Ingenious Brain

Future-Proofing Businesses

Recycling of Batteries: Innovations and Technology Outlook

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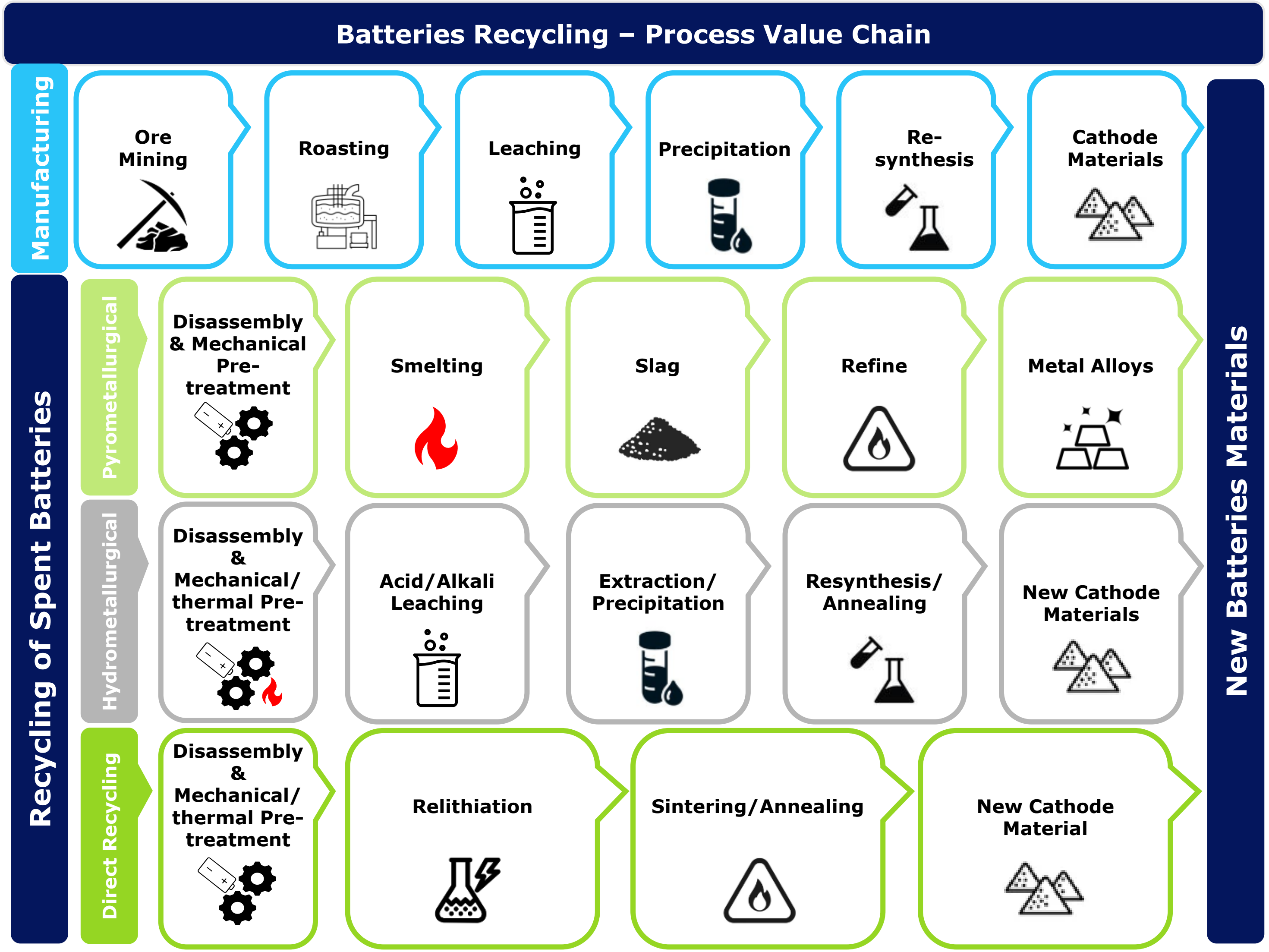
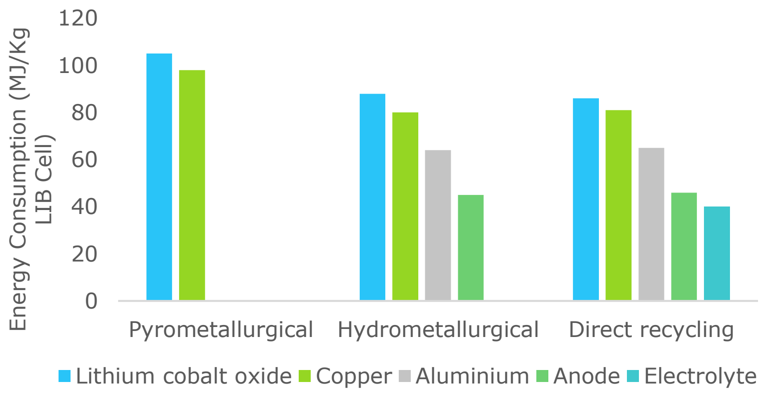
Overview of Key Batteries Recycling Technologies

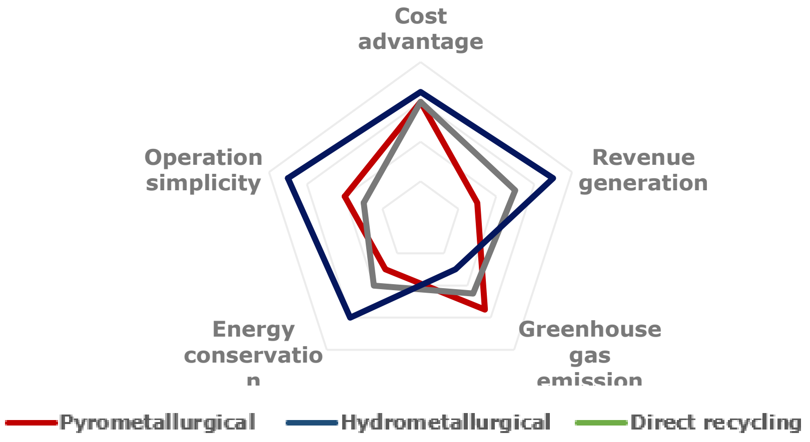


Reduction of Cost of Energy by Using Recycled Components in Li-ion Battery



Recycled

Batteries Recycling Technology – Opportunity Radar



Source: IeB analysis

Technology Shift: Batteries Recycling Technologies

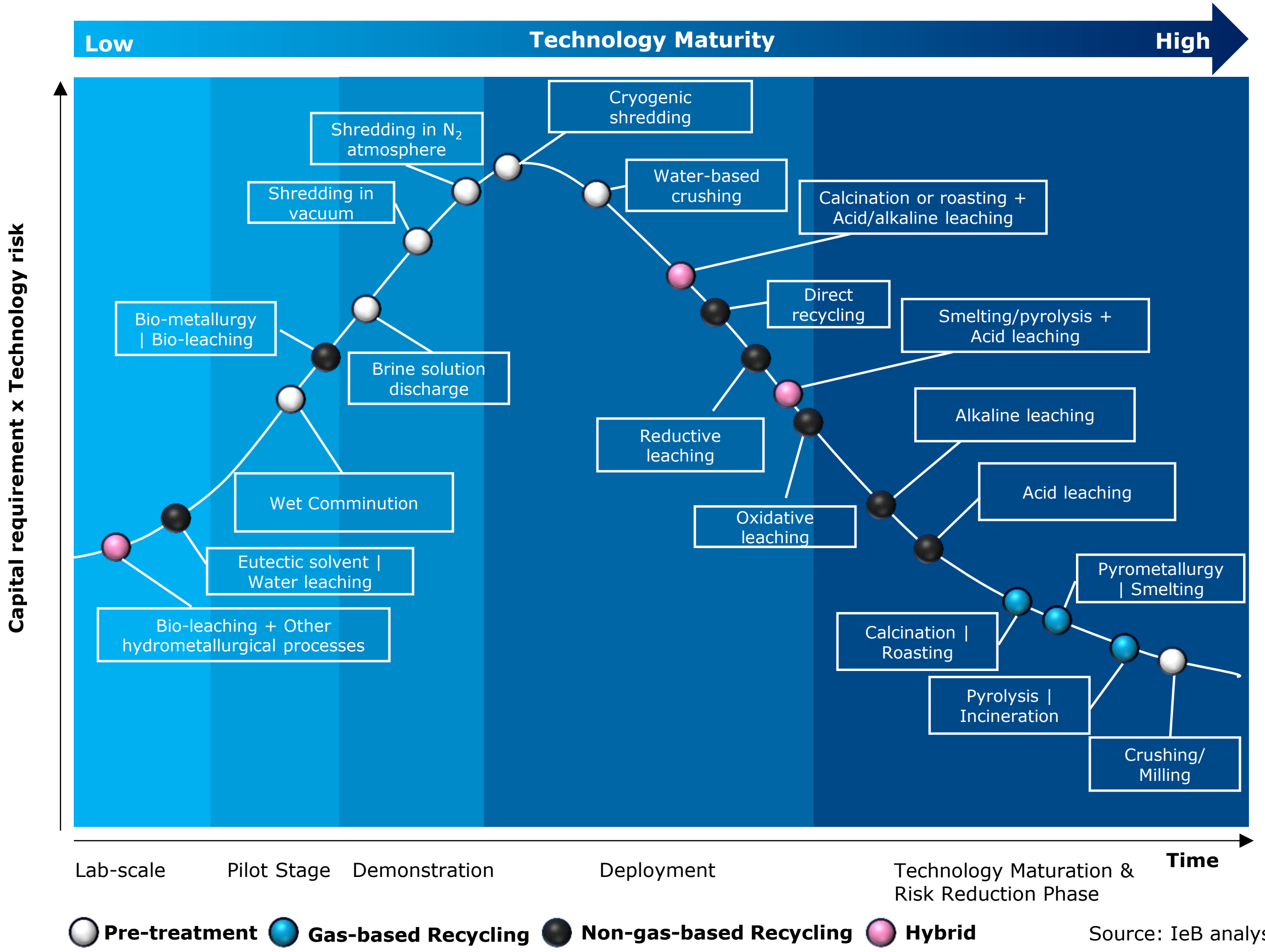
Publication Year	Mechanical Pre-treatment				Thermal Pre-treatment				Gas-based Recycling Technologies				Non-gas-based Recycling Technologies								Hybrid Recycling Technologies			
	Electric-discharge	Crushing / Milling	Water-based crushing	Brine solution discharge	Cryogenic shredding	Shredding in vacuum	Shredding in N_2 atmosphere	Wet Comminution	Pyrometallurgy (Smelting)	Calcination	Roasting	Pyrolysis /Incineration	Acid leaching	Reductive leaching	Oxidative leaching	Alkaline leaching	Eutectic solvent leaching	Water leaching	Direct recycling	Biometallurgy	Calcination or roasting + Acid leaching	Pyrolysis + Acid leaching	Calcination or roasting + Alkaline leaching	Other hybrid technologies
2013	2	10							2			3	6											
2014		8							6			5	8	2		1								
2015	2	15							9			9	12											2
2016		22							15			3	9	5	2	3				1			1	3
2017	5	19	1	1					12			6	17	8	12	8						1		
2018	4	25				1			19		2		25	15	8	15		1	1	4	2	1	3	8
2019	8	30	2	1		1	1		22	2			20	21	19	22	2		2		7			4
2020	12	33		3	1				18	1	3	3	26	17	16	32		3		8	6	4	6	16
2021	15	31	1	8	3	5	2	1	23	3	6	2	28	29	26	29	8		3	7	11	3	11	19
2022	19	35	5	12	10	7	5	3	25	8	11		38	38	41	37	15	6	10	12	14	11	17	18
2023	22	40	9	18	16	12	10	8	28	16	22	2	59	46	46	52	17	8	24	27	18	20	19	24

Notations Emerging pre-treatment and batteries recycling technologies

Source: IeB analysis

Technology Maturity Curve: Batteries Recycling Technologies

Technologies Maturity Curve for Battery Recycling Technologies



Source: IeB analysis

TRL Levels	Definition
Level: 1 (Ideation Phase)	▪ Scientific research begins to be translated into applied R&D
Level: 2 to 3 (Research Phase)	▪ Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis ▪ Active R&D is initiated
Level: 4 to 5 (Development)	▪ The basic technological components are integrated to establish that the pieces will work together ▪ The basic technological components are integrated so that the system configuration is similar to the final application in almost all respects
Level: 6 (Demonstration)	▪ Engineering-scale models or prototypes are tested in a relevant environment
Level: 7 to 8 (Deployment)	▪ The final design is virtually complete, and a demonstration of an actual system prototype in a relevant environment ▪ The technology has been proven to work in its final form and under expected conditions
Level: 9 (Matured Technology)	▪ The technology is in its final form and is operated under a full range of operating conditions

Technology Outlook: Mechanical Treatment

Pre-treatment Process	Definition	Advantages	Limitations
Electrical Discharge	▪ The discharge process takes place via a standard resistor where the energy is dissipated as heat	▪ Increases safety by reducing the risk of short circuits ▪ Potential for energy recovery ▪ Automation possible	▪ Only applicable for large modules and packs ▪ Difficult to discharge portable cells without using saltwater solution, which generates toxic and flammable gases ▪ Rebound can occur if discharged too rapidly
Brine Solution Discharge	▪ Immersion of spent batteries in salt solutions	▪ Cost-effective method ▪ Reduces the likelihood of thermal events during recycling	▪ Energy cannot be recovered ▪ Lithiated anode of charged cells has the potential to react violently with water if the cell casing is compromised ▪ Produces H_2 and Cl_2 gases (flammable)
Crushing/Milling	▪ Crushing or milling involves mechanically breaking down battery components into smaller pieces to facilitate further processing and material separation	▪ Enables the extraction of valuable materials such as lithium, cobalt, and nickel. ▪ Can be integrated into automated processing lines to enhance throughput	▪ Generates dust and potentially toxic particulates that must be managed ▪ Requires robust safety protocols to prevent accidental fires or exposure
Water-based Crushing	▪ Uses water or a water-based solution to crush and cool batteries simultaneously, mitigating the risk of thermal events and explosions	▪ Reduces the risk of fire by keeping temperatures low during the crushing process ▪ Helps in separating materials due to differential settling rates in water	▪ Water contamination with electrolytes and other soluble materials ▪ Requires treatment of wastewater before disposal or recycling

Source: IeB analysis

Technology Outlook: Thermal Treatment

Pre-treatment Process	Definition	Advantages	Limitations
Cryogenic Shredding	▪ The cells are immersed in liquid nitrogen and frozen, reducing cell reactivity to zero and subjected to thermal treatment	▪ Safe, even in cases of metallic Li or Li plating	▪ Only gives a short time for processing before cells become live again ▪ Li and electrolyte must be neutralized post processing ▪ Energy intensive, high cost, poor scalability
Shredding in Vacuum	▪ Comminution and shredding under an inert gas blanket	▪ Avoids wetting materials ▪ Cheaper to operate than using inert gas	▪ Only suitable for batch processing ▪ Parts of shredder may need to be placed under vacuum to avoid fires post shredding ▪ Will not stop a fire once started, requires gas handling and supply
Shredding in N_2 Atmosphere	▪ This procedure utilized a nitrogen atmosphere, and the cells are heated to 300 °C to burn the binder and carbon material	▪ Continuous shredding possible with right feeding mechanism	▪ More expensive than vacuum shredding ▪ May need inert conveyance line post shredding to avoid fires/explosions
Wet Comminution	▪ Comminution under a spray of water or LiOH solution that acts as heat sink	▪ Cost-effective method ▪ Any exposed Li is hydrolyzed	▪ Waste effluent may require cleaning ▪ HF is formed

Source: IeB analysis

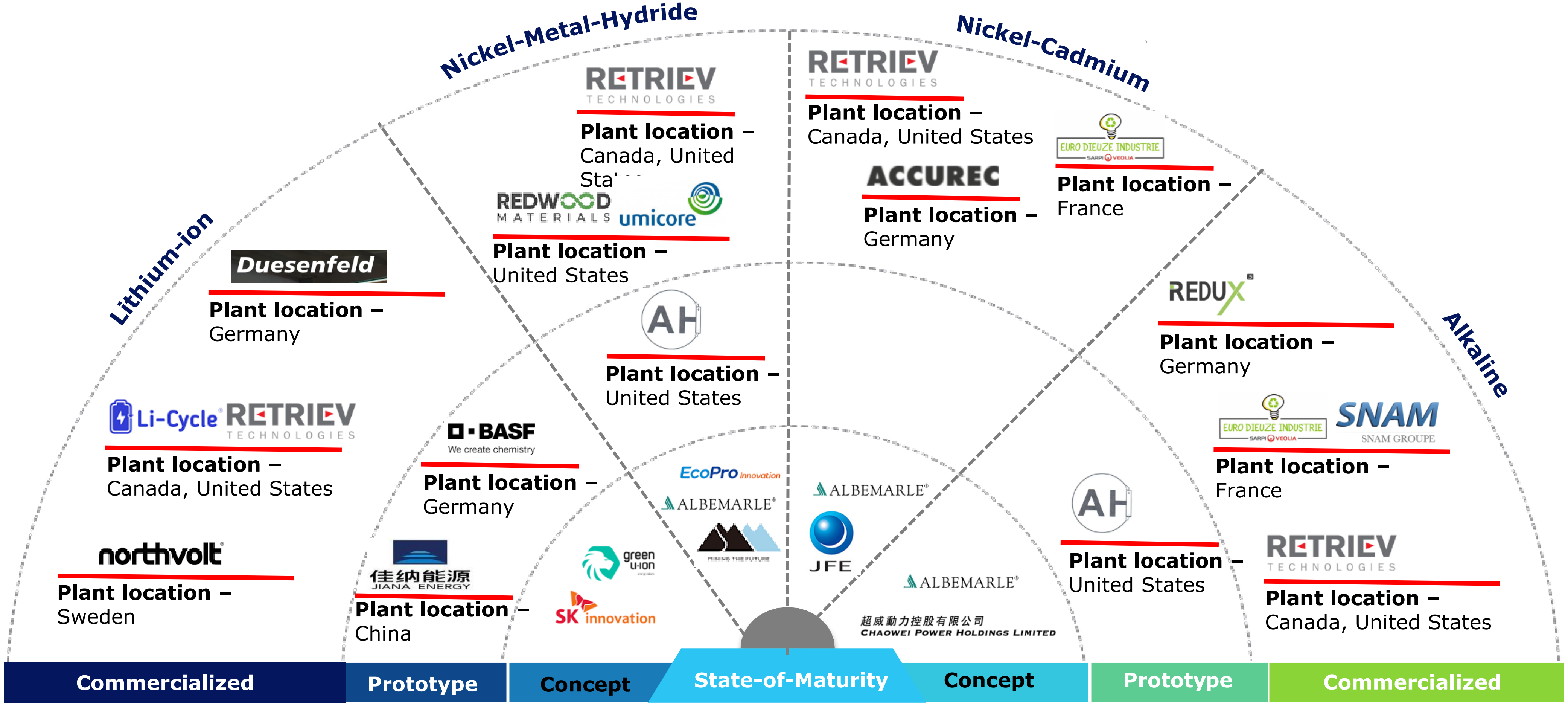
Technology Outlook: Refining Technologies

Battery recycling techniques	Definition	Pros	Cons	Recovered materials
Hydrometallurgy	▪ Process where contained metals are transferred into metal salt through acids, bases or salts ▪ **Different Steps**: Leaching, Precipitation, Ion exchange, Solvent Extraction, Electrolysis	▪ Applicable to any battery chemistry & configuration ▪ High recovery rate and purity ▪ Mild reaction conditions ▪ No gaseous emissions ▪ Can be built on smaller scale ▪ Requires **0.125 MJ** electrical energy per kg of battery	▪ Requires highly efficient pre-treatment (sorting, crushing) for high recycling efficiency ▪ Various reagents required for recovery steps ▪ High operating cost ▪ **3.76 L of wastewater** are produced per kg of battery	▪ Cathode material ▪ Aluminium ▪ Copper
Pyrometallurgy (Smelting)	▪ Treatment of materials at high temperatures to effect conversion to raw metals or intermediate compounds ▪ **Different Steps:** Metal reduction, Salt roasting, Electric arc treatment	▪ Applicable to any battery chemistry & configuration ▪ Easiness of procedure	▪ Gas clean-up required to avoid release of toxic substances ▪ High energy consumption ▪ Hazardous gaseous emissions ▪ Due to low volatility, **Li, Mn and Al** is lost ▪ Requires **4.68 MJ** electrical energy per kg of battery	▪ Part of Cathode material ▪ Copper
Direct Recycling (Supercritical CO_2)	▪ The discharged and disassembled battery cells are treated with supercritical CO_2 followed by lowering of temperature and pressure	▪ All battery materials can be recovered ▪ Low environment impact	▪ Recovered material may not perform as well as virgin material ▪ **Still in research stage** ▪ High plant setup costs	▪ Almost all the components ▪ (except separators)

Source: IeB analysis

Universe of Key Players: Batteries Recycling

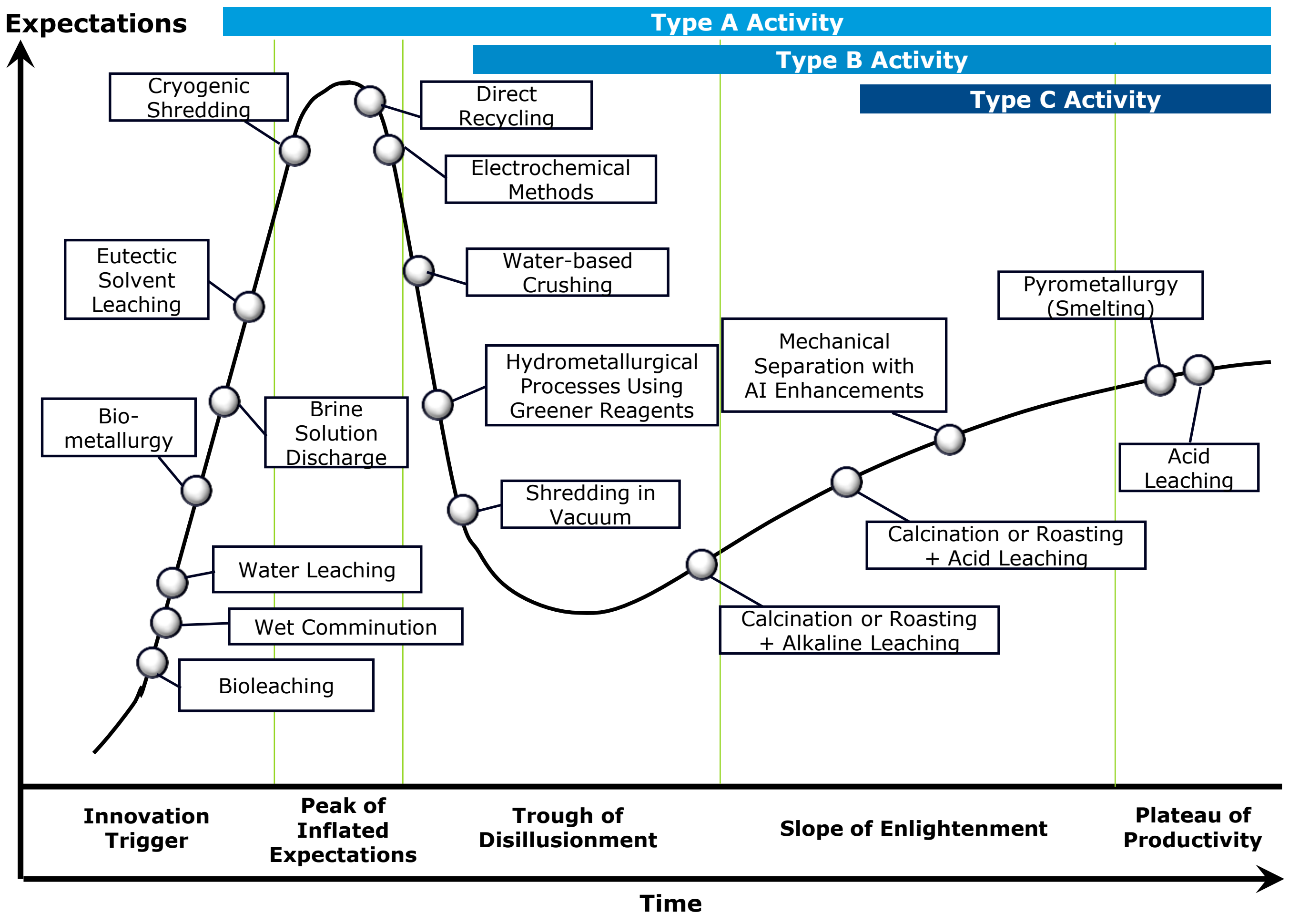
State of Maturity



Source: IeB analysis

Hype Cycle for Batteries Recycling Processes: Time to Market

Hype Cycle for Batteries Recycling



Priority Matrix

	Years to mainstream adoption			
	Less than 2 years	2 to 5 years	5 to 10 years	More than 10 years
Trans-formational	Invest aggressively if not already adopted	Conservative investment profile	Moderate investment profile	Aggressive investment profile
High	Conservative investment Profile	Moderate investment profile	Aggressive investment profile	Invest with caution
Moderate	Moderate investment profile	Aggressive investment profile	Invest with caution	Invest with extreme caution
Low	Aggressive investment profile	Invest with caution	Invest with extreme caution	Invest with extreme caution

Low — Investment Favorability — High

Source: IeB analysis

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Use of Gases in Batteries Recycling Technologies

Batteries Recycling Technologies	Technology Maturity Level	Type of Gases	Application of Gases
Cryogenic Shredding	TRL > 6	▪ Liquid N_2	▪ Inducing cryogenic environment for shredding ▪ Makes battery materials brittle and easier to process while reducing the risk of thermal incidents
Shredding in N_2 or Inert Atmosphere	TRL > 6	▪ Nitrogen ▪ Argon or other inert gases	▪ Provides an inert atmosphere to prevent fires and explosions
Pyrometallurgy (Smelting) | Roasting	TRL ≥ 9	▪ Oxygen	▪ Facilitates the combustion processes
Oxidative Leaching	TRL 8 to 9	▪ Oxygen	▪ As an oxidative agent ▪ Enhance the reaction rates of leaching
Reductive Leaching	TRL 8 to 9	▪ Hydrogen ▪ Carbon monoxide ▪ SO_2	▪ As a reducing agent ▪ Donates electrons to metal ions, thereby reducing them during the leaching process
Direct Recycling	TRL > 6	▪ Supercritical CO_2	▪ As a solvent for extraction of electrolytes

Source: IeB analysis

Commercialization Challenges and Mitigation Strategies

Commercialization Challenges	Mitigation Strategies	Impact
01 High CAPEX and OPEX | Technological Barriers ▪ Initial setup and operating costs for battery recycling plants can be high due to the requirement of complex recycling technology ▪ The recycling process must evolve to handle diverse battery chemistries and designs	**Development of Advanced Recycling Technologies** ▪ Development of advanced recycling process, including pre-treatment processes ▪ Such developments include bioleaching, eutectic solvent/ water-based leaching, hybrid recycling processes, etc.	High
02 Collection and Transportation ▪ Efficient collection and transportation of spent batteries to recycling facilities is logistically challenging and costly ▪ Further safety concern during transportation of spent batteries, particularly because of the hazardous nature of some batteries	**Improved Collection Infrastructure** ▪ Implementation of more robust and widespread battery collection networks ▪ Partnerships between manufacturers, retailers, and government agencies can help facilitate the return of used batteries	Medium
03 Regulatory Challenges & Lack of Consumer Awareness ▪ Compliance with stringent environmental and safety regulations can increase operational complexity and costs ▪ Lack of consumer awareness and incentives for recycling	**Regulatory Incentives & Consumer Awareness** ▪ Support from Governments through subsidies, tax breaks, and stricter production and disposal regulations that encourage recycling ▪ Raising consumer awareness campaigns about the benefits of battery recycling	Medium

Legend: High, Medium, Low

Source: IeB analysis

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