused on achieving a circular battery supply chain
  - Be engaged in all technical conversations: talks, panels, breakout sessions
  - Share your technical expertise and opinions
  - Listen and learn
  - Network and find partners that complement your strengths
  - Enjoy!

How are we going to achieve these objectives?

- Presentations
  - #1. Stating the Problems and the Opportunities
  - #2. Material, Design, and Manufacturing
- Fireside chats
  - #1: Disassembly, Remanufacturing, Second Use, Rejuvenation, and Recycling
  - #2. Circularity of Battery Supply Chain and Commercialization
- Breaks and networking
- Breakout sessions
  - #1. Challenges and Opportunities Along the Supply Chain
  - #2. Technical Solutions for Materials, Design, and Manufacturing
  - #3. Circularity of Battery Supply Chain and Commercialization
- Breakfast, lunch, and dinner
- Follow up conversations

Thank you for your attention

- Comments or questions?

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