Transforming Mine Waste into Carbon Sinks: Extracting Magnesium for CO_2 Mineralization

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PCCC-8

CSIRO

Australia's National Science Agency

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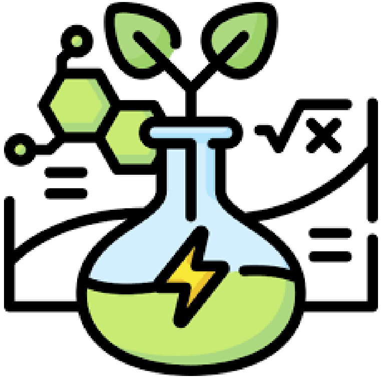
CSIRO

- 49 sites in Australia and two sites overseas
- 5,672 people
- Over 4,000 industry and government partners
- 1,600 small and medium businesses (SMEs)

Mineral resources RU:

- Leading research in mineral extraction and beneficiation
- Delivering innovation for the mining industry



Energy RU:

- Leading research in energy transformation and carbon management
- Advancing CCUS technologies towards NZE targets

SIMiDAC Team - Acknowledgment

Dr Dia Milani – Energy RU
- Process simulation, integration, and optimisation
- Solar field and energy storage design and sizing
- Project liaison and management

Dr Paul Feron – Energy RU
- Amine development and commercialisation
- Direct air capture and integrated CO_2 utilisation
- Science lead and mentorship

Dr Phillip Fawell – Mineral Resources RU
- Experience with tailings circuits
- Focus on physical properties of suspensions
- Industry connections

Dr Haftom Weldekidan – Mineral Resources RU
- CERC fellow from Macquarie university
- 2 years work experience at the Uni of Guelph - Canada
- Expertise in solar fuels and hydrogen

Dr Graeme Puxty – Energy RU
- Lead scientist on absorption liquid development
- Experience in chemical and physical processes for CO_2 separation
- Focus on novel process integrations

Dr Robbie McDonald – Mineral Resources RU
- Lead of the experimental program
- Expert in hydrometallurgy and mineral characterisation
- HSE and operation safety

Dr Nouman Mirza – Energy RU
- Solvent development chemist
- Catalysis chemistry
- Experience with pilot plant operation

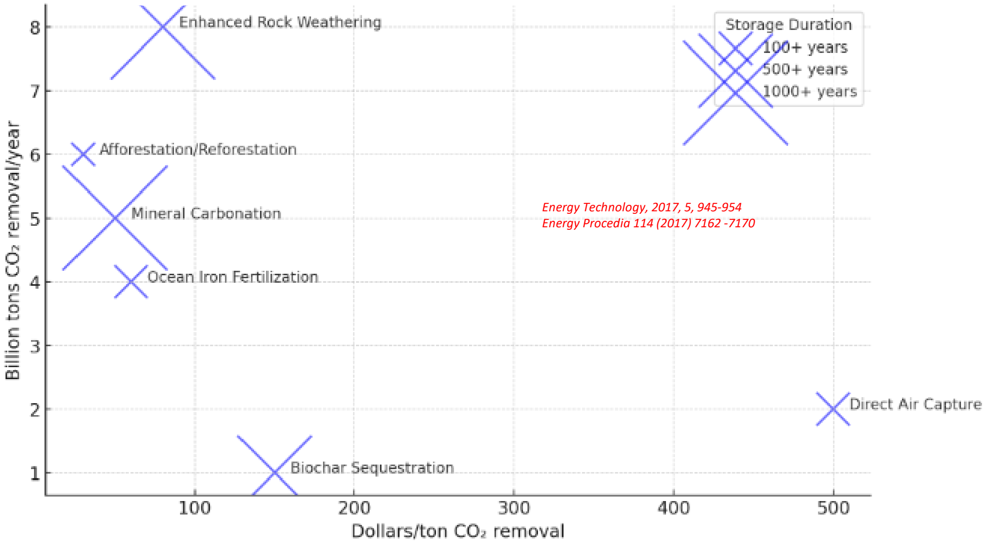
Dr Tara Hosseini– Energy RU
- Lead scientist on electrochemical energy systems
- Experience in technoeconomic and LCA
- Focus on mineral processing technologies

Background

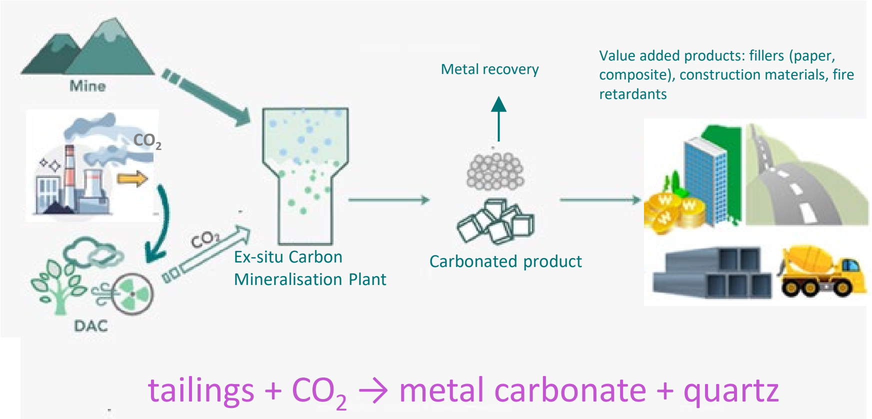
- 38 billion tonnes of CO_2 emission in 2024
- Atmospheric CO_2 has hit 430 ppm – highest in millions of years
- Main sources: energy sector (75%); transportation and industry (steel, cement and chemical production)

Source (IEA, 2024 report)

CO_2 sequestration technologies



Accelerated mineral carbonation (AMC)

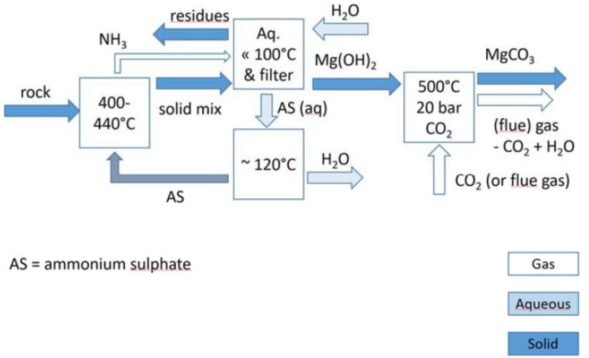


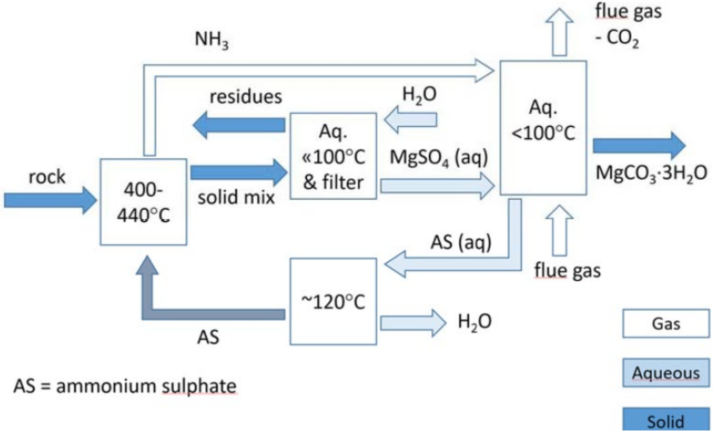
tailings + CO_2 → metal carbonate + quartz

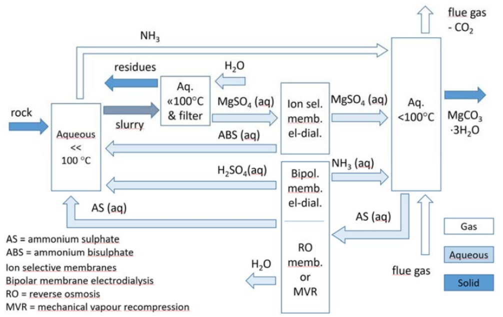
Why mineral carbonation?

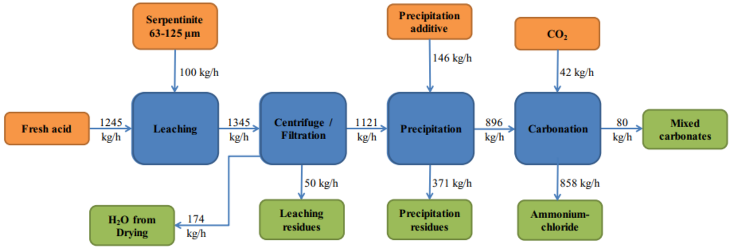
- Mineral carbonation occurs in nature
- Challenges: the natural process is slow!
- AMC:
  - Faster
  - Wide availability/cheaper raw materials, can store 3700 Mt/year CO_2
  - Potential recovery of critical minerals
  - Energy intensive, costly, difficult to recycle reagents

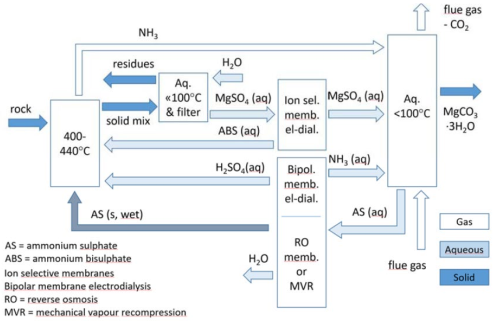
AMC process routes







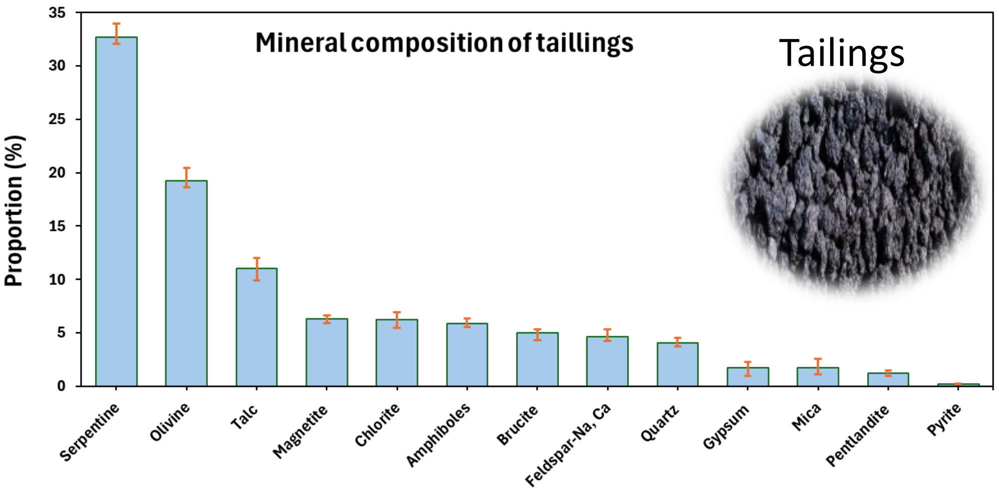




(Zevenhoven and Häggqvist, 2022)

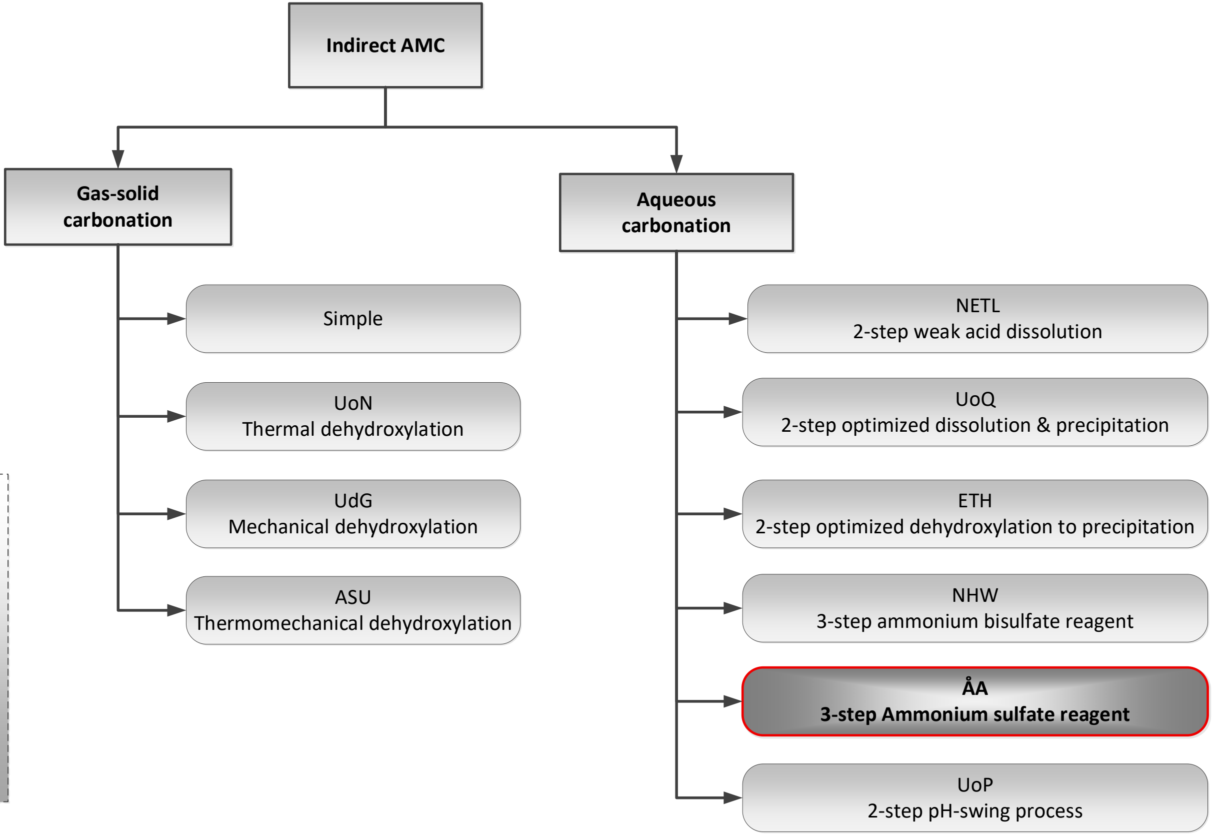
Tailings compositions

- Obtained from an Australian mining site
- Characterised with QXRD, SEM, ICP
- Identified around 13 minerals
- Tailings rich in serpentine and olivine
- Has high concentration of Mg (~20%)



Composition of the tailings, wt.%														
SiO_2	MgO	CaO	Al_2O_3	Cr_2O_3	Fe_2O_3	K_2O	Mn_3O_4	Na_2O	NiO	SO_3	Cl	**Other**	**LOF**	**Total**
37.1	33.2	1.5	2.2	0.3	11.4	0.3	0.1	1.2	0.8	3.4	0.9	2	7.2	100

AMC – Roasting

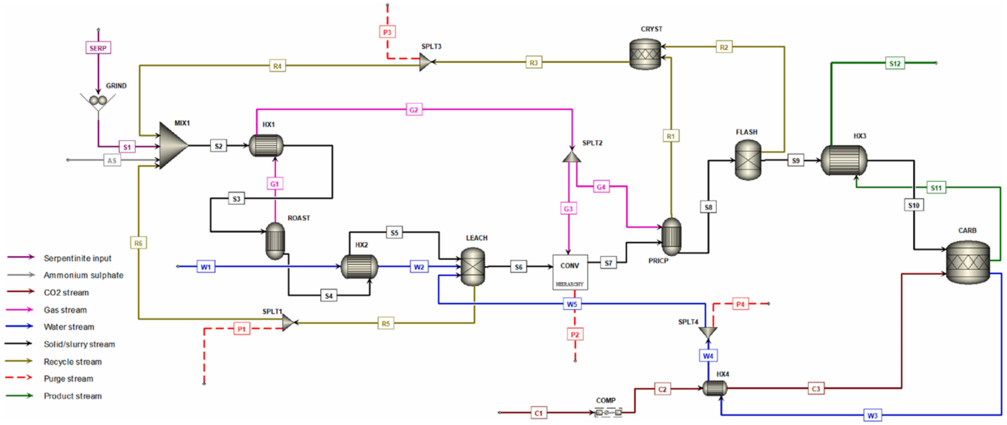


<u>Leading research institutes:</u>

UoN	University of Newcastle, Australia
UdG	Universidad de Granada, Spain
ASU	Arizona State University, USA
NETL	National Energy Research Laboratory, USA
UoQ	University of Quebec, Canada
ETH	Eidgenössische Technische Hochschule Zürich, Switzerland
NHW	Nottingham/Heriot-Watt Universities, UK
ÅA	Åbo Akademi, Finland
UoP	University of Pennsylvania, USA

Roasting process model

- Modelling was done using aspen plus and is based on the Åbo Akademi (ÅA) Conventional Carbonation process routes.
- Model shows processes for extracting magnesium by roasting magnesium rich-tailings at 400 °C.
- Ammonium sulfate was considered as a reagent.



Model optimized results

Parameters	Roasting	unit	Ref.
Magnesium Extraction	85	%	Aspen plus
Energy demand for grinding	1	MJ/kg $MgCO_3$	Aspen plus
Particle size	<80	um	Aspen plus
Water usage	0.5	Kg_{H2O}/kg $MgCO_3$	Aspen plus
Heat demand	22	MJ/kg $MgCO_3$	Aspen plus & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
Heat recovery from leaching	11	MJ/kg $MgCO_3$	Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
Heat recovery from carbonation	6	MJ/kg $MgCO_3$	Aspen & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
Recycling (ammonium sulfate)	0.5	MJ/kg $MgCO_3$	Aspen plus
CO_2-to-product ratio	0.6	Kg_{CO2}/kg $MgCO_3$	Aspen & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
CO_2 conversion rate	85	%	Aspen & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
CO_2 emission reduction	69	kt_{CO2}/year	Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025

- Optimized process parameters including water usage, particle distribution and temperature.
- Evaluated:
  - Energy required for roasting, leaching and energy required to recycle used reagents.
  - Energy generated carbonating the $Mg(OH)_2$.
- Analyzed the carbon footprint of the whole process (roasting, leaching and carbonation processes).

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Roasting the tailings

- Temperature 400 °C
- Roasting time 3 hours
- Reagent used ammonium sulfate (tailings: ammonium sulfate =1:3)
- Tailings particle sizes considered - 25 to 110 µm

Metal extraction

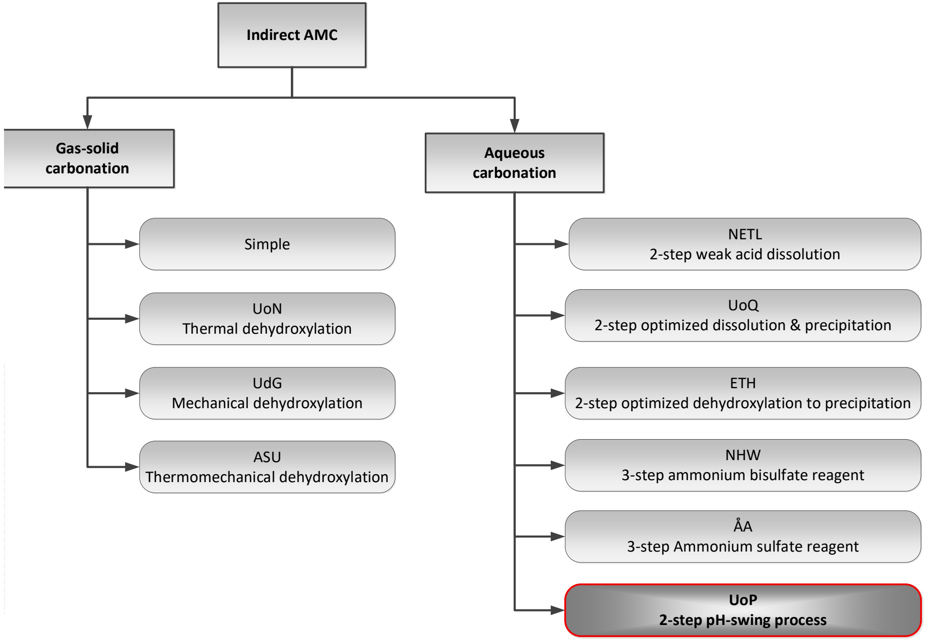
PSD, µm	Mg %	Fe %	Ni %	Si %	Al %
<25	89	28	91	11	57
<80	83	27	81	12	45
<110	70	24	75	5	41

- Formed efremovite ($(NH_4)_2Mg_2(SO_4)_3$) and sabieite ($NH_4Fe(SO_4)_2$)
- Almost all serpentine and significant amount of olivine decomposed
- Quartz, actinolite and talc remained

AMC -pH swing (leaching)

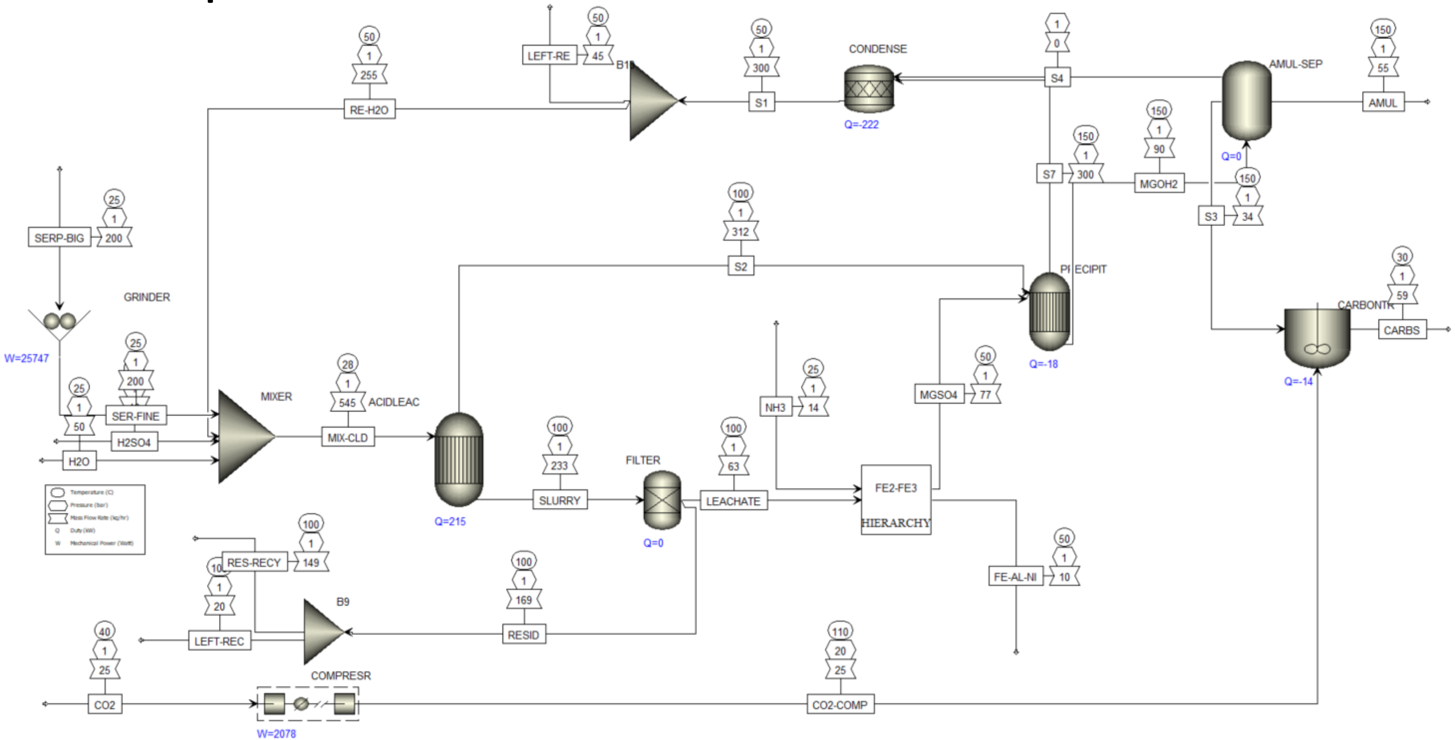
Roasting:

- Requires high temperature.
- Extraction is low unless tailings is finely ground.
- Is energy intensive.
- These limitations prompted alternative approach – pH swing (acid leaching) to explore more efficient extraction pathways.



pH-Swing modelling

Acid leaching:- Sulfuric acid, stoichiometric amount, Ambient temperature and pressure



Model optimized results

Parameters	Roasting	**pH swing**	unit	Ref.
Magnesium Extraction	70	**90**	%	Aspen plus
Energy demand for grinding	1	**0**	MJ/kg $MgCO_3$	Aspen plus
Particle size	<110	**<110**	um	Aspen plus
Water usage	0.5	**1**	Kg_{H2O}/kg $MgCO_3$	Aspen plus
Heat demand	22	**2**	MJ/kg $MgCO_3$	Aspen plus & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
Heat recovery from leaching	11		MJ/kg $MgCO_3$	Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
Heat recovery from carbonation	6	**6**	MJ/kg $MgCO_3$	Aspen & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
Recycling (ammonium sulfate)	0.5	**0.5**	MJ/kg $MgCO_3$	Aspen plus
CO_2-to-product ratio	0.6		Kg_{CO2}/kg $MgCO_3$	Aspen & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
CO_2 conversion rate	85	**90**	%	Aspen & Milani et.al., Cleaner Eng. Tech. Vol. 26, 2025
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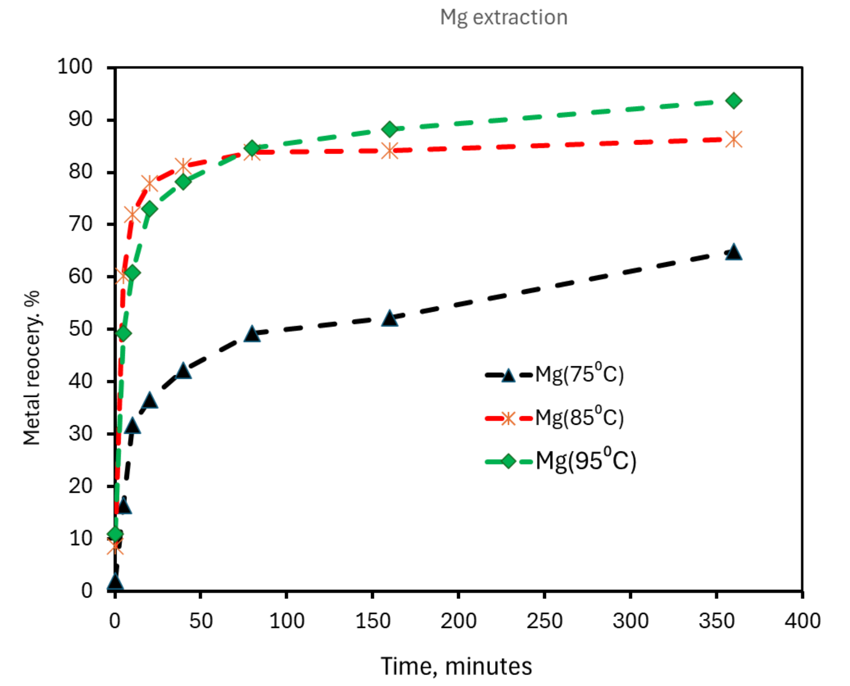
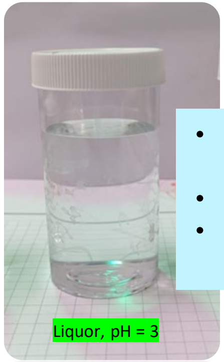
Leaching test



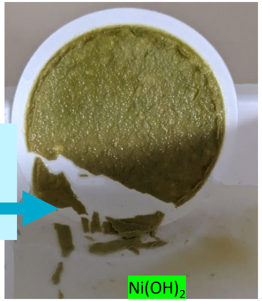
- Sulfuric acid (acid: tailings =1)
- Pulp density 20 %, atmospheric leaching
- Temperatures considered, 75 to 95°C
- All the olivine and lizardite decomposed
- Chlorite and quartz left undecomposed
- Magnesium extraction above 90 %

pH adjustment for Mg-rich liquor



- Added H_2O_2 to oxidise ferrous to ferric
- Increased pH to 4.3 with NH3
- Precipitated almost all the irons

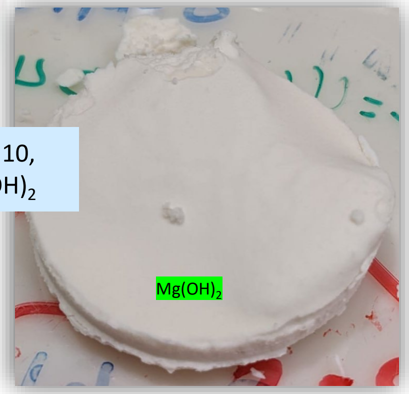
Raising the pH to 8.5
Precipitated Ni



Mg-rich stream for carbonation

Conc. Mg/L			
Fe	**Mg**	**Ni**	**pH**
4.07	29800	158	4
>1.0	30300	154	7
>1.0	30200	43.1	8.5
>1.0	23300	>1	9.3

Increase pH to 10, produce, $Mg(OH)_2$



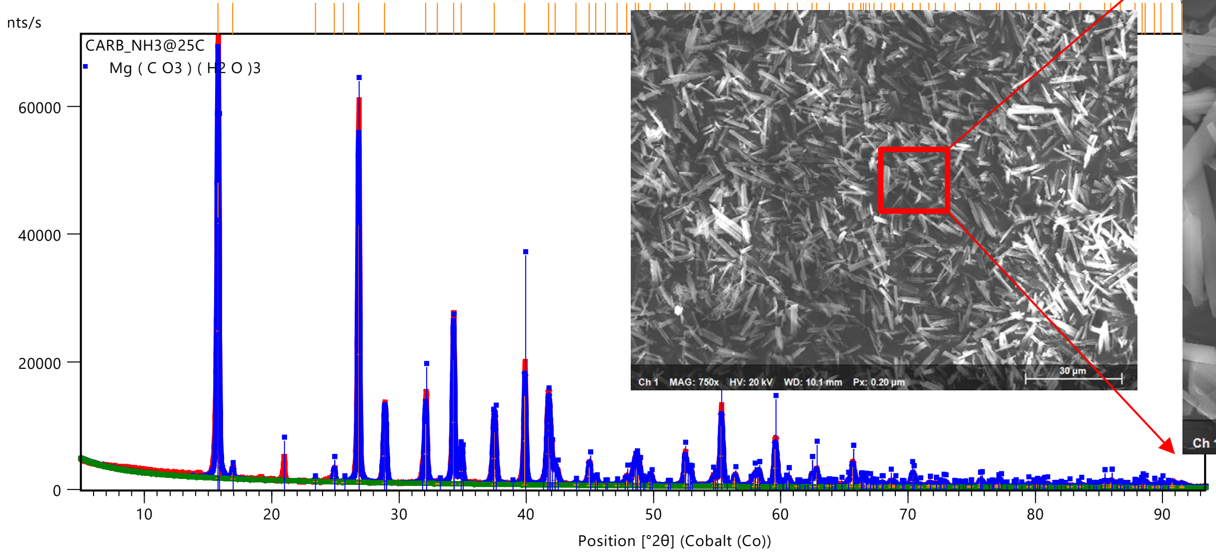
BET surface area, m2/g	Average pore diameter, Å	Pore width, Å
30	151	343

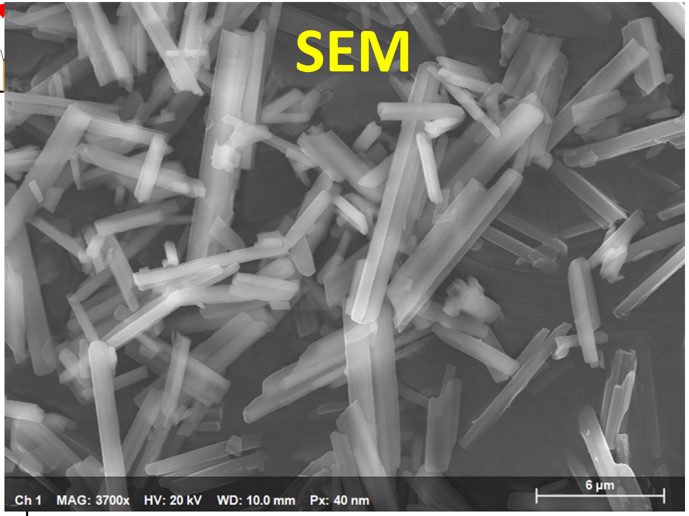
Carbonating Mg-rich streams

- In a closed vessel reactor
- Added stoichiometric amount of NH_3 solution
- pH >8, room temperature
- CO_2 gas injected at 150 cc/min

Carbonation

XRD analysis



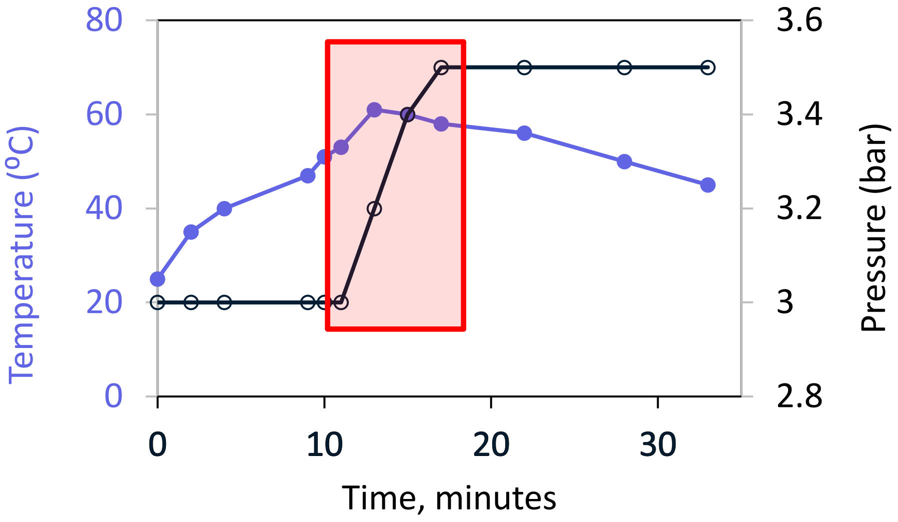


- XRD confirms conversation to Nesquehonite ($MgCO_3.3H_2O$)
- Complete conversion of Mg into $MgCO_3.3H_2O$
- SEM confirms morphology of the product

$$MgSO_4(aq) + 2NH_3 + 4H_2O + CO_2(g) \rightarrow MgCO_3.3H_2O + 2(NH_4)_2SO_4(aq)$$

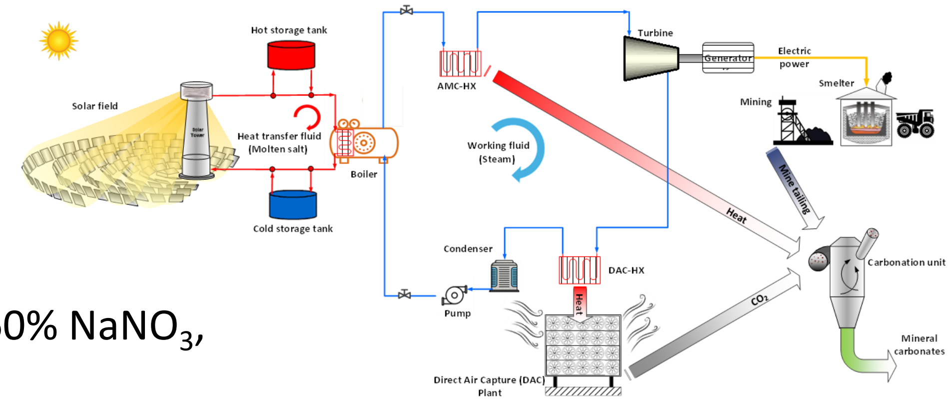
Temperature and pressure profiles

- Temperature increased to 61°C, then started to decrease.
- Indicating the end of carbonation reaction.
- Only 13 minutes to convert all the Mg to $MgCO_3.3H_2O$.
- Consistent with the temperature, the pressure also started to build up from 11 minutes.



Solar integration

- **Process Flow**: CST *(Concentrating solar techno.)* → Boiler → AMC-HX → Turbine → DAC-HX



- **Key Components**:
- *CST system*: Delivers thermal energy
- *HTF (heating transferring fluid)*: Molten salt (60% $NaNO_3$, 40% KNO_3)
- *AMC*: Mineral carbonation for CO_2 sequestration
- *DAC*: CO_2 capture from the atmosphere
- *Rankine Cycle*: For electricity generation

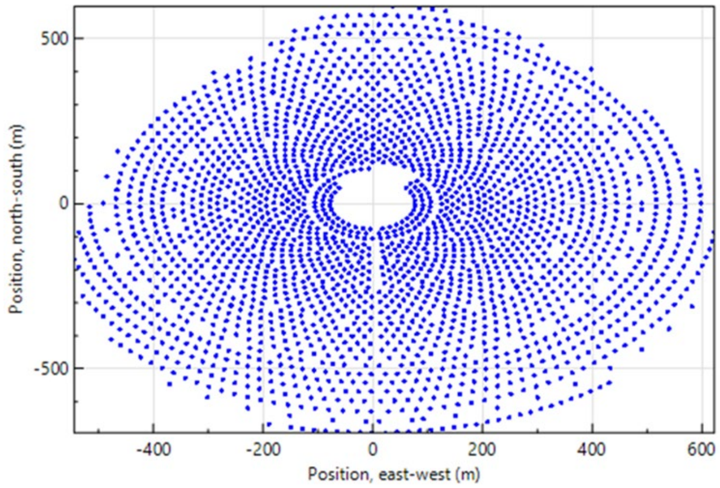
(Milani et al., 2025)

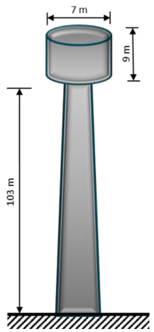
Solar system sizing – CST and TES

- Sizing was done using the NREL based System Advisor Model (SAM).
- CST was designed to deliver 20 MWe.
- Includes a 10–hour thermal energy storage (TES) system to meet nominal loads over the year.
- 50% of this for mining and auxiliary loads on site.
- Remaining (50%) for AMC and DAC operation.

Sizing

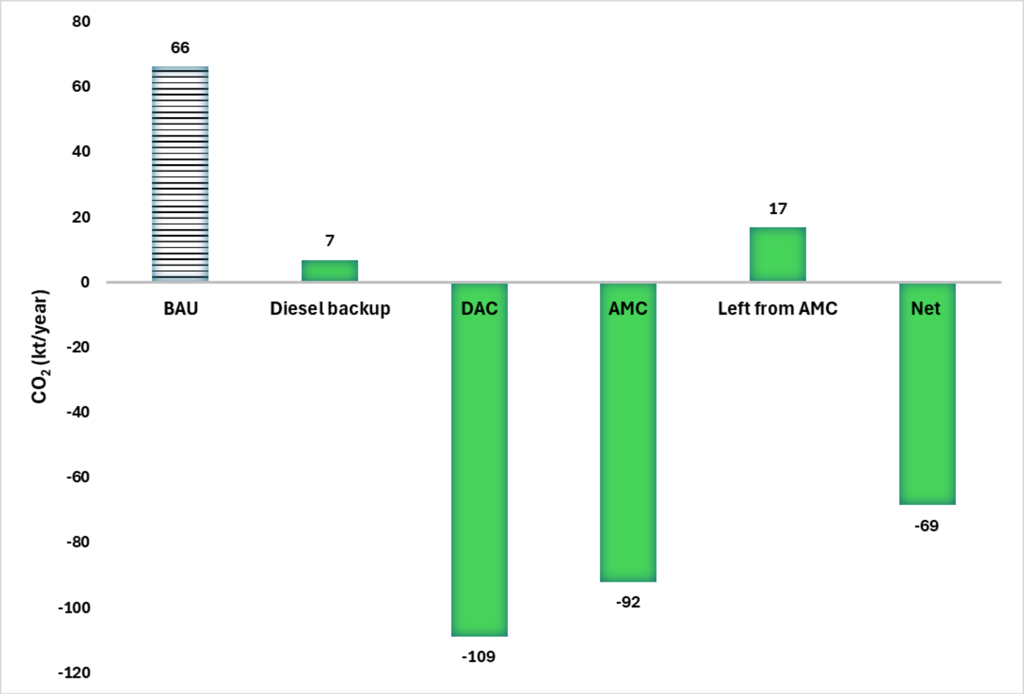
- Land area for the CST: 1.3 km^2
- Heliostats: 2411 units
- Tower height: 103 m
- Receiver: 9 m height, 7 m diameter





(Milani et al., 2025)

GHG Emissions Reduction



Business As Usual (BAU)

- CO_2 emission is 66 kt CO_2/year
- Diesel consumption 24 million L/year

With CST

- Produce 176 kt/year carbonates – locking 92 kt/year of atmospheric CO_2
- Generate 10 MW electricity (turbine),
- 10.7 MJ/kg for CO_2 production in DAC
- AMC generates 5.8 MJ net heat/kg carbonate products produced
- Diesel backup consumption reduced to only 2.5 million L/year
- Avoiding further 69 kt/year CO_2 (negative emissions)
- The total CO_2 avoidance is **204**%

Conclusion

- Roasting of Mg-rich tailings using ammonium sulfate at 400°C enables partial Mg extraction but is energy intensive and requires fine grinding.
- pH swing using sulfuric acid offer a low-temperature alternative with higher Mg extraction (>90%) and simpler process conditions.
- Carbonation of Mg-rich streams produces nesquehonite ($MgCO_3 \cdot 3H_2O$)
- Solar thermal integration enhances process sustainability and reduces GHG emissions.

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Thank you

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