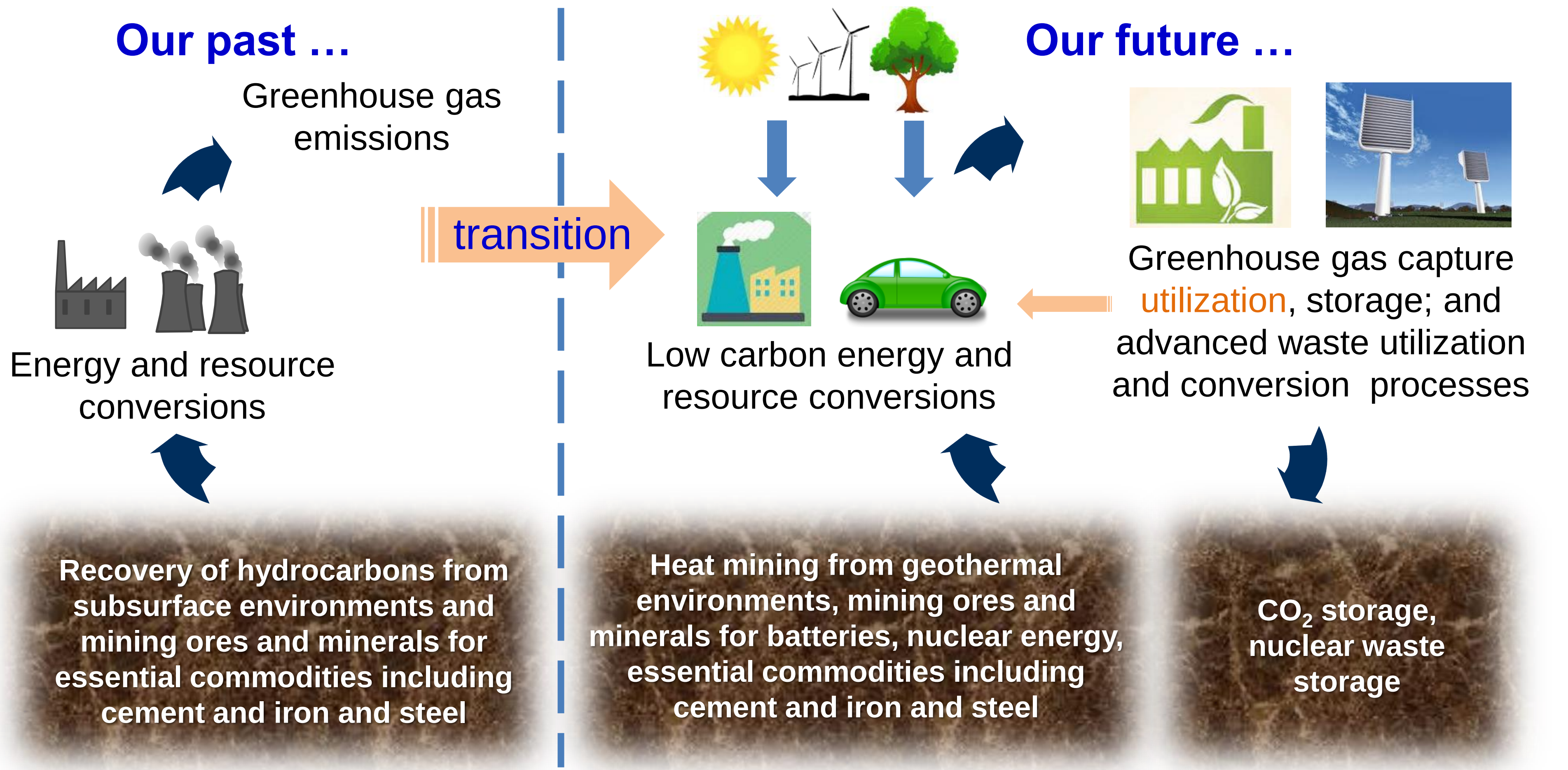
Integrated and Sustainable Pathways for CO_2 Capture and Mineralization with Recovery of High Value Metals and Filler Materials (INSPIRE)
DE – FE0032398 (Managed by Kara Zabetakis)

Greeshma Gadikota | Sustainable Energy and Resource Recovery Group | Civil and Environmental Engineering | Cornell University

Cornell Engineering

DOE FECM Project Update Meeting | August 7, 2024



How do we innovate while managing the need to meet our energy and resource demand in response to a changing climate?

INSPIRE Team

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Associate Professor

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Co-PI, MIT
Professor

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Chief Scientist

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Yuan Jiang, PNNL

Industry Partners
Novelis Inc | Nucor

INSPIRE Team at Cornell University

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PI, Cornell University
Associate Professor

Porus Jadhav
PhD student
Cornell University

Dhruv Mehta
PhD student
Cornell University

INSPIRE Aim and Objectives

The ***aim*** of INSPIRE is to develop molecularly integrated CO_2 capture and mineralization pathways with inherent recovery of high value metals using multifunctional solvents and electrochemically mediated transformations.

The ***two primary objectives*** of the INSPIRE technology are to:

(i) demonstrate the recovery of acids (alongside $CaCO_3$, $Mg(OH)_2$ and H_2) from industrial wastewater for recovering Fe- and Al-rich solids followed by the use of CO_2-bearing solids for recovering Ca- and Mg-carbonates, and electrochemical separation of base metals such as Ni, Zn, Co as carbonates, and Cu in Mode 1 in alkaline industrial residues bearing more than 5 wt% of (non-carbonate) Al, Fe, Mg, and Ca-components,

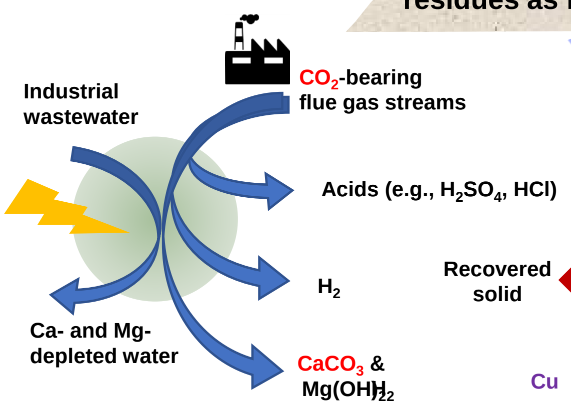
(i) develop an integrated approach for the recovery of Ni, Zn, Co as carbonates, Cu metal, and solid carbonate product bearing Ca, Mg, Fe, or Al in Mode 2 in alkaline industrial residues where a single metal component is dominant (e.g., Al is at least 5-fold greater compared to other major elements such as Fe, Mg, Ca).

INSPIRE Mode 1: Metal Recovery and Carbon Mineralization

Schematic representation of the INSPIRE technology for selective metal recovery integrated with CO_2 capture and conversion.

(A) Mode 1: Compositions of Al, Fe, Ca, Mg exceed 5 wt%

Photo-Assisted Electrochemical Recovery of Acids, H_2, $CaCO_3$, and $Mg(OH)_2$ via CO_2 capture and mineralization



(2) $2RNHCO_2^{-}RNH_3^{+} + M'O = [M(RNH_2)_4, CO_3], CO_2$

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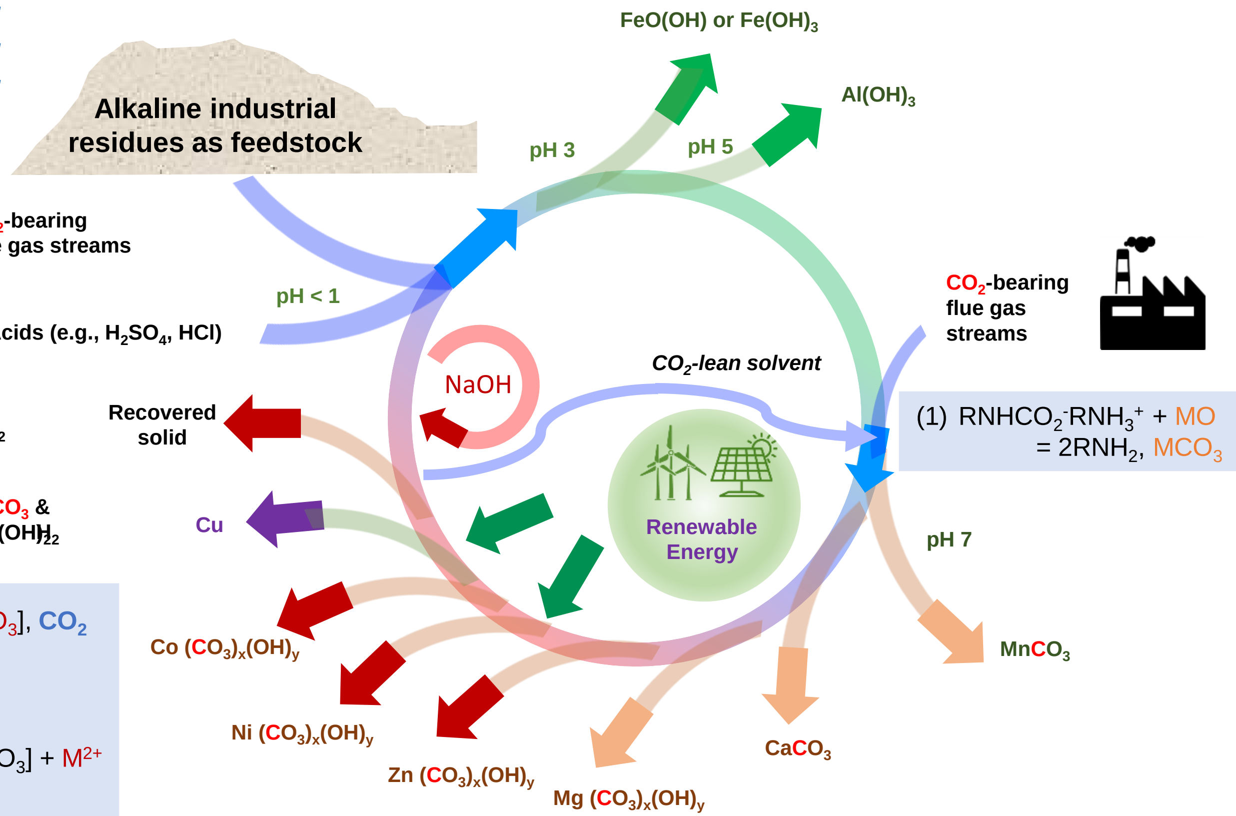
(4) $[M(RNH_2)_4, CO_3] + Cu^{2+} = [Cu(RNH_2)_4, CO_3] + M^{2+}$

(5) $M^{2+} + Na_2CO_3 + H_2O = M(CO_3)_x(OH)_y + NaOH$

Integrated CO_2 capture and mineralization for recovering high value metals



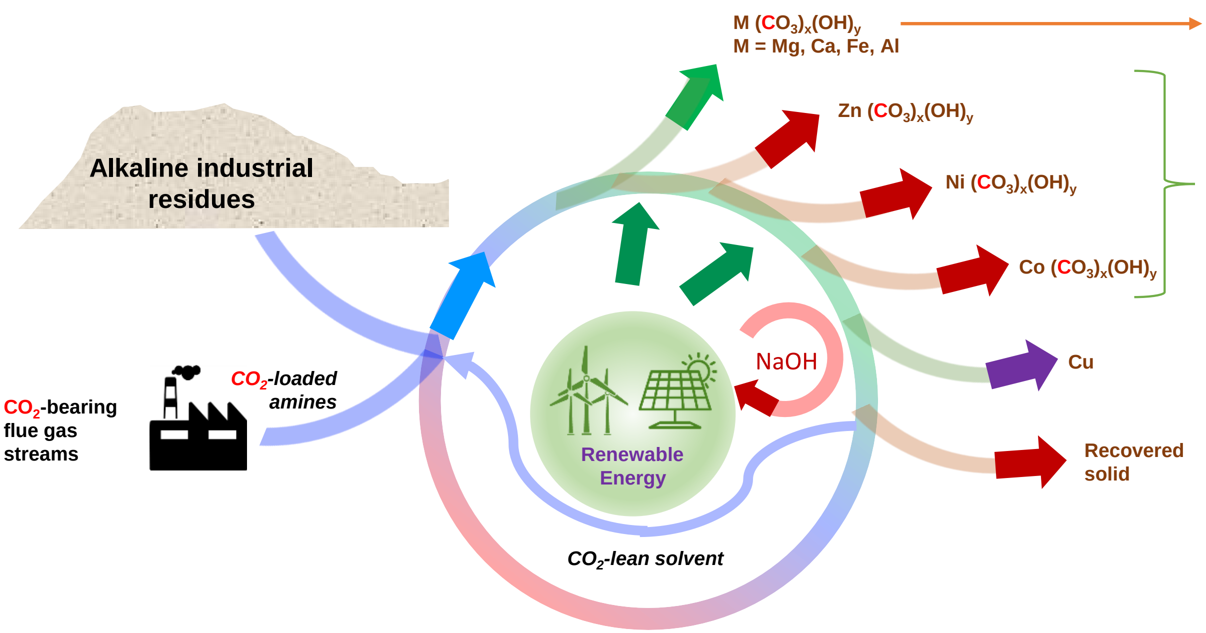
Mode 1 is applied for alkaline residues with Al, Fe, Ca, and Mg content exceeding 5 wt%

INSPIRE Mode 2: Metal Recovery and Carbon Mineralization

Schematic representation of the INSPIRE technology for selective metal recovery integrated with CO_2 capture and conversion.

(B) Mode 2: Compositions of one of the following elements: Al, Fe, Ca, Mg is at least 5 fold greater compared to other elements,

Integrated CO_2 capture and mineralization for recovering high value metals



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(4) $[M(RNH_2)_4, CO_3] + Cu^{2+} = [Cu(RNH_2)_4, CO_3] + M^{2+}$

(5) $M^{2+} + Na_2CO_3 = \underline{M(CO_3)_x(OH)_y}$

Mode 2 is applied for alkaline residues with Al, Fe, Ca, and Mg content at least 5 fold greater compared to other elements

Key Tasks and Subtasks

	Task & Subtasks	Year 1 Q1	Year 1 Q2	Year 1 Q3	Year 1 Q4	Year 2 Q1	Year 2 Q2	Year 2 Q3	Year 2 Q4
1	**Project Management and Planning (including kick-off meeting)**	1.1							
2	**Material characterization, solvent synthesis and identify solvents**								
	2.1 Characterize chemical and morphological features of alkaline materials	2.1							
	2.2 Synthesize third generation solvents and determine CO_2 capture behavior		2.2						
	2.3 Determine the appropriate solvents based on thermodynamics and kinetics			2.3					
3	**Metal recovery using CO_2-bearing solvents and electrochemical approaches**				3.1S				
4	**Extractive carbon mineralization for Mn, Ca, and Mg recovery**				4.1				
5	**Experimental setup for electromediated stripping, recovery, and solvent regeneration**				5.1				
6	**Develop frameworks for techno-economic assessments and life cycle analyses**								
	6.1 Develop frameworks for process-scale analyses and TEA				6.1				
	6.2 Develop a framework to assess life cycle impacts				6.2				
C1	**Engage K-12 students in science education and communication**				C1.1				
7	**Recover Al – and Fe – bearing solids**					7.1			
8	**Recover Mn-, Ca-, and Mg-bearing carbonates**								
	8.1 Phase separation, compositional analyses, quantification of CO_2 capture and mineralization						8.1		
	8.2 Produce Ca-carbonate via integrated CO_2 capture and conversion								8.2
9	**Electromediated critical metal stripping, recovery, and solvent regeneration**								
	9.1 Selective Ni stripping by Cu^{2+} ion substitution						9.1		
	9.2 Selective Ni and Co stripping by Cu2+ substitution and metal recovery by carbon mineralization							9.2	9.3
10	**Conduct whole system TEA and LCA**								
	10.1 Evaluate the overall techno-economic impacts								10.1
	10.2 Assess whole system life cycle impacts								10.2
C2	**Expand internship opportunities for underrepresented students and women**								C2.1
C3	**Engage women, rural communities, and general public through symposia organization and presentations**								C3.1

Milestones

	Type	Milestones
1. Project Management	Y1, Q1	1.1. Develop the communication plan and other deliverables and organize the project kick-off meeting
2. Material characterization, solvent synthesis and identification for metal recovery	Y1, Q1	2.1. Quantify the chemical compositions and morphological features of the alkaline industrial residues from secondary aluminum processing and steel making
	Y1, Q2	2.2. Synthesize third generation solvents and quantify CO_2 capture behavior
	Y1, Q3	2.3. Identify 2-3 appropriate solvent systems
3. Metal recovery	Y1, Q4	3.1. Leach > 60% of Ni and > 80% of Ca from select alkaline industrial residues - SMART; Go – No Go Milestone
4. Extractive carbon mineralization of Mn, Ca, and Mg recovery	Y1, Q4	4.1. Achieve selective separation of Mn, Ca, and Mg-carbonates
5. Experimental setup for electromediated separation	Y1, Q3	5.1. Demonstrate a working experimental setup for separating metals of interest
6. Develop frameworks for TEA and LCA	Y1, Q4	6.1. Complete the TEA framework for INSPIRE
	Y1, Q4	6.2. Complete the LCA framework for INSPIRE
7. Recover Al- and Fe-bearing solids	Y2, Q1	7.1. Achieve the precipitation of Al- and Fe-rich solids from select alkaline industrial residues with yields > 60% - SMART
8. Recover Mn-, Ca-, and Mg-bearing carbonates	Y2, Q2	8.1. Recover > 90% of select solvents after Mn,Ca, and Mg-carbonate precipitation - SMART
	Y2, Q4	8.2. Produce > 10 kg of $CaCO_3$ based on optimal conditions - SMART
9: Electromediated metal recovery	Y2, Q3	9.1 Selective electrochemical recovery of Ni, Co, Zn-carbonates
	Y2, Q4	9.2. Develop solvent regeneration strategy
10: Conduct whole system TEA and LCA	Y2, Q4	10.1. Final TEA for the fully integrated INSPIRE technology
	Y2, Q4	10.2. Final LCA for the fully integrated INSPIRE technology

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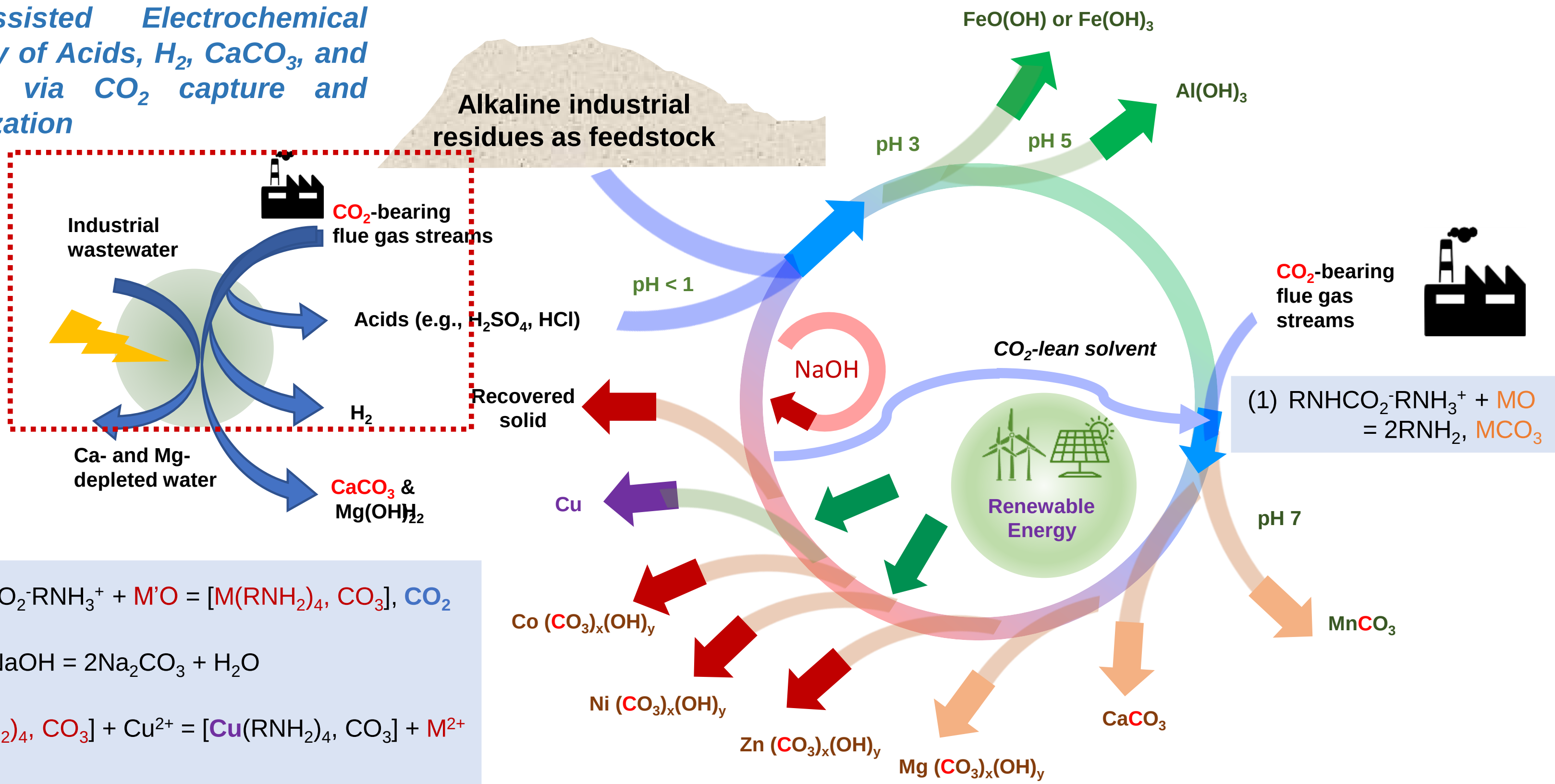

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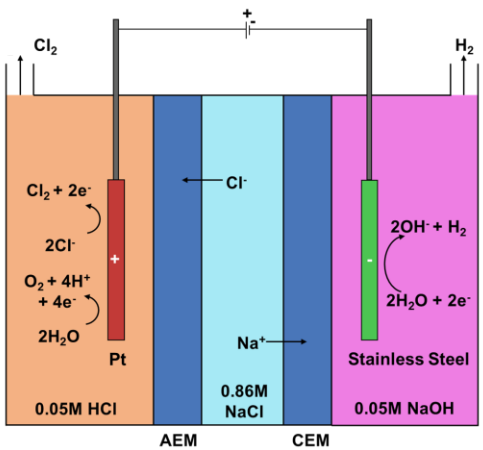
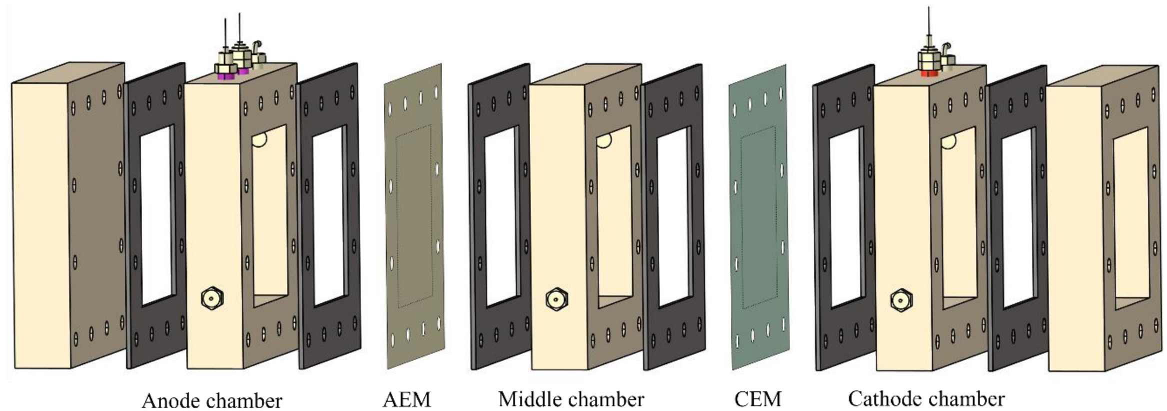
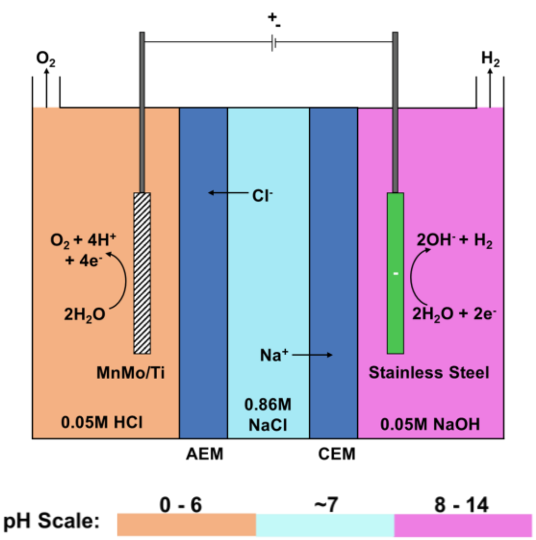
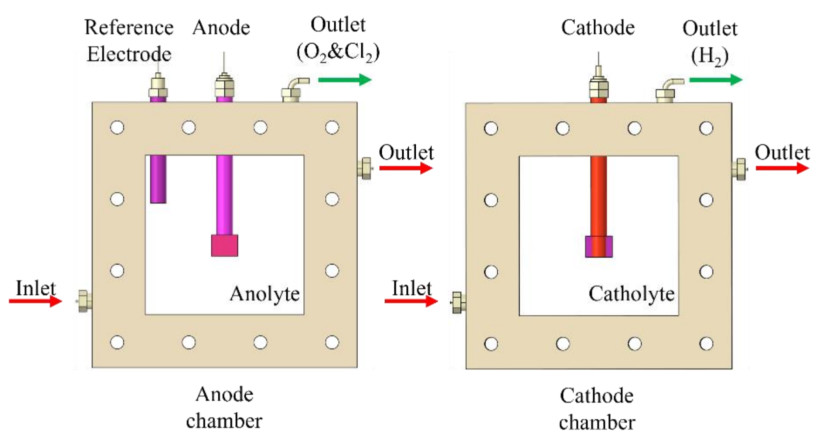
Advances in Direct Electrolysis of Brine

How can we produce acids, bases, H_2, and O_2 by harnessing brine and electricity while suppressing Cl_2 gas evolution?







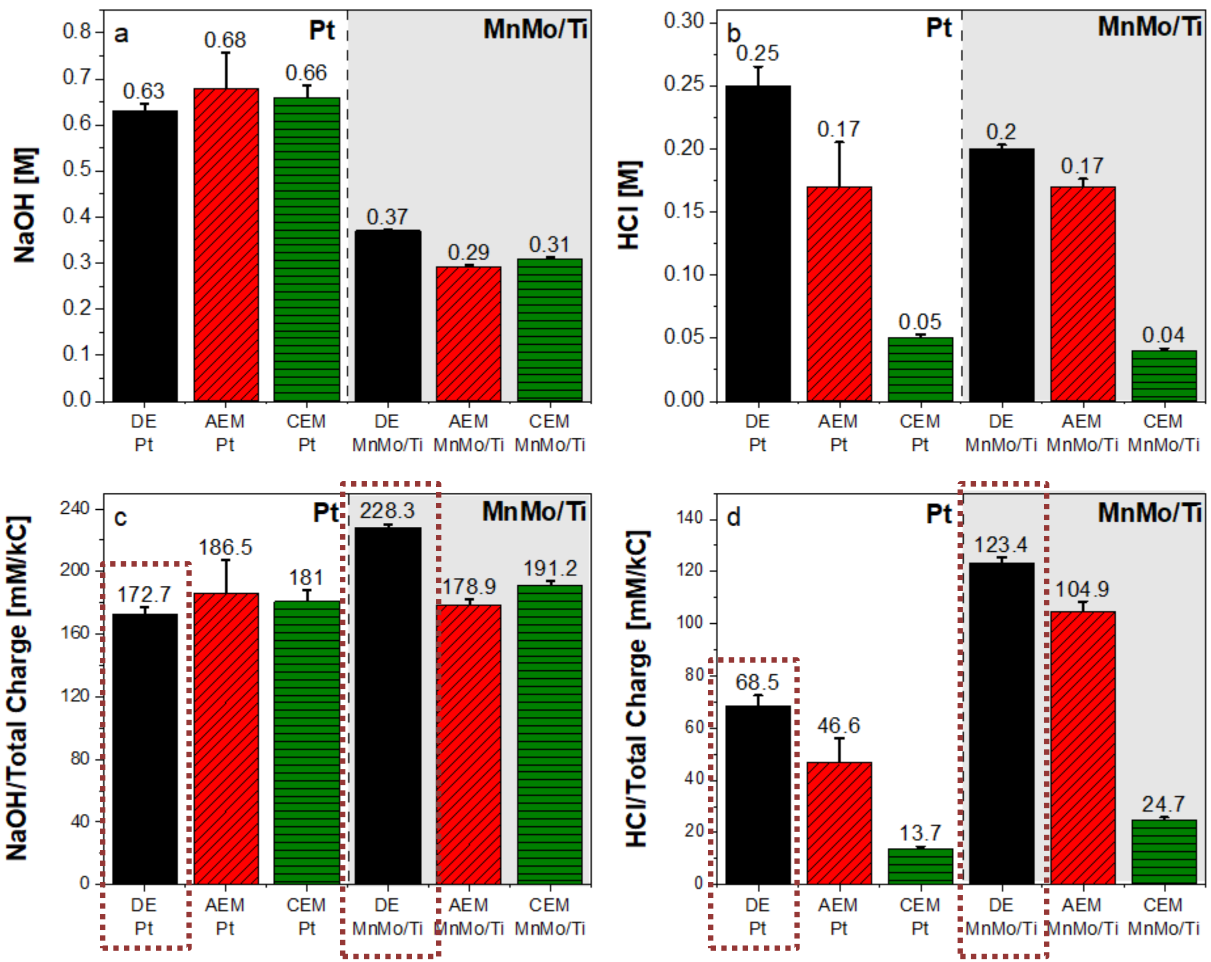


What is the effectiveness of using MnMo/Ti electrode for suppressing Cl_2 gas evolution?

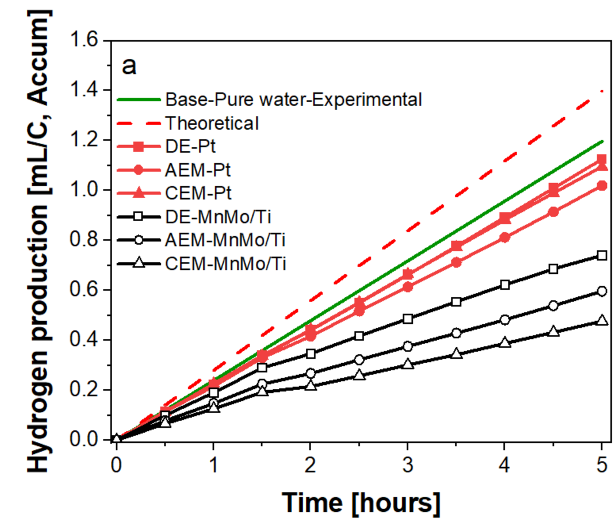
Kim, Lu, Ochonma, and Gadikota, ***ACS Energy and Fuels***, 2024 (Invited Article)

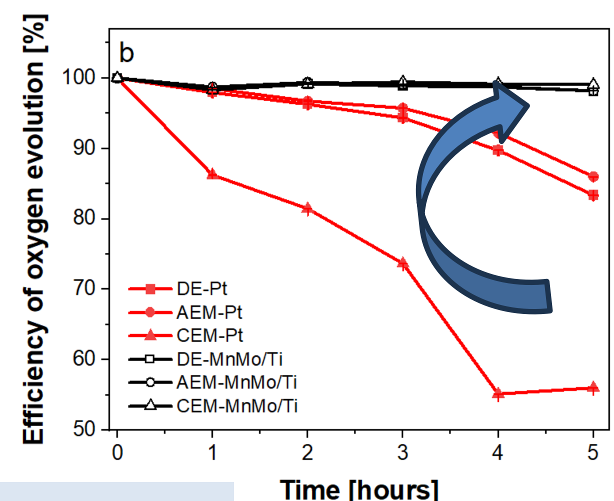
Advances in Direct Electrolysis of Brine

NaOH and HCl yields normalized to charge are higher using MnMo/Ti vs. Pt electrode



Lower H_2 yield using MnMo/Ti electrode





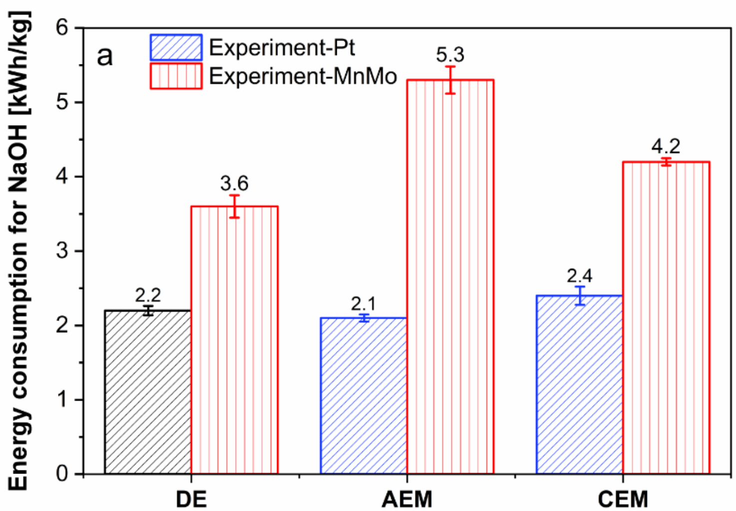
O_2 gas evolution is enhanced using using MnMo/Ti electrode

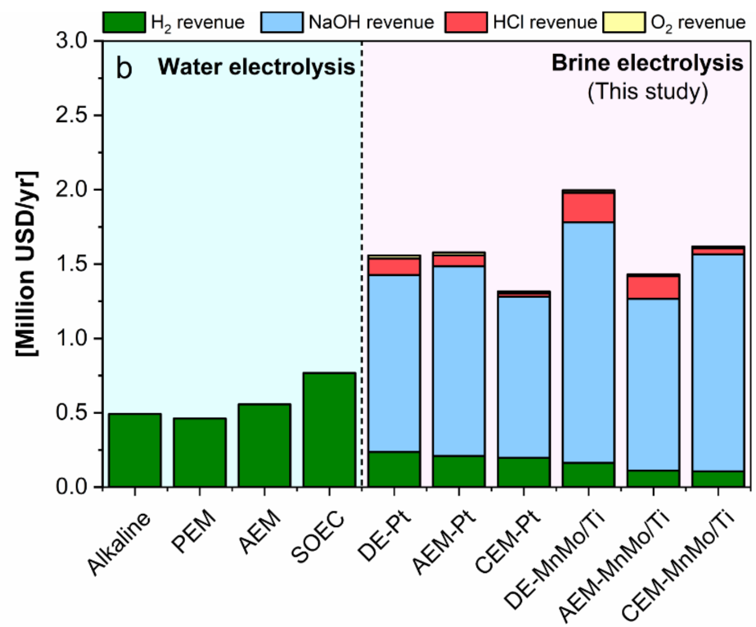
Advances in Direct Electrolysis of Brine

Calculated oxygen evolution efficiencies using various electrodes and membrane configurations

Anode	System	Total Coulomb [C]	Cl_2 [mol]	Cl_2 Evolution Efficiency [%]	O_2 Evolution Efficiency [%]
Pt	DE	3,647	0.0031	16.6	83.4
Pt	AEM	3,647	0.0026	13.4	86.0
Pt	CEM	3,647	0.0083	44.0	56.0
MnMo/Ti	DE	1,621	0.0002	1.8	98.2
MnMo/Ti	AEM	1,621	0.0002	1.8	98.2
MnMo/Ti	CEM	1,621	0.0001	0.9	99.1

Significant decrease in Cl_2 gas evolution efficiency and enhancement in O_2 gas evolution efficiency using MnMo/Ti electrode compared to Pt electrode





Energy consumption for producing NaOH is higher using MnMo/Ti electrode but economics are more favorable with brine electrolysis compared to water electrolysis!

Ongoing work involves developing novel electrodes for direct electrolysis!

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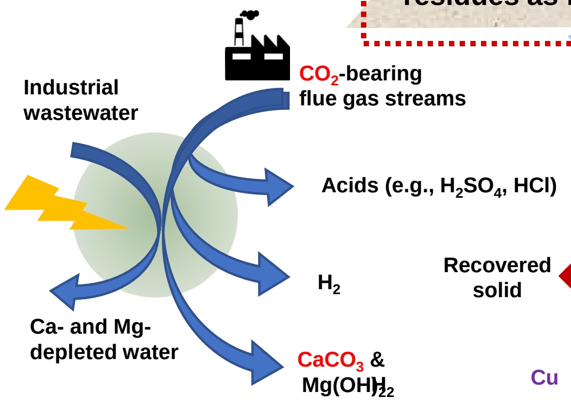
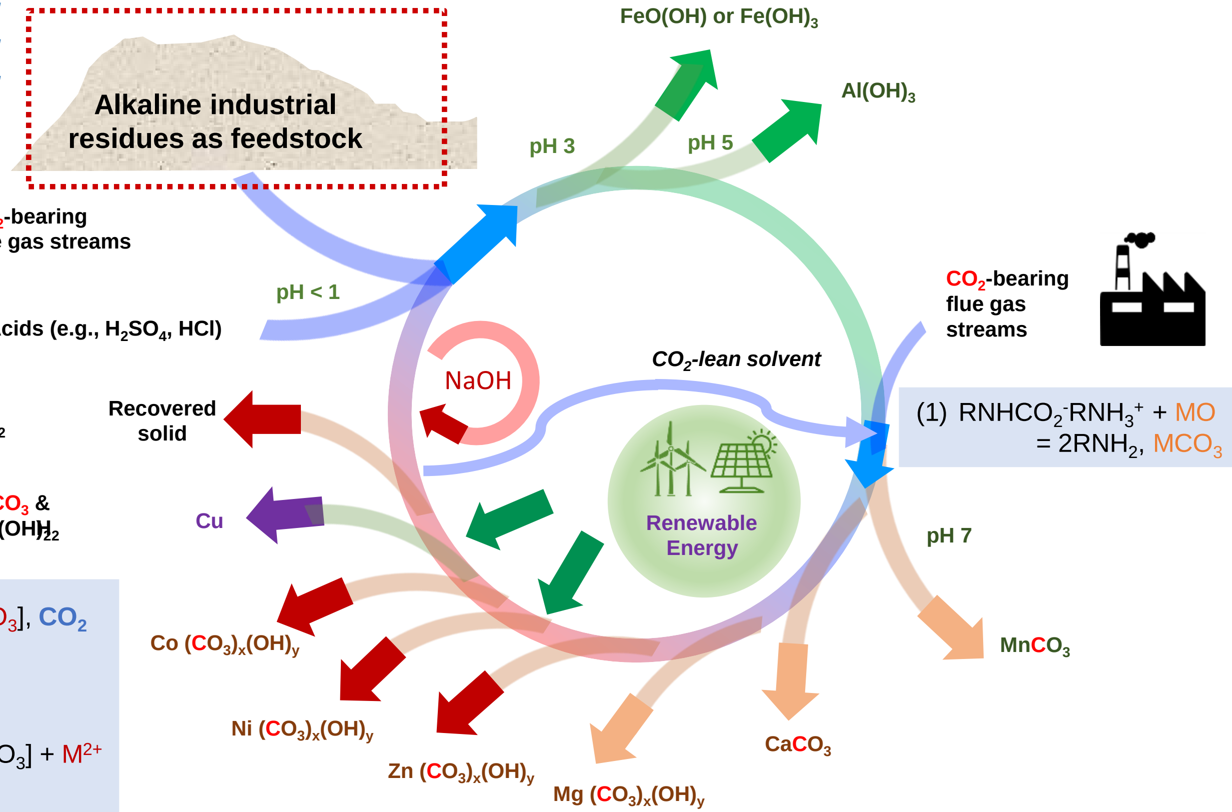


Integrated CO_2 capture and mineralization for recovering high value metals



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Mode 1 is applied for alkaline residues with Al, Fe, Ca, and Mg content exceeding 5 wt%

Milestone 2.1: Quantify the chemical compositions and morphological features of the alkaline industrial residues from secondary aluminum processing and steel making

Major Elements	EAF Steel Slag Wt.(%)	EAF Ladle Slag Wt.(%)
CaO	**33.8**	**33.4**
MgO	**11.6**	**31.3**
Na_2O	0.04	0.08
K_2O	0.04	0.1
Al_2O_3	**7.23**	**11.2**
Fe_2O_3	**21.4**	**5.35**
SiO_2	**18**	**9.66**
MnO	4.68	0.92
ZnO	--	--
Cr_2O_3	1.4	0.11
NiO	--	--
CuO	--	--

Compositions of
Ca- and Mg-bearing content
exceeds 40 %.

Ultramafic mine tailings can contain ~ 40 – 50% SiO_2, and 30 – 40% Mg-oxide, 5 – 15% Fe-oxides in addition to ~ 100 – 2000 ppm of Ni

Black Dross

Major elements	Wt (% oxides)
SiO_2	**12.29**
TiO_2	2.381
Al_2O_3	**38.40**
FeO*	**1.11**
MnO	0.978
MgO	**11.77**
CaO	**2.10**
Na_2O	13.44
K_2O	9.13
P_2O_5	0.138
LOI (%)	-0.17
Total	99.13

White Dross

Major elements	Wt % (oxides)
SiO_2	**n.d.**
TiO_2	0.089
Al_2O_3	**104.22**
FeO*	**0.28**
MnO	0.213
MgO	**3.90**
CaO	**0.15**
Na_2O	0.11
K_2O	0.22
P_2O_5	0.011
LOI (%)	-10.69
Total	99.12

Compositions of
Ca- and Mg-bearing content
is less than 20 %.

Cu ~ 200 – 500 ppm;
Ni ~ 50 – 100 ppm;
Cr ~ 50 – 200 ppm

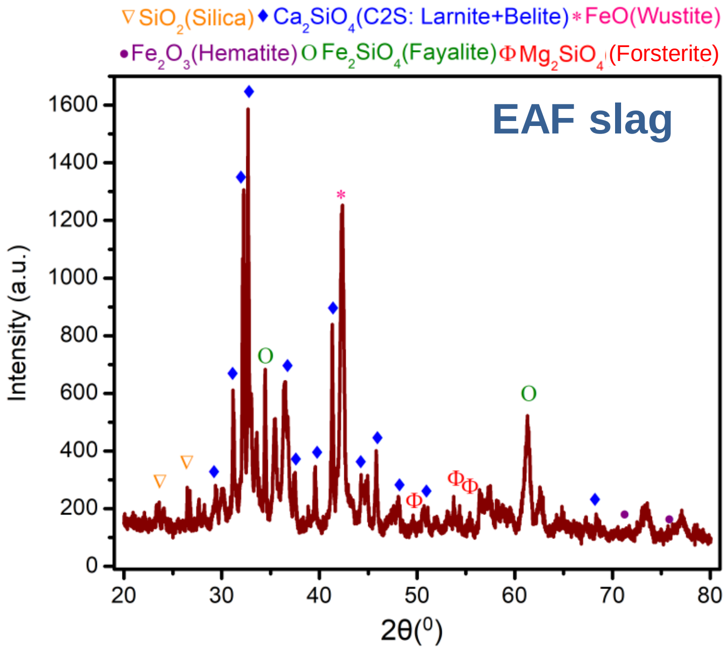
Milestone 2.1: Quantify the chemical compositions and morphological features of the alkaline industrial residues from secondary aluminum processing and steel making

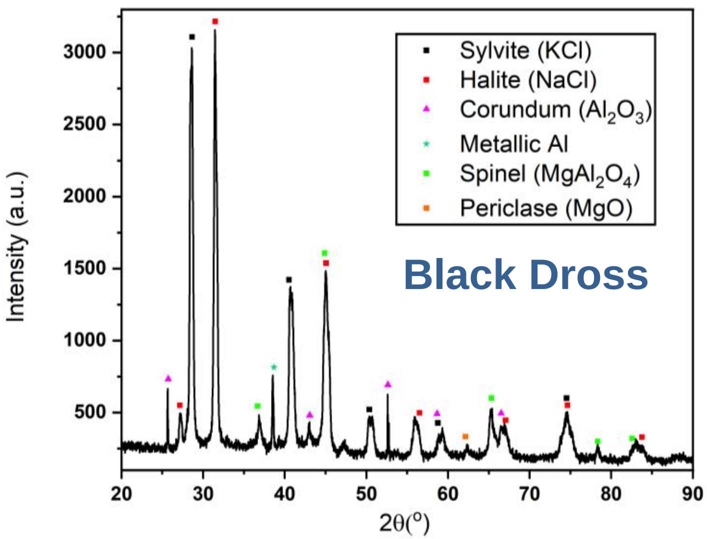
- **Evidence of Ca-, Mg-, and Fe-silicates, silica, and iron oxide phases in EAF slags**

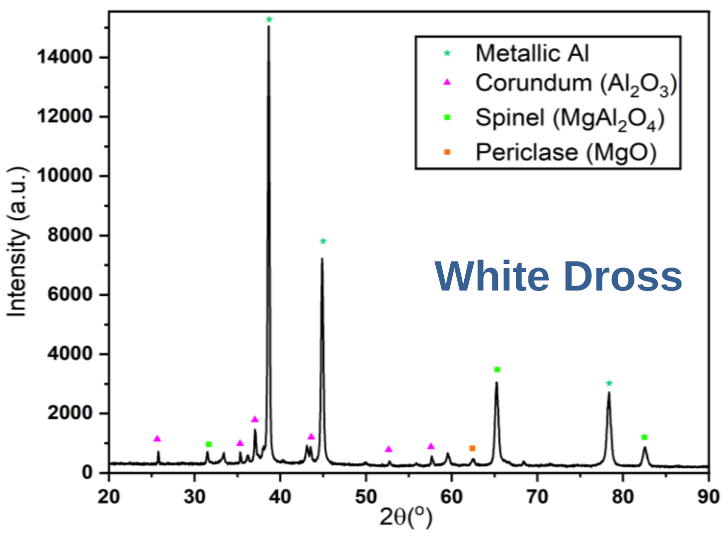
- **Evidence of soluble KCl and NaCl phases in addition to insoluble Al_2O_3, Al, MgO, and $MgAl_2O_4$ phases in black dross**

- **Evidence of metallic Al, Al2O$_3$, $MgAl_2O_4$, and MgO phases in white dross.**

- **Significant differences in the compositions of the slags and dross materials motivate advances in customized pathways to recover high value products**







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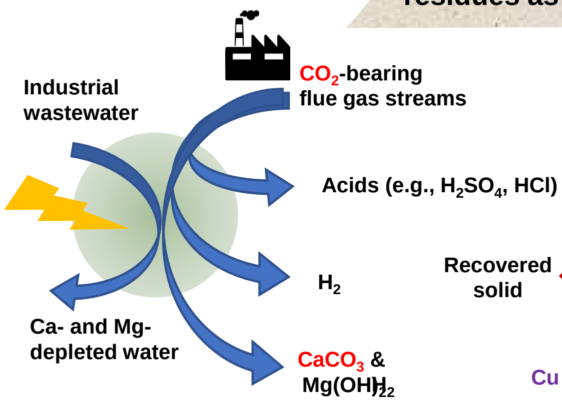
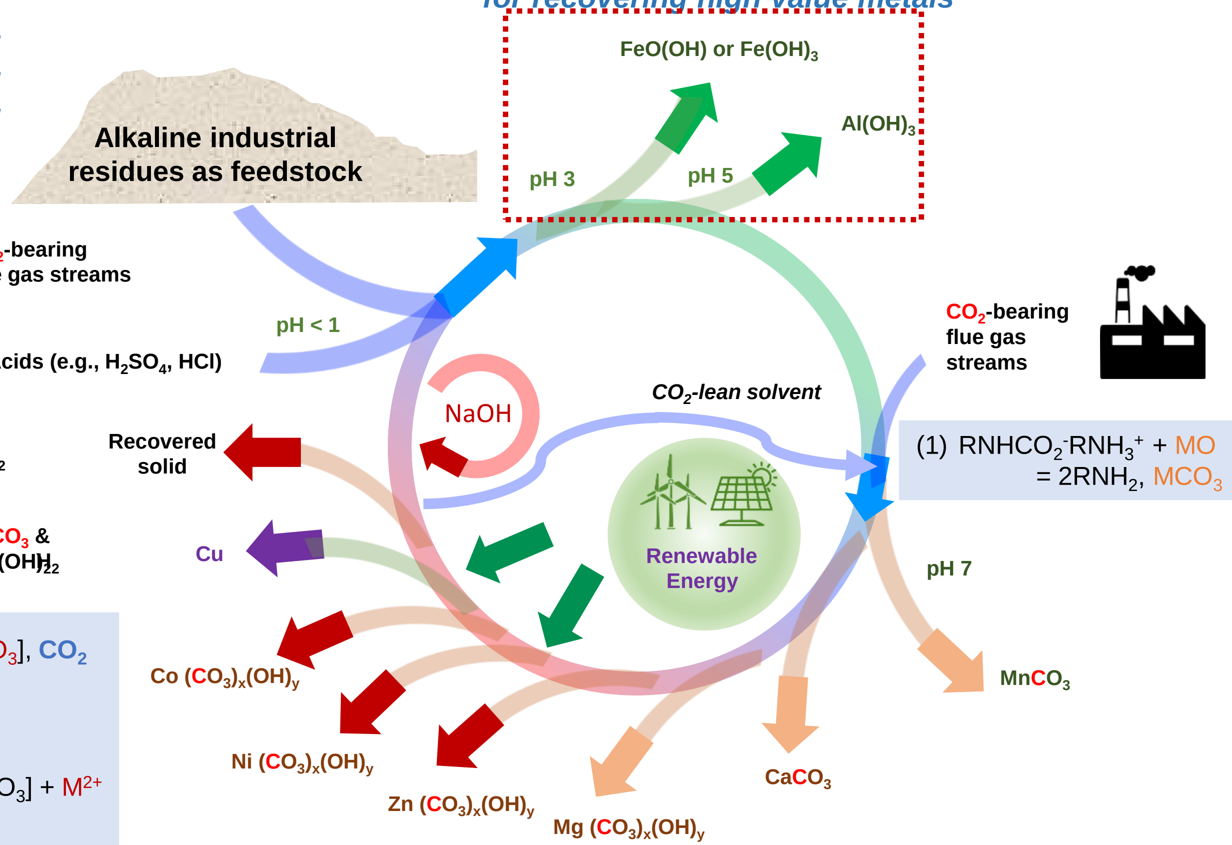


Integrated CO_2 capture and mineralization for recovering high value metals



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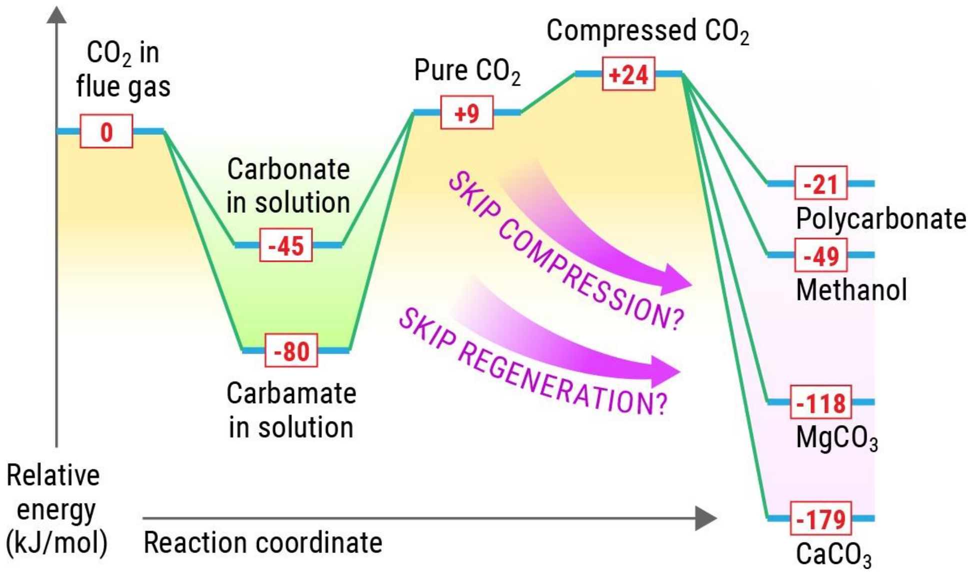
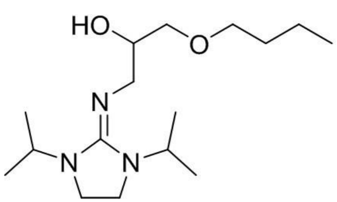
Task 2. Material Characterization, Solvent Synthesis, and Determination of Key Solvents

Water-lean solvents are a prime medium for integration of capture *and mineralization and metal recovery.*



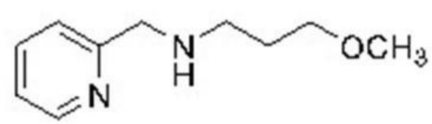
- Overall process is catalytic with respect to solvent
- Catalytic exothermic mineralization offsets endothermic solvent regeneration
- Bypasses CO_2 compression
- PNNL’s single-component water-lean solvents are tunable bi-dentate ligands for cation chelation

Alkanolguanidines



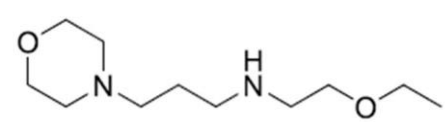
e.g. 1-BEIPADIP-2-BOL

Aminopyridines (AP)



e.g. 2-MeOEAMP

Diamines (DA)



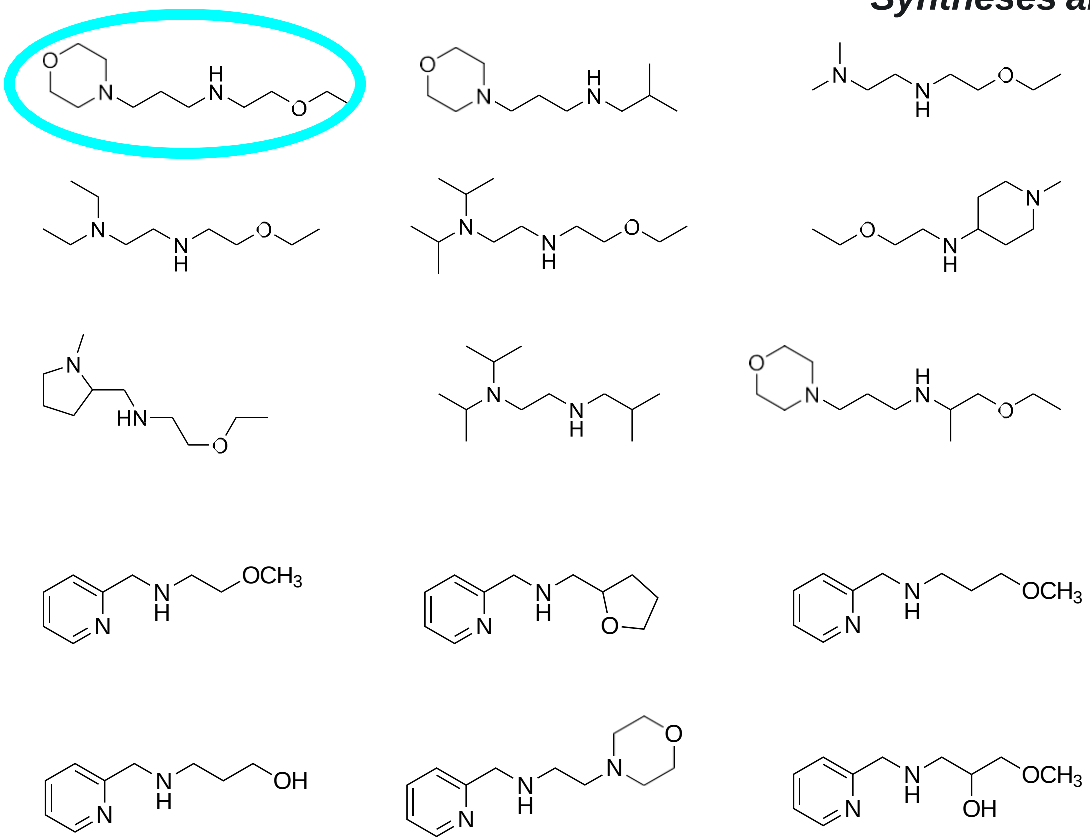
e.g. EEMPA: N-(2-ethoxyethyl)-3-morpholinopropan-1-Amine

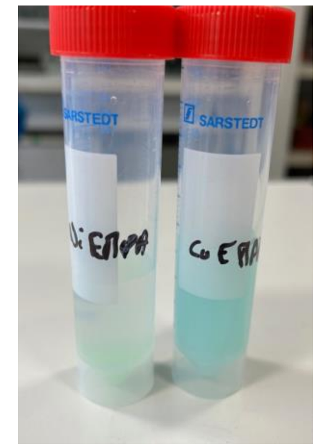
Brickett et al. Chem. Sci., **2022**,13, 6445-6456

Task 2. Material Characterization, Solvent Synthesis, and Determination of Key Solvents

Towards Designing Candidate Solvents: **PNNL has libraries of available solvents from three classes to select from and reduced-order models enable us to quickly design and synthesize solvents with tailored properties (as needed).**

Syntheses are designed for use of off-the-shelf reagents.

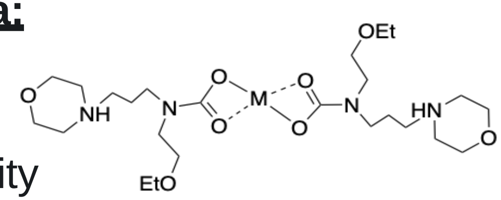




2-EEMPA w/wo CO_2 + Ni and Co

Design Criteria:

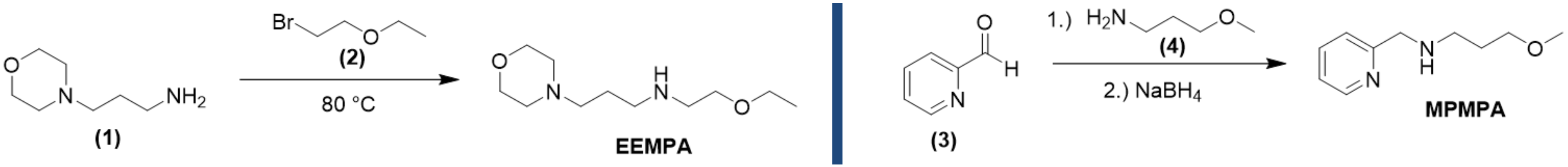
- Hardness
- pKa
- Nucleophilicity
- Conductance
- Binding enthalpy
    - -60 to -85 kJ/mol



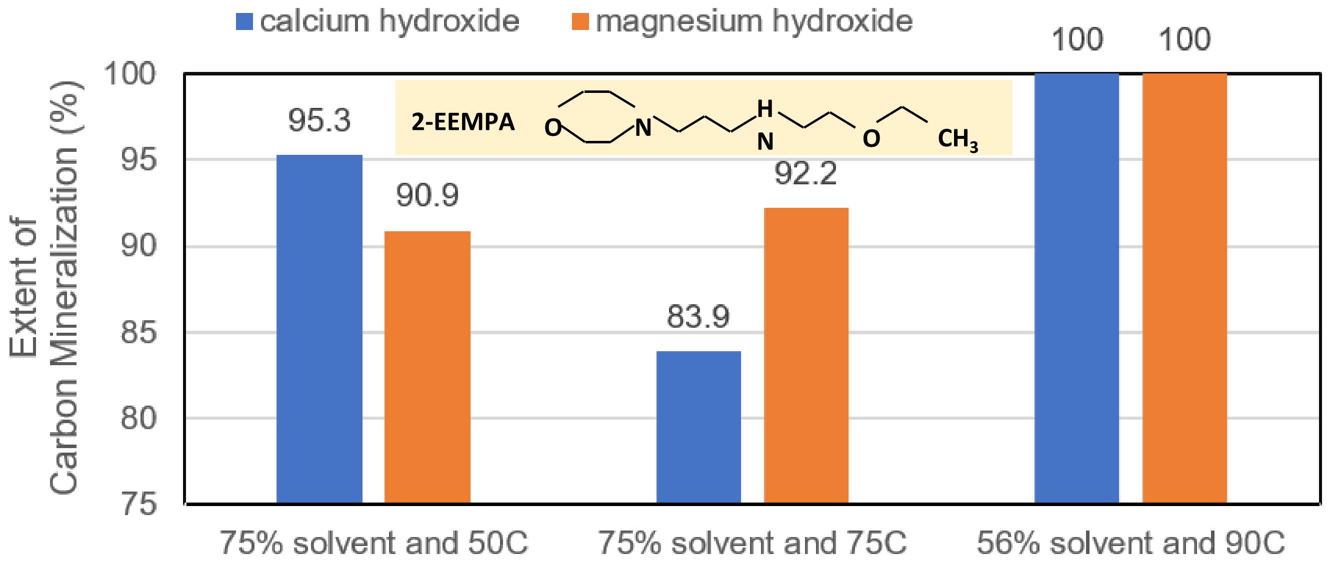
Cantu et. al. *ChemSusChem.*, **2020**, DOI: 10.1002/cssc.202000724.

Milestone: 2.2: Synthesize third generation solvents and quantify CO_2 capture behavior and **2.3:** Identify 2 – 3 appropriate solvent systems

Water – lean solvents developed at PNNL



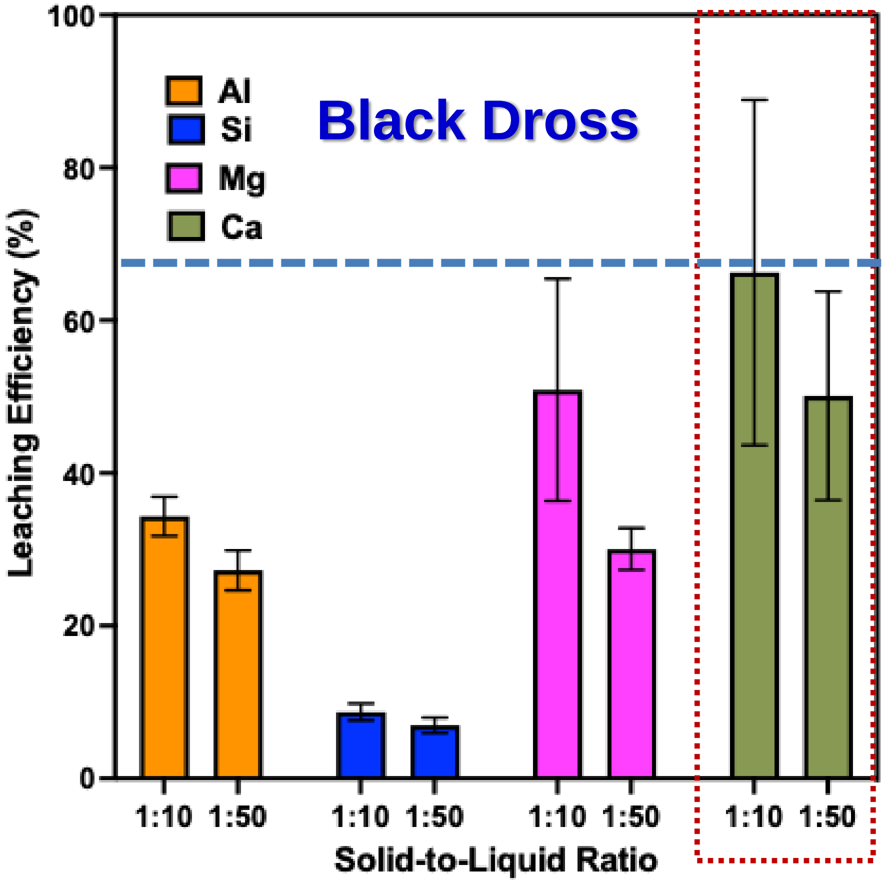
Evidence of the carbon mineralization of $Ca(OH)_2$ and $Mg(OH)_2$ using 2-EEMPA in gas – liquid – solid mode. Experimental conditions include pCO_2 of 1 atm, 15 wt% solid in a well-stirred slurry environment



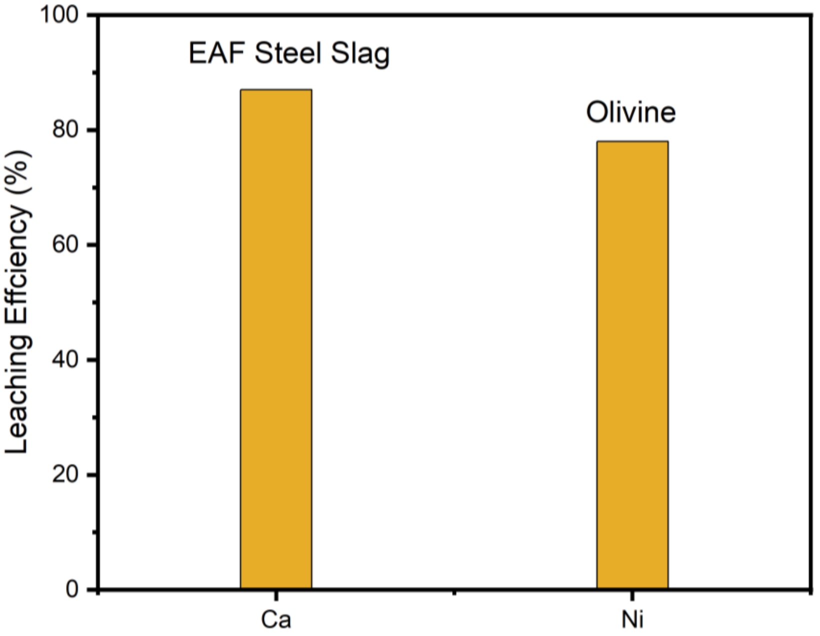
The team will build on these studies for the selective separation of Mn, Ca, and Mg-bearing carbonates in INSPIRE.

Milestone 3.1: Leach > 60% of Ni and > 80% of Ca from select alkaline industrial residues - SMART; Go – No Go Milestone

Inorganic acid driven leaching



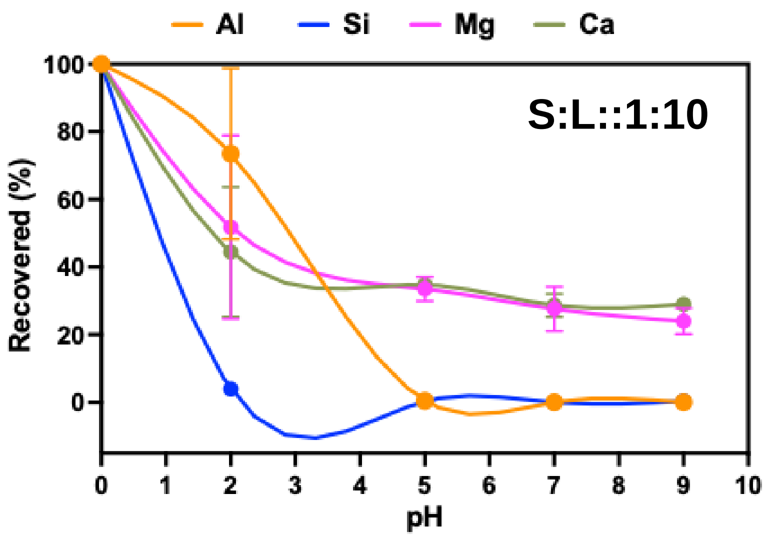
Dissolution of black dross in a 2 M HCl solution at 50 °C and 300 rpm for two hours

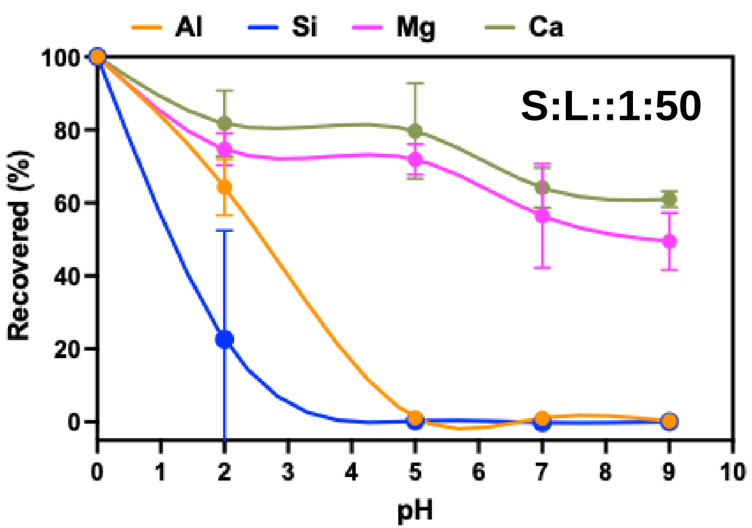


87% leaching of Ca in EAF slag and **78% leaching of Ni** in olivine was observed using 1.5 M HCl on stirring at 300 rpm at 40 °C for 60 minutes.

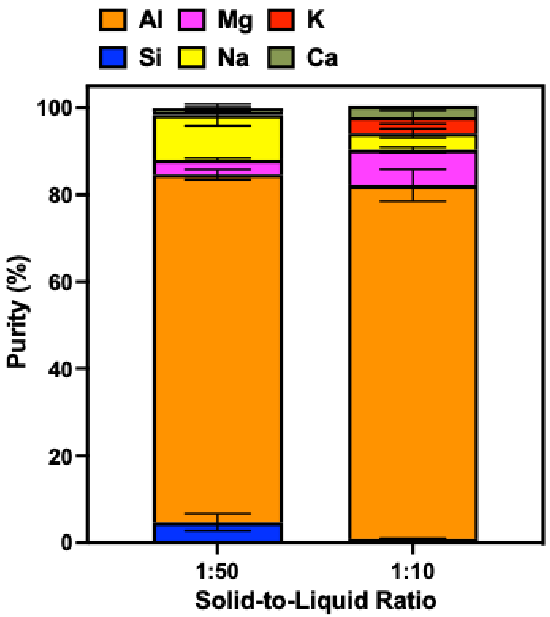
Task 3. Metal Recovery

Decreasing concentrations => precipitation of dissolved ions



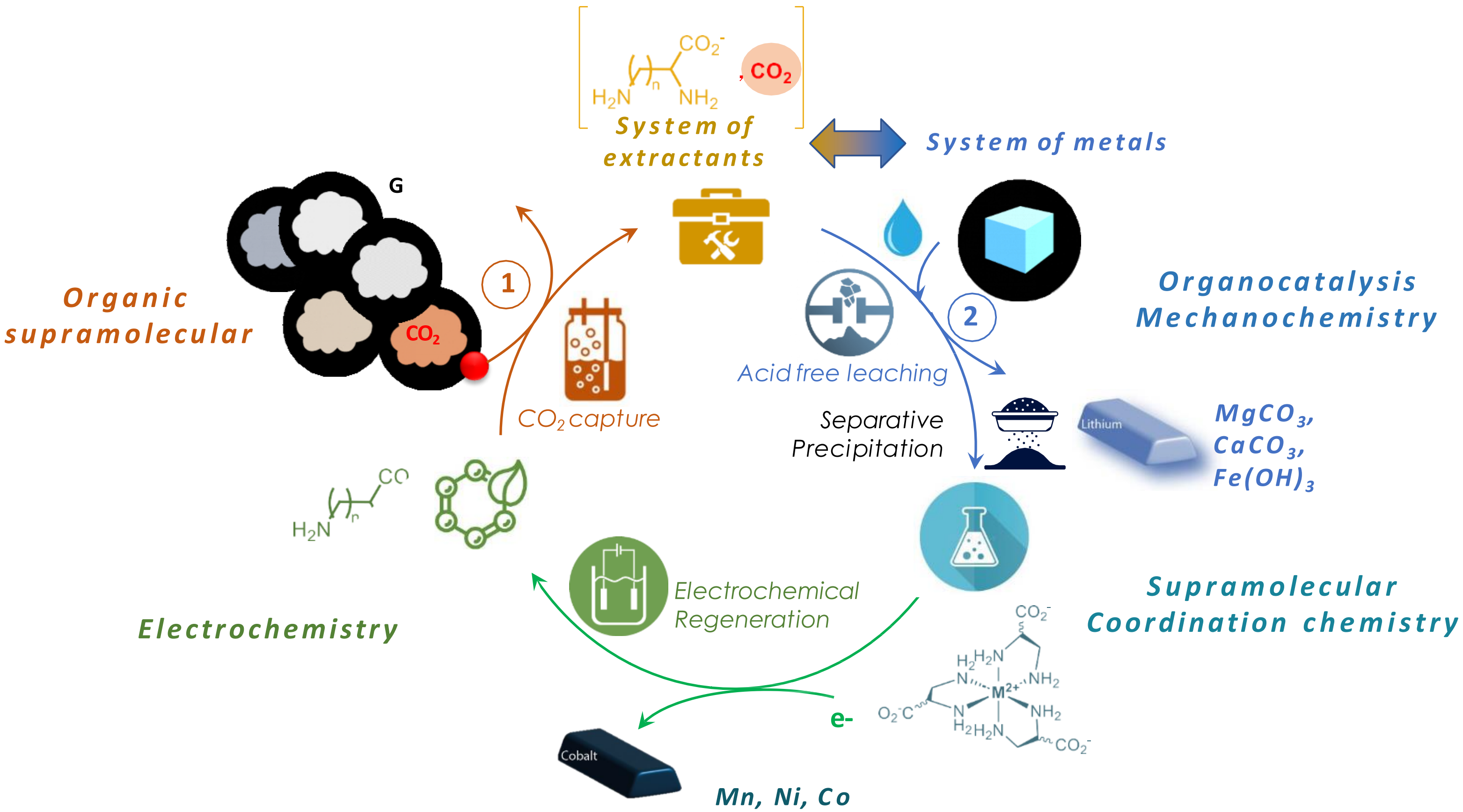


- Gradual increase in the pH from 2, 5, 7, and 9 using sodium hydroxide (NaOH) results in the precipitation of various products. Near complete recovery of Si and Al is achieved.
- High content of Al in the solid recovered at pH 5 is noted.
- Similar quantity of Al is noted in the recovered product with S:L::1:50 and 1:10



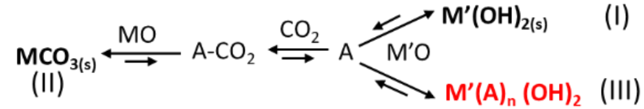
Task 3. Metal Leaching using CO_2-Bearing Solvents and Electrochemical Approaches

Acid – free leaching and metal recovery



Advance sustainable pathways to recover energy critical metals by harnessing selective chelation ability of specific ligands.

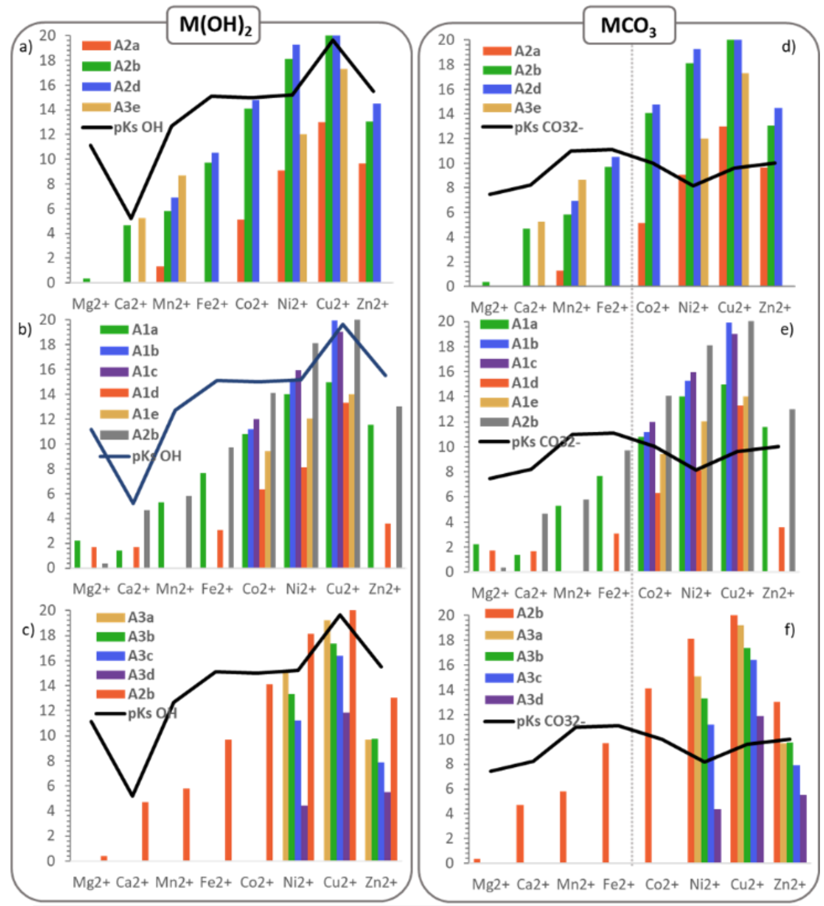
Task 3. Metal Leaching using CO_2-Bearing Solvents and Electrochemical Approaches

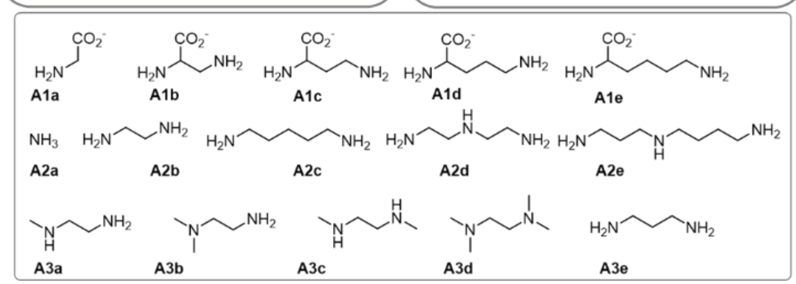


Harness differences in the binding affinities of various metals for ligands to drive metal separations

Thermodynamic constants of competing solvent-metal complexation (columns) vs hydroxylation (black line) (a-c) and carbonation (d-f) (black line).

Bottom: water-lean solvent models (A3), polyamines (A2) and aminoacid solvents (A1) reported in the literature.

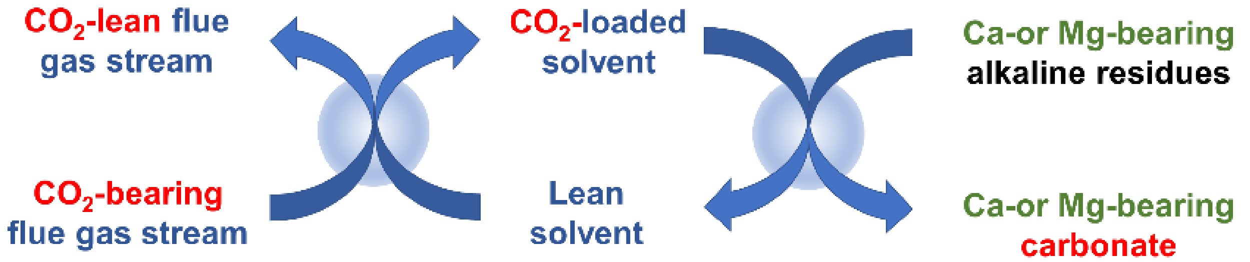




Next steps: Advance experimental efforts to determine the effectiveness of various solvents in effectively capturing energy relevant metals.

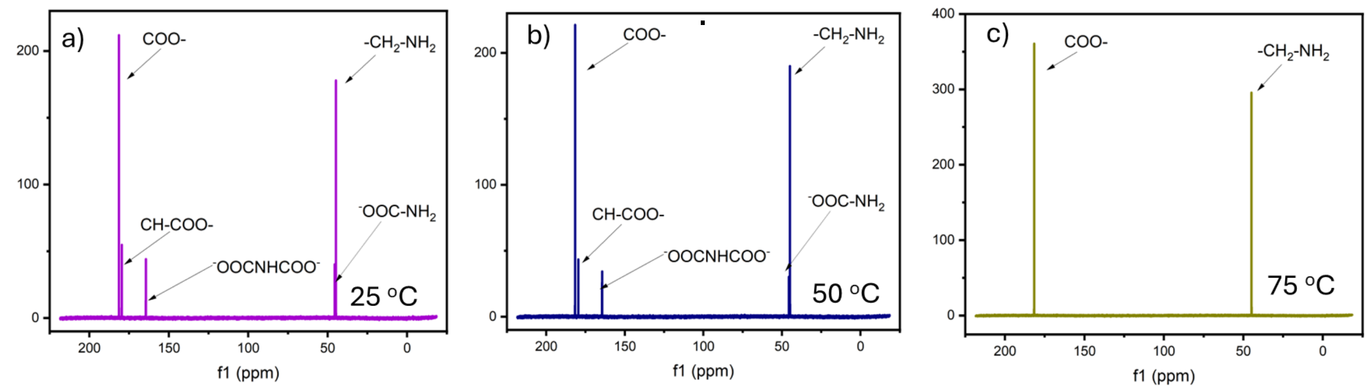
Task 4. Extractive carbon mineralization of Mn, Ca, and Mg recovery

Milestone 4.1. Achieve selective separation of Mn, Ca, and Mg-carbonates



How do we quantify solvent regeneration?

^{13}C NMR comparison for solvents recovered after mineralization of $Ca(OH)_2$ using CO_2 pre-loaded 2.5 M Na-Glycinate at: a) 25^0C, b) 50^0C and c) 75^0C.



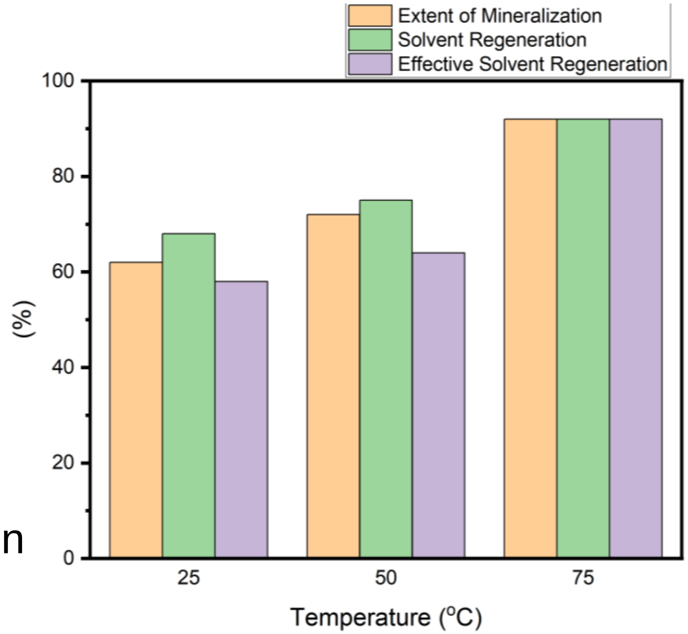
$$H_2NCH_2COO^- + CO_2 \rightleftarrows {}^-OOCNCH_2COO^- + H^+$$

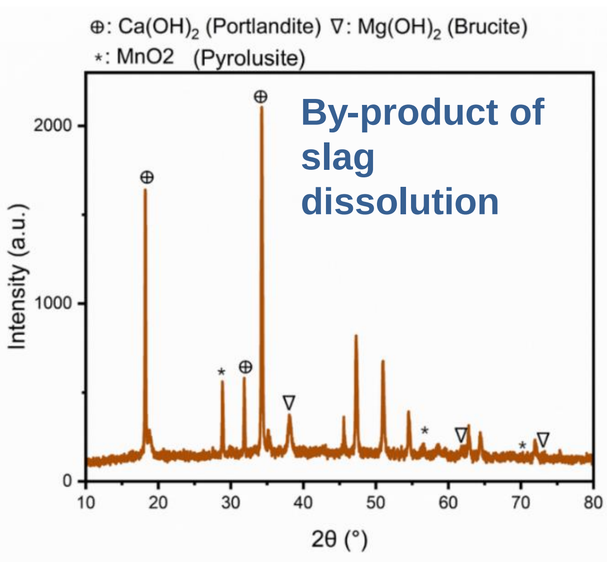
$${}^-OOCNCH_2COO^- + H_2O \rightleftarrows H_2NH_2COO^- + HCO_3^-$$

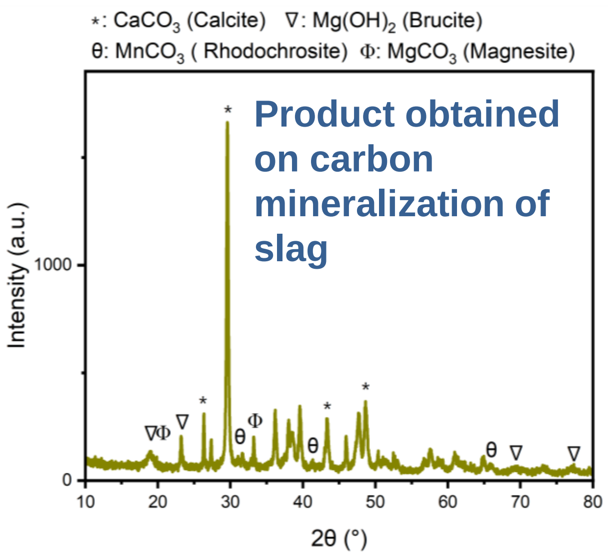
$$CO_{2(aq)} + OH^- \rightleftarrows HCO_3^- \rightleftarrows CO_3^{2-} + H^+$$

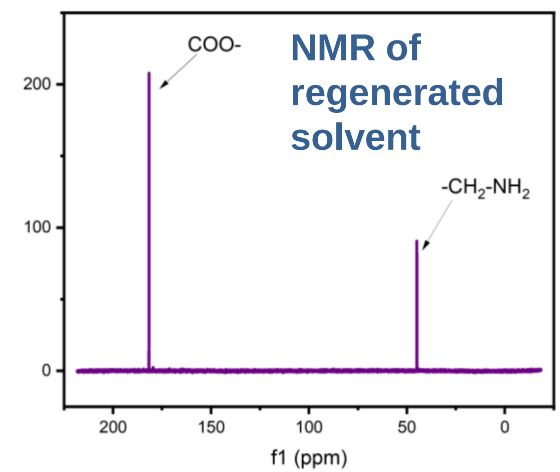
Task 4. Extractive carbon mineralization of Mn, Ca, and Mg recovery

- Extent of mineralization, solvent regeneration and effective solvent regeneration for mineralization of $Ca(OH)_2$ using CO_2 pre-loaded 2.5 M Na - Glycinate at 25 ^{0}C, 50 ^{0}C and 75 ^{0}C.
- Extent of carbon mineralization ~ 92% and solvent regeneration ~ 92% is realized using $Ca(OH)_2$
- Solvent regeneration ~ 94% is achieved on the mineralization of by-product obtained on slag dissolution

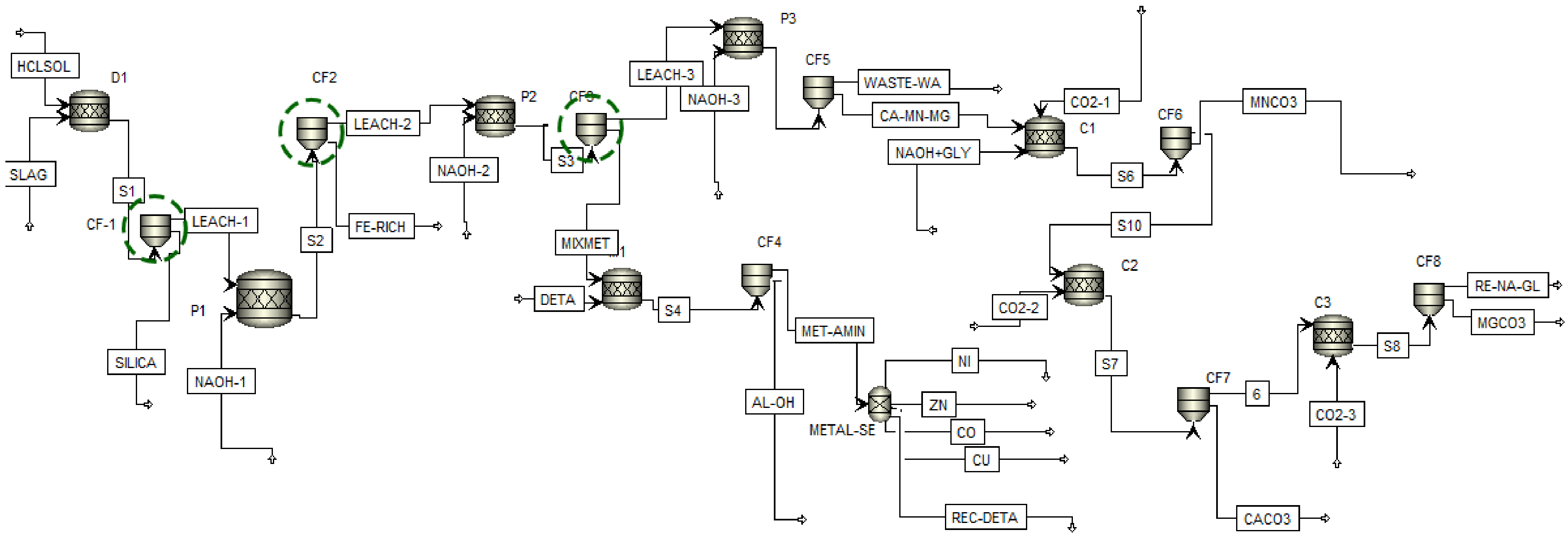








Milestone 6.1. Complete the TEA framework for INSPIRE



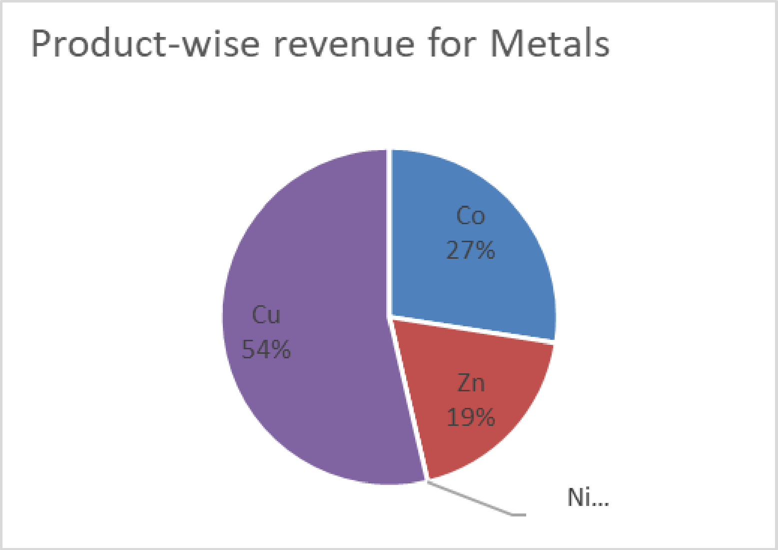
Key criteria	USD
Total Operating Cost	$174,221.06
Total Raw Materials Cost	$160,842.59
Total Product Sales	$555,884.26
Total Utilities Cost	$158.16
Operating Profit per ton	$220,662.44

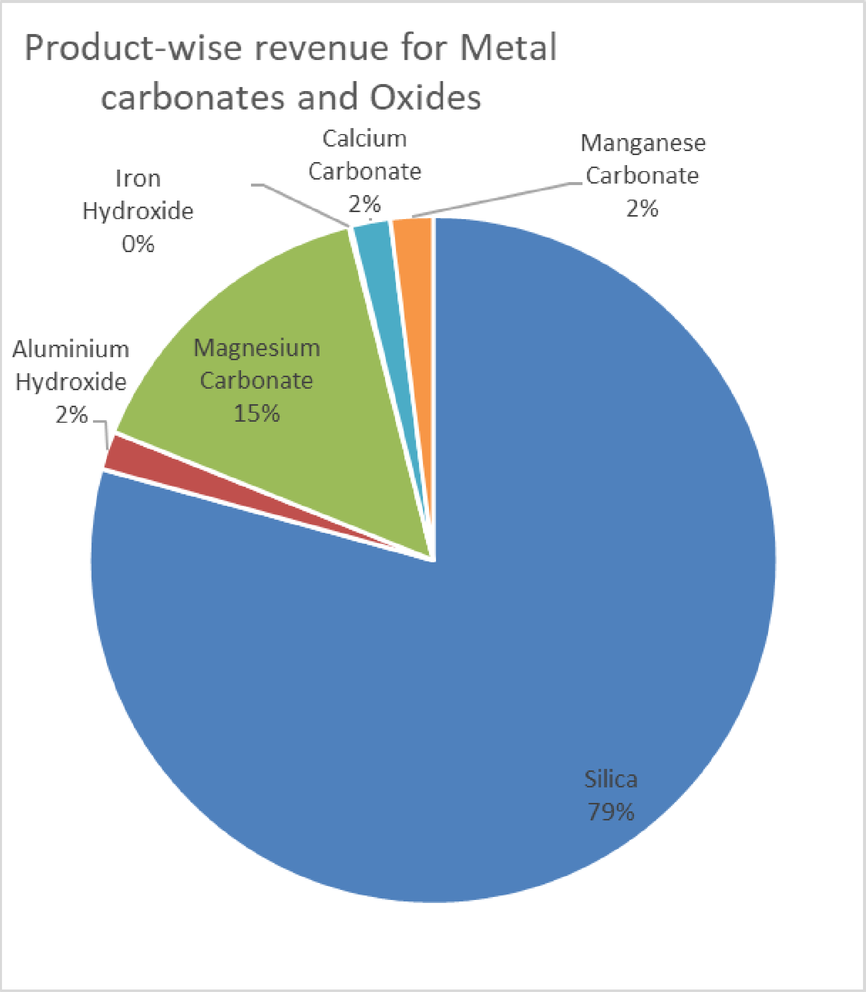
#	Assumptions
1	The costs of crushing and grinding slag is $10/ton which is incorporated in ASPEN.
2	The tax credits for carbon capture are considered to be $20/ton of CO_2 captured. In ASPEN, this is reflected as -$0.02 per kilogram to incorporate it into raw material costs.
3	The separation efficiency of the centrifuge filters in ASPEN model is set at 99%. The power required for processing 1 m^3/hr. of feed rate in a centrifuge filter is 1 kW.
4	Solvent recovery rates are set at 90% for CO_2 capture solvent (Sodium Glycinate) and 95% for metal-recovery solvent (DETA). These rates are factored into the calculation of raw material costs.

Milestone 6.1. Complete the TEA framework for INSPIRE

- The annual slag processing volume amounts to 8,640 tons, based on plant operation for 360 days per year. Each ton of slag yields a profit of $220,662.44, predominantly derived from the sale of carbonates and metal oxides. Additionally, revenue is generated from the recovery of critical metals.

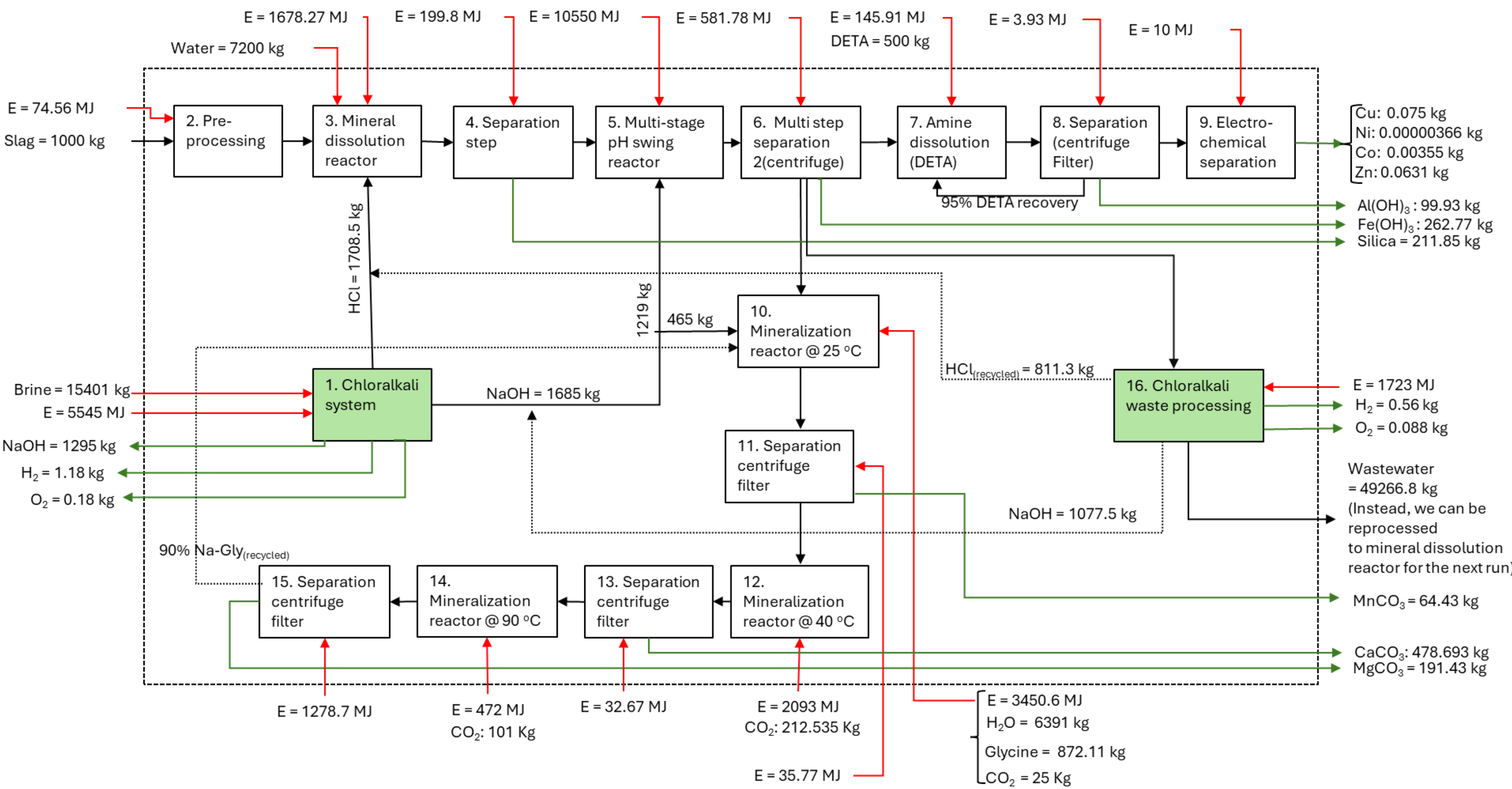
- About 338 tons of CO_2 captured per ton of slag.



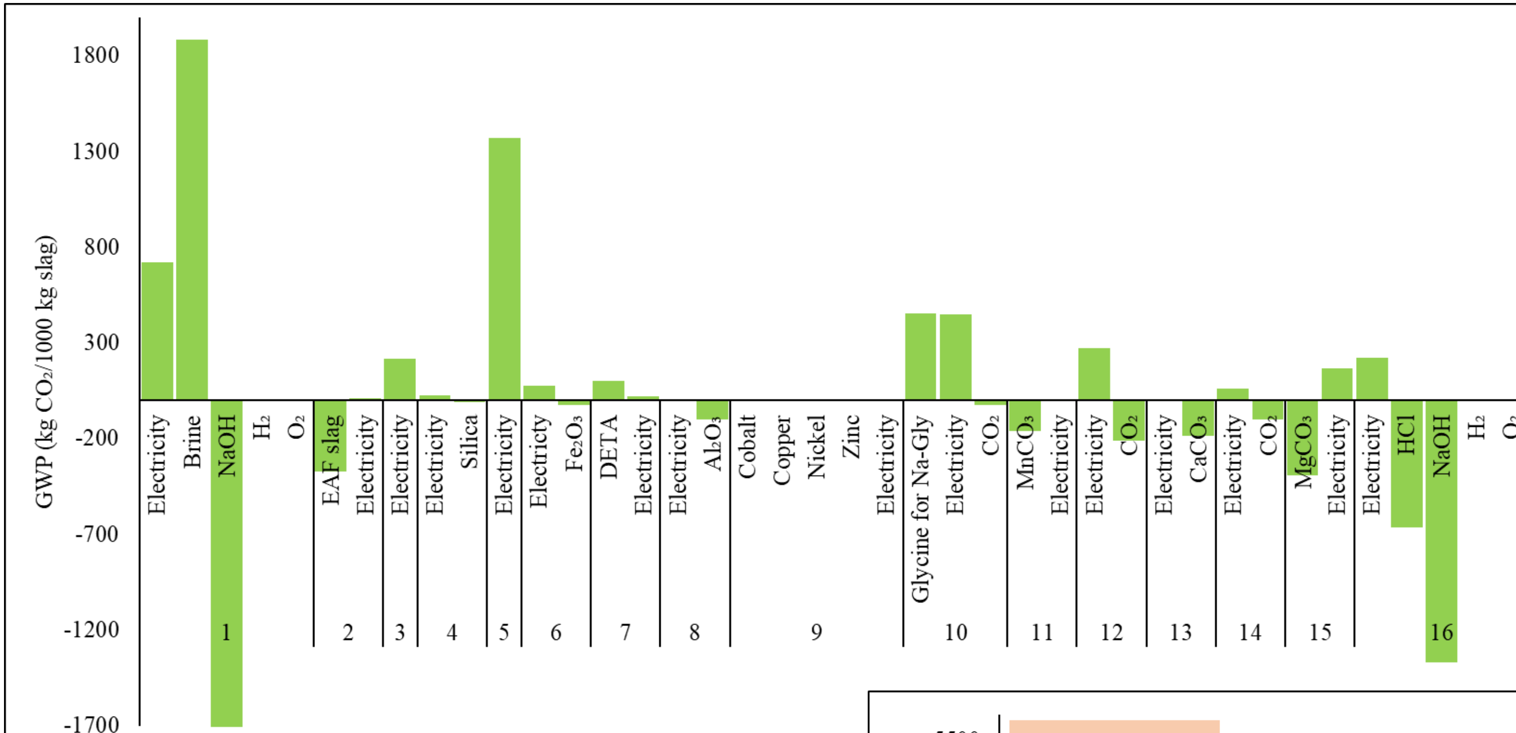


Milestone 6.2. Complete the LCA framework for INSPIRE

LCA is based on processing 1 ton of slag coupled with the electrochemical co-generation of NaOH, HCl, H_2, and O_2 for extracting energy critical metals and producing inorganic carbonates via CO_2 capture and mineralization.

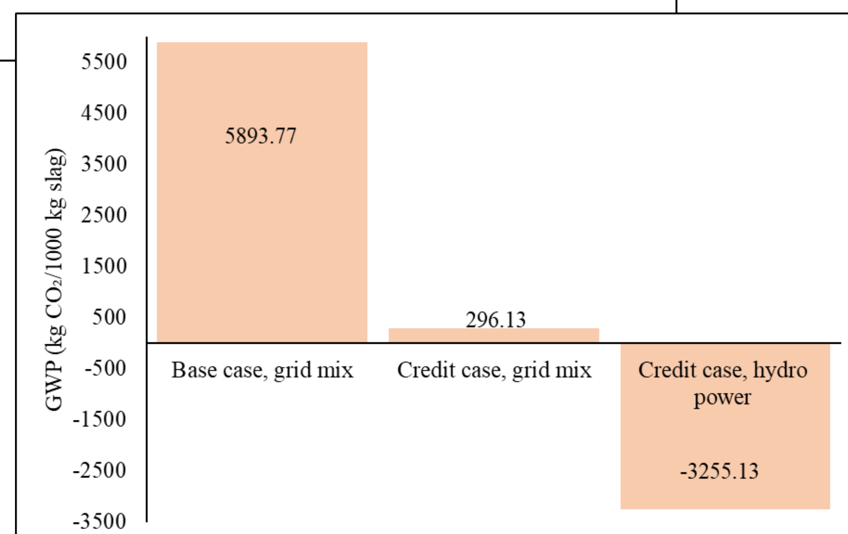


Milestone 6.2. Complete the LCA framework for INSPIRE



CO_2 emissions are predominantly from electricity, brine, and solvent. Negative emissions arise from co-product generation.

Switching to electricity from renewable energy resources and crediting the products can result in carbon – negative products.



Outreach Activities

C1. Engage K – 12 community in science education and communication

The REACT (Research Education and Activities for Community Teachers) program connects K-12 educators with cutting-edge research at Cornell University. Organized by graduate students, this initiative highlights the latest research techniques and advancements for teachers, aiming to bring cutting-edge research into their classrooms. Dhruv Mehta participated in the virtual lab tour, where he showcased various equipment and analytical instruments in the lab used for research on carbon capture and metal recovery.

Upcoming activities

We are organizing the ACS Women in Energy Symposium in the ACS Fall Meeting in Denver, Colorado from August 18 – 22, 2024.

We welcome you to attend!

Key Tasks and Subtasks

The team has made significant progress on Tasks 1 – 6 during the first year

	Task & Subtasks	Year 1 Q1	Year 1 Q2	Year 1 Q3	Year 1 Q4	Year 2 Q1	Year 2 Q2	Year 2 Q3	Year 2 Q4
1	**Project Management and Planning (including kick-off meeting)**	1.1							
2	**Material characterization, solvent synthesis and identify solvents**								
	2.1 Characterize chemical and morphological features of alkaline materials	2.1							
	2.2 Synthesize third generation solvents and determine CO_2 capture behavior		2.2						
	2.3 Determine the appropriate solvents based on thermodynamics and kinetics			2.3					
3	**Metal recovery using CO_2-bearing solvents and electrochemical approaches**				3.1S				
4	**Extractive carbon mineralization for Mn, Ca, and Mg recovery**				4.1				
5	**Experimental setup for electromediated stripping, recovery, and solvent regeneration**				5.1				
6	**Develop frameworks for techno-economic assessments and life cycle analyses**								
	6.1 Develop frameworks for process-scale analyses and TEA				6.1				
	6.2 Develop a framework to assess life cycle impacts				6.2				
C1	**Engage K-12 students in science education and communication**				C1.1				
7	**Recover Al – and Fe – bearing solids**					7.1			
8	**Recover Mn-, Ca-, and Mg-bearing carbonates**								
	8.1 Phase separation, compositional analyses, quantification of CO_2 capture and mineralization						8.1		
	8.2 Produce Ca-carbonate via integrated CO_2 capture and conversion								8.2
9	**Electromediated critical metal stripping, recovery, and solvent regeneration**								
	9.1 Selective Ni stripping by Cu^{2+} ion substitution						9.1		
	9.2 Selective Ni and Co stripping by Cu2+ substitution and metal recovery by carbon mineralization							9.2	9.3
10	**Conduct whole system TEA and LCA**								
	10.1 Evaluate the overall techno-economic impacts								10.1
	10.2 Assess whole system life cycle impacts								10.2
C2	**Expand internship opportunities for underrepresented students and women**								C2.1
C3	**Engage women, rural communities, and general public through symposia organization and presentations**								C3.1

Milestones

Milestones 1.1, 2.1, 2.2, 6.1, and 6.2 are achieved.
Significant progress is being made towards Milestones 2.3, 4.1, 5.1, 6.1, and 6.2.
Green: completed | Blue: In Progress | Black: To Begin

	Type	Milestones
1. Project Management	Y1, Q1	**1.1.** Develop the communication plan and other deliverables and organize the project kick-off meeting
2. Material characterization, solvent synthesis and identification for metal recovery	Y1, Q1	**2.1.** Quantify the chemical compositions and morphological features of the alkaline industrial residues from secondary aluminum processing and steel making
	Y1, Q2	**2.2.** Synthesize third generation solvents and quantify CO_2 capture behavior
	Y1, Q3	2.3. Identify 2-3 appropriate solvent systems
3. Metal recovery	Y1, Q4	**3.1.** Leach > 60% of Ni and > 80% of Ca from select alkaline industrial residues - SMART; Go – No Go Milestone
4. Extractive carbon mineralization of Mn, Ca, and Mg recovery	Y1, Q4	**4.1.** Achieve selective separation of Mn, Ca, and Mg-carbonates
5. Experimental setup for electromediated separation	Y1, Q3	**5.1.** Demonstrate a working experimental setup for separating metals of interest
6. Develop frameworks for TEA and LCA	Y1, Q4	**6.1.** Complete the TEA framework for INSPIRE
	Y1, Q4	**6.2.** Complete the LCA framework for INSPIRE
7. Recover Al- and Fe-bearing solids	Y2, Q1	**7.1.** Achieve the precipitation of Al- and Fe-rich solids from select alkaline industrial residues with yields > 60% - SMART
8. Recover Mn-, Ca-, and Mg-bearing carbonates	Y2, Q2	**8.1.** Recover > 90% of select solvents after Mn,Ca, and Mg-carbonate precipitation - SMART
	Y2, Q4	8.2. Produce > 10 kg of $CaCO_3$ based on optimal conditions - SMART
9: Electromediated metal recovery	Y2, Q3	9.1 Selective electrochemical recovery of Ni, Co, Zn-carbonates
	Y2, Q4	9.2. Develop solvent regeneration strategy
10: Conduct whole system TEA and LCA	Y2, Q4	10.1. Final TEA for the fully integrated INSPIRE technology
	Y2, Q4	10.2. Final LCA for the fully integrated INSPIRE technology

Thank you!