Åbo Akademi University

CSLF Workshop on CDR

Mineralisation

report IEA/CON/21/274

Ron Zevenhoven, prof.
ÅA Process and systems engineering

28-6-2022 @Bergen, no

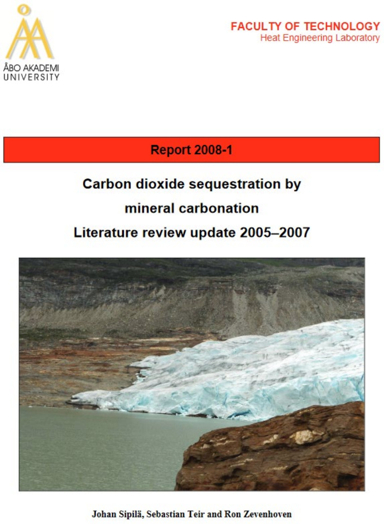
To be addressed

- Report produced for IEA GHG IEA/CON/21/274

  Mineral carbonation using mine tailings –

  A strategic overview of potential and opportunities
- Draft report Sept. 9, 2021, revised Nov. 1, 2021 and Feb. 4, 2022.
- Co-authors
  - Jens Back, PhD candidate @ ÅA
  - Johan Fagerlund @ Citec Oy, Turku
  - Peter Sorjonen-Ward, Geological Survey of Finland, Kuopio
- ÅA project work today

You may remember



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FACULTY OF TECHNOLOGY
Heat Engineering Laboratory

Report 2008-1

Carbon dioxide sequestration by
mineral carbonation
Literature review update 2005–2007

Johan Sipilä, Sebastian Teir and Ron Zevenhoven

CO_2 mineral sequestration

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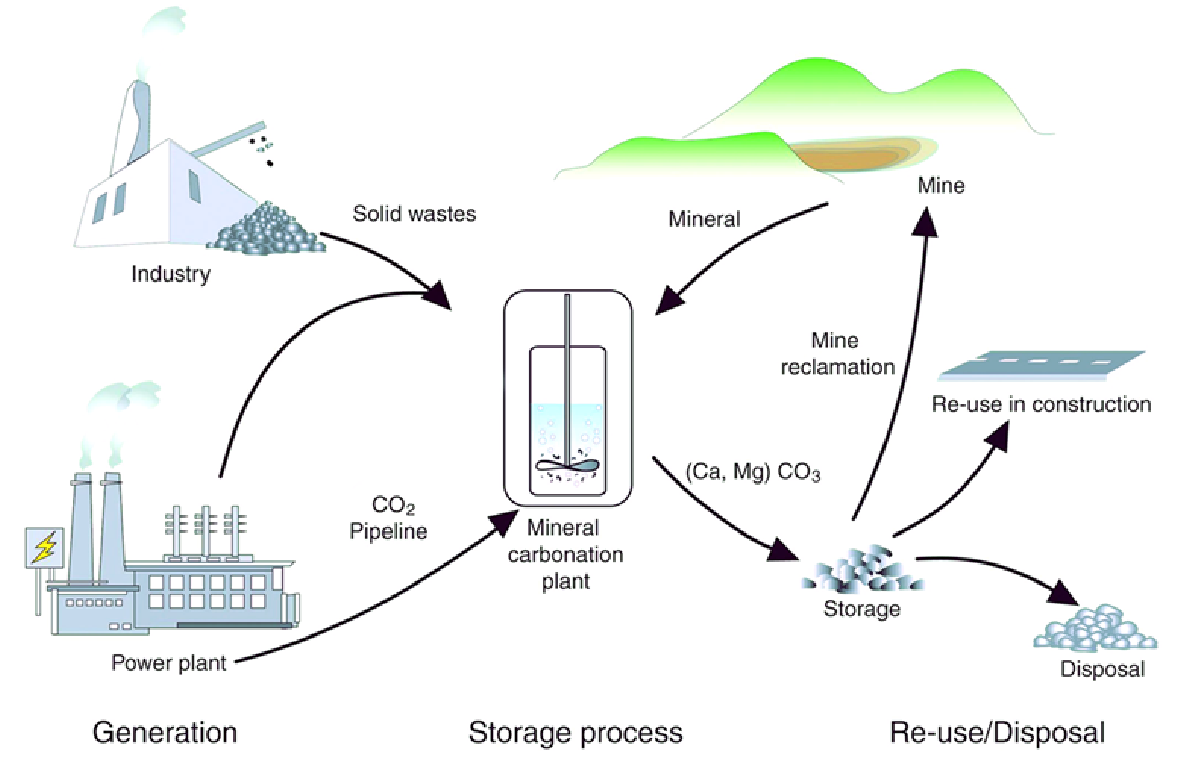
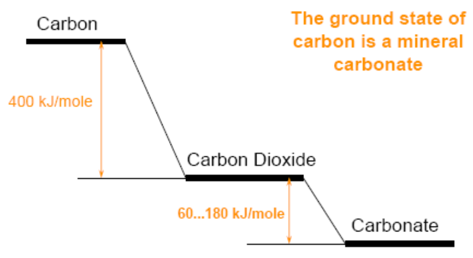
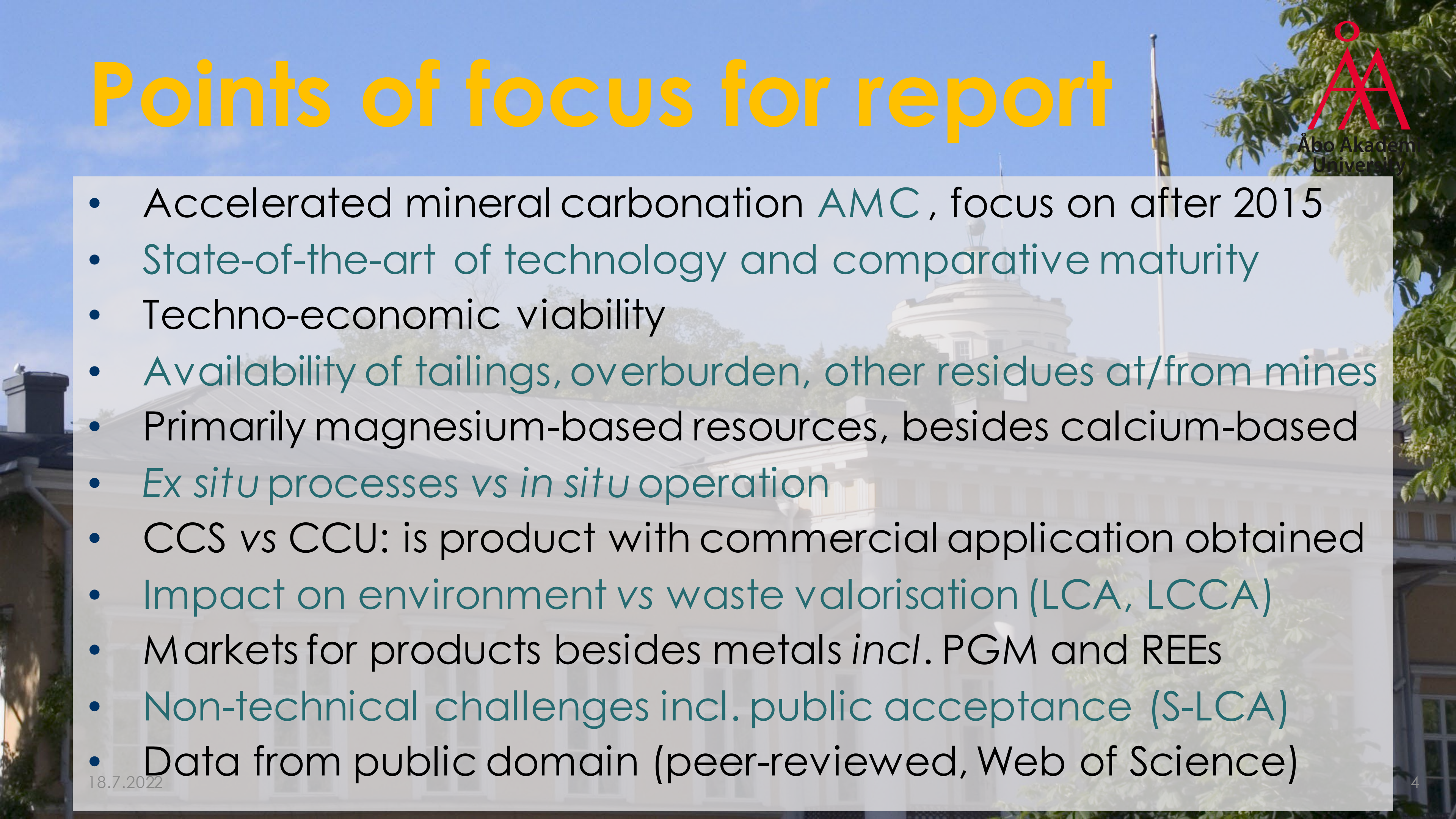




IPCC SRCCS 2005 Chapter 7

Overall carbonation chemistry, with M = Mg or Ca (or Fe, ...)

$MO.ySiO_2.zH_2O\ (s) + CO_2\ (g) <=> MCO_3\ (s) + ySiO_2\ (s) + zH_2O\ (l) + HEAT$



Points of focus for report

- Accelerated mineral carbonation AMC , focus on after 2015
- State-of-the-art of technology and comparative maturity
- Techno-economic viability
- Availability of tailings, overburden, other residues at/from mines
- Primarily magnesium-based resources, besides calcium-based
- *Ex situ* processes vs *in situ* operation
- CCS vs CCU: is product with commercial application obtained
- Impact on environment vs waste valorisation (LCA, LCCA)
- Markets for products besides metals *incl*. PGM and REEs
- Non-technical challenges incl. public acceptance (S-LCA)
- Data from public domain (peer-reviewed, Web of Science)

Key performance indicators

- Availability and quality of rock resources
- Technology readiness levels (TRLs) for *ex situ* process routes
- Valuable products and economic viability
- Toxic or otherwise problematic by-products
- Environmental footprint and life cycle assessment (LCA)
- Public acceptance studies

Content of report 1/2

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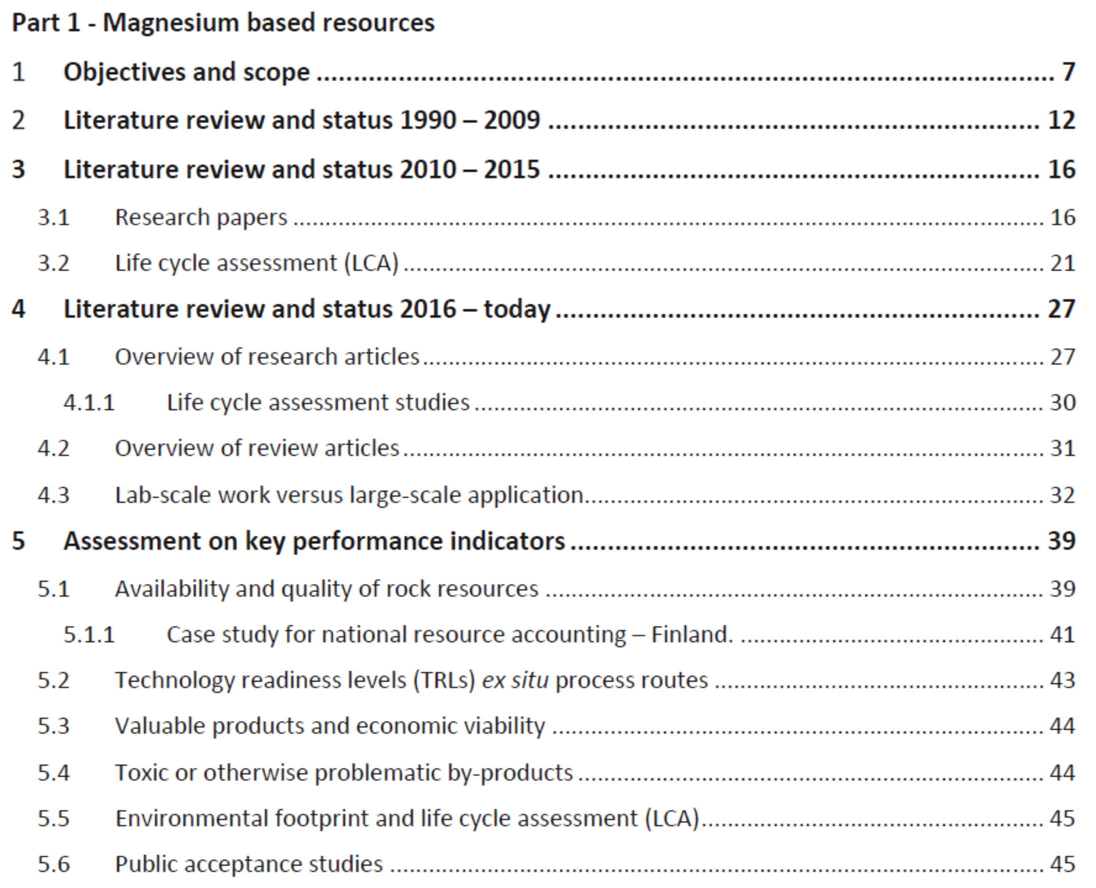

Part 1 - Magnesium based resources

Content of report 2/2

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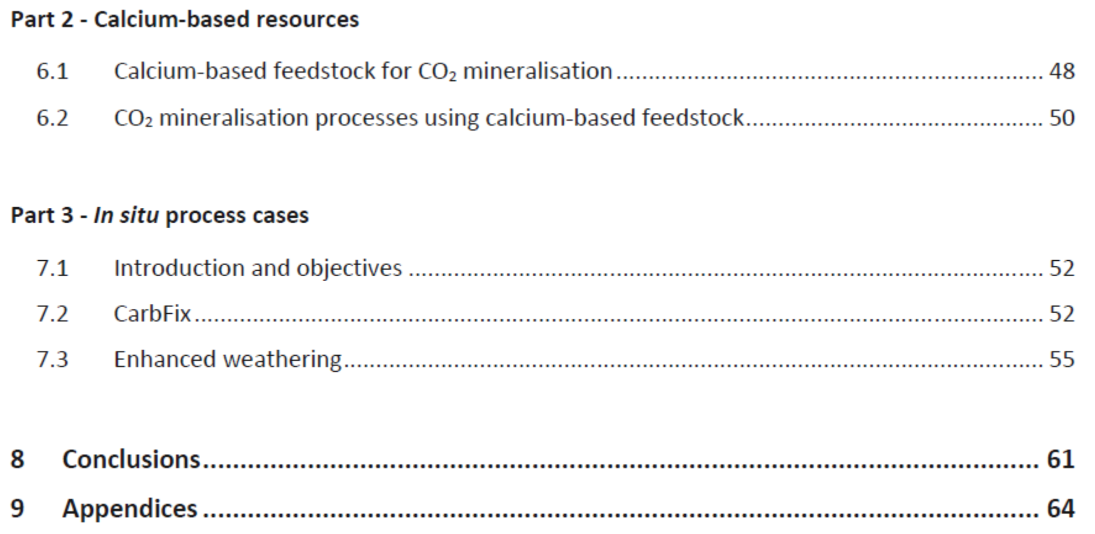
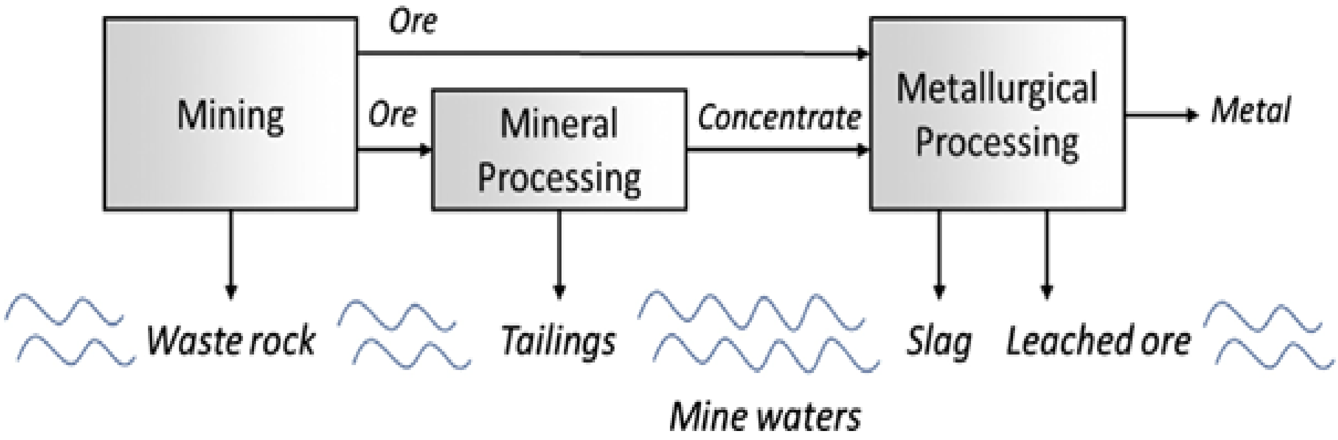


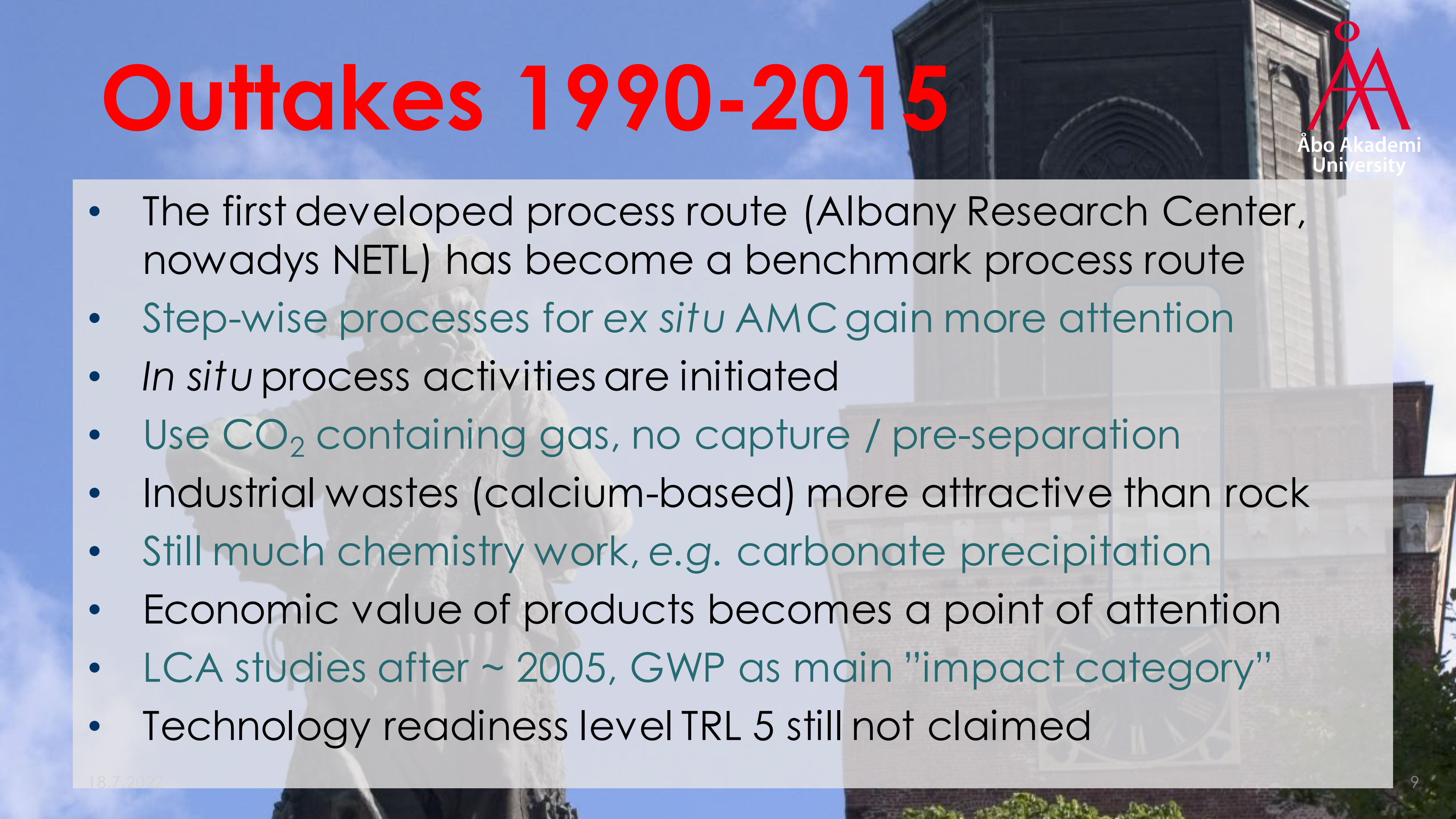
Part 2 - Calcium-based resources

Part 3 - *In situ* process cases

Mine tailings, waste rock, ..



Lèbre et al. 2017,
doi: 10.1016/j.mineng.2016.12.004



Outtakes 1990-2015

- The first developed process route (Albany Research Center, nowadys NETL) has become a benchmark process route
- Step-wise processes for ex *situ* AMC gain more attention
- *In situ* process activities are initiated
- Use CO_2 containing gas, no capture / pre-separation
- Industrial wastes (calcium-based) more attractive than rock
- Still much chemistry work, e.g. carbonate precipitation
- Economic value of products becomes a point of attention
- LCA studies after ~ 2005, GWP as main ”impact category”
- Technology readiness level TRL 5 still not claimed

Outtakes 2016-2021

- Mining tailings' untapped potential more appreciated
- A significant number of review papers
- Advancing beyond TRL 4 is problematic for most:
  - Chemical kinetics (days → hours → minutes)
  - Energy use (heat, power): less than for capture as part of CCS
  - Recovery and re-use of chemical additives
- Small markets for magnesium carbonate (hydrates) @ 300 €/t
- A review from 2020: "*it is time to put a stop to the repeated strategies, including elevating the process conditions, utilising energy-intensive thermo-mechanical feedstock, and large-scale expensive chemical consumptions*."
- More LCA studies but still often only GWP as impact category
- Remediation of problematic waste piles is a benefit for society

AMC pilot scale projects

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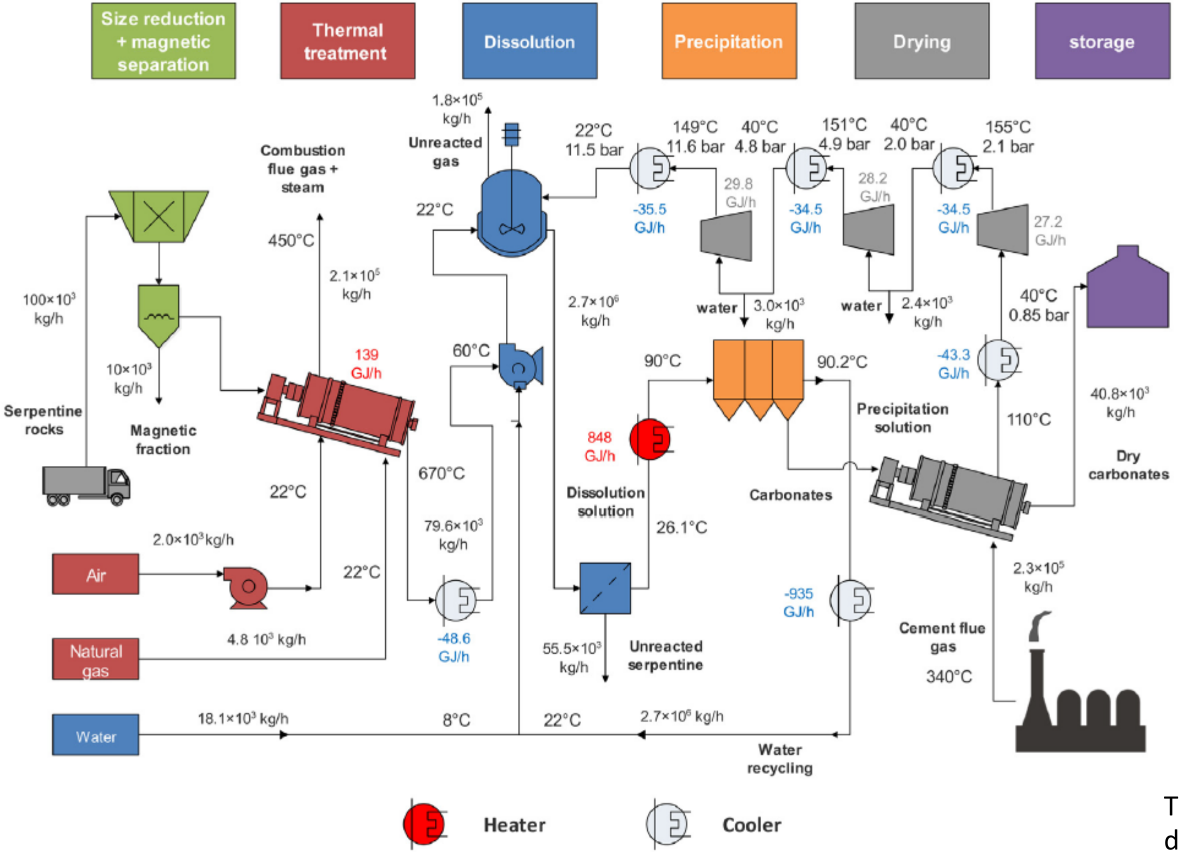
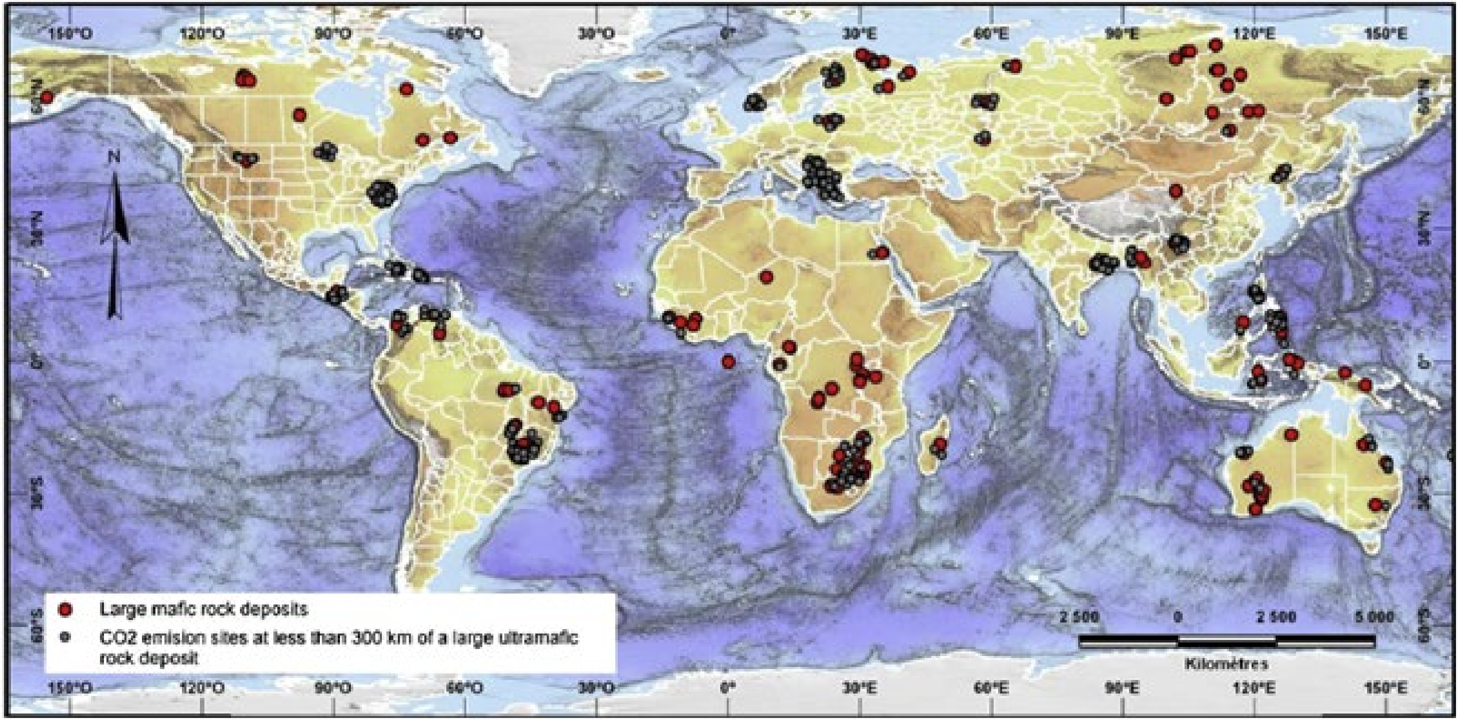
Project	Technology and feedstock	Comment
Carmex (New Caledonia, France)	Direct aqueous mineral carbonation of mafic/ultramafic mining wastes	New Caledonia is an excellent candidate for implementing mineral carbonation due to the availability of both suitable mineral feedstocks and proximity to CO_2 emission sources. (Ended 2012)
MCi (New South Wales, Australia)	Proprietary direct aqueous carbonation of various industrial wastes and mine tailings	Demonstration projects planned with Japanese ITOCHU Corporation. The business model of MCi is that the cost of CO_2 capture is outweighed by producing valuable materials
Québec process (INRS, Québec, Canada)	Aqueous mineral carbonation process using heat treated serpentinite-based tailings and cement plant flue gas	Potentially commercially viable process, provided there is sufficient market for the produced magnesium carbonate
HiGCarb process (CSC, Kaohsiung, Taiwan)	Rotating packed bed using hot-stove gas (28.8 vol% CO_2) and wastewater for blast oxygen furnace slag carbonation	Carbonate product used as cement additive and fast conversion times indicate potential feasibility for further scale-up in the near future
Kawashima-Daini project, Japan	Indirect aqueous carbonation of concrete sludge to produce $CaCO_3$ using boiler flue gas	Net CO_2 reduction achieved, but the low reaction rates and large feedstock amounts needed / ton of CO_2 represents a barrier for further development
CarbonVault™	Carbonation of diamond mine tailings by De Beers Group using various AMC technologies	Pilot testing delayed in 2020/2021. Environmental targets include carbon neutral mining operations by 2030

Promising, much information



Tebbiche, I., et al. 2021,
doi: 10.1016/j.cherd.2021.06.002

Ultramafic rock < 300 km from CO_2 emissions



Bodénan, F. et al. 2014,
doi: 10.1016/j.mineng.2014.01.011

Example of report Appendix table on potential rock resources

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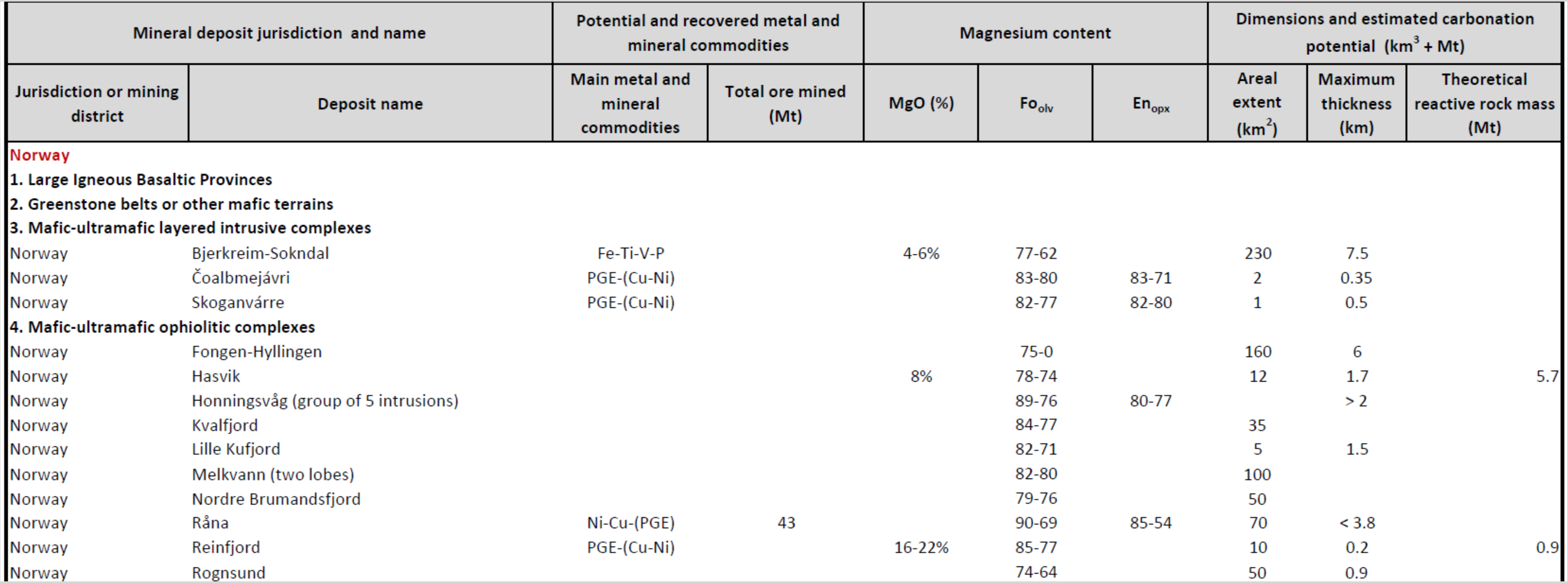

Mineral deposit jurisdiction and name		Potential and recovered metal and mineral commodities		Magnesium content			Dimensions and estimated carbonation potential (km^3 + Mt)		
Jurisdiction or mining district	Deposit name	Main metal and mineral commodities	Total ore mined (Mt)	MgO (%)	Fo_{olv}	En_{opx}	Areal extent (km^2)	Maximum thickness (km)	Theoretical reactive rock mass (Mt)
Norway									
1. Large Igneous Basaltic Provinces									
2. Greenstone belts or other mafic terrains									
3. Mafic-ultramafic layered intrusive complexes									
Norway	Bjerkreim-Sokndal	Fe-Ti-V-P		4-6%	77-62		230	7.5	
Norway	Čoalbmejávri	PGE-(Cu-Ni)			83-80	83-71	2	0.35	
Norway	Skoganvárre	PGE-(Cu-Ni)			82-77	82-80	1	0.5	
4. Mafic-ultramafic ophiolitic complexes									
Norway	Fongen-Hyllingen				75-0		160	6	
Norway	Hasvik			8%	78-74		12	1.7	5.7
Norway	Honningsvåg (group of 5 intrusions)				89-76	80-77		> 2	
Norway	Kvalfjord				84-77		35		
Norway	Lille Kufjord				82-71		5	1.5	
Norway	Melkvann (two lobes)				82-80		100		
Norway	Nordre Brumandsfjord				79-76		50		
Norway	Råna	Ni-Cu-(PGE)	43		90-69	85-54	70	< 3.8	
Norway	Reinfjord	PGE-(Cu-Ni)		16-22%	85-77		10	0.2	0.9
Norway	Rognsund				74-64		50	0.9	

Conclusions

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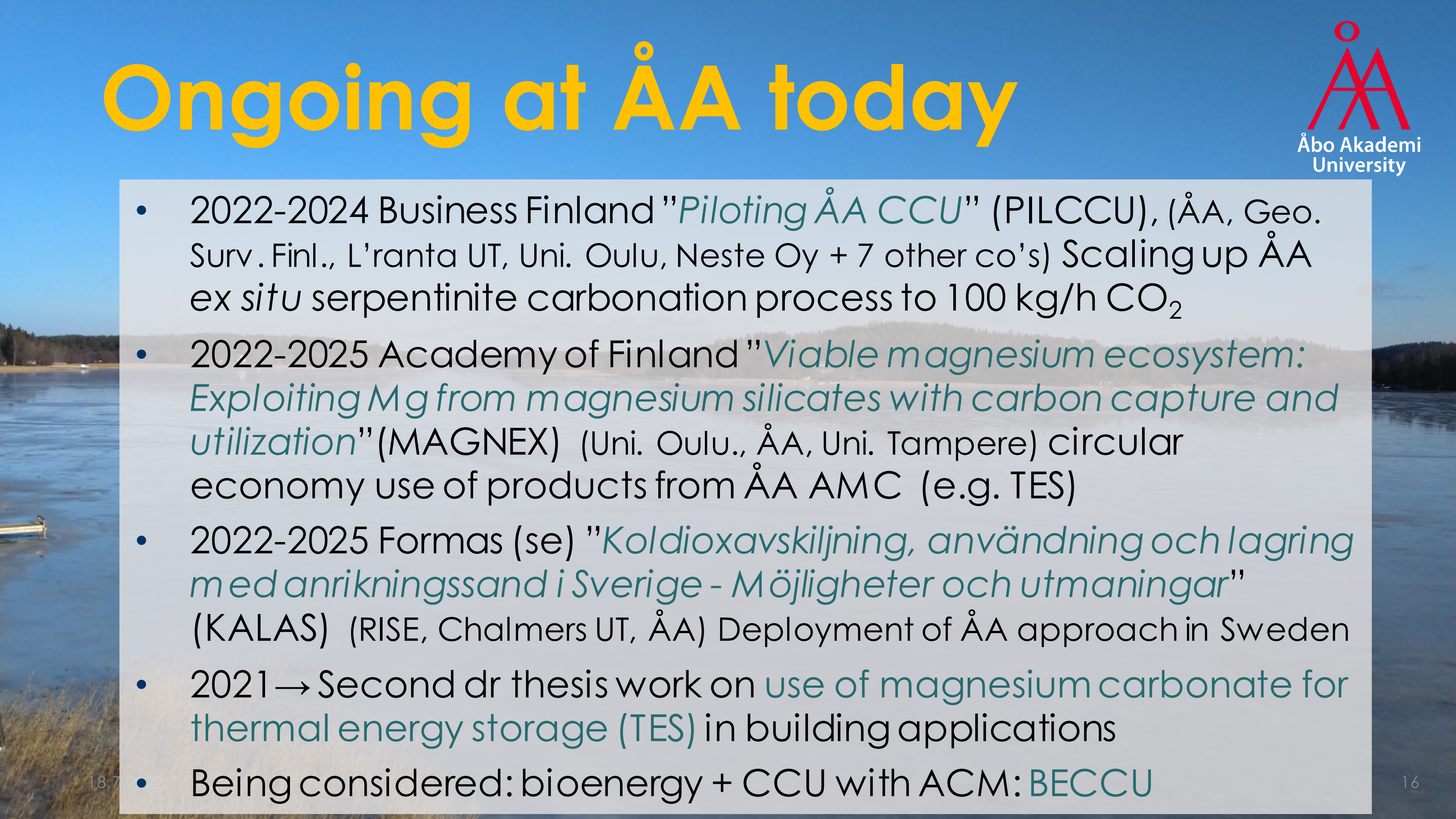
- Limited reported information (~ 10 publications, since 2015) that could support a > 0.1 Mt/a CO_2 business case
- TRL = 6 claimed by one actor; for calcium-based feedstock = 9
- Mining wastes availability may allow several Gt/a AMC
- Still much lab-scale work rather demo/pilot scale deployment
- CO_2 emissions pricing main driver for development rather than bussiness opportunities offered by products, or waste handling
- Hardly any reporting on hazardous / problematic side-streams
- LCA-type studies are entering the field
- Public awareness ~ 0, some knowledge on (conventional) CCS
- Summer 2020: new interest when CO_2 ETS costs became > 50 €



Ongoing at ÅA today

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- 2022-2024 Business Finland ”*Piloting ÅA CCU*” (PILCCU), (ÅA, Geo. Surv. Finl., L’ranta UT, Uni. Oulu, Neste Oy + 7 other co’s) Scaling up ÅA ex *situ* serpentinite carbonation process to 100 kg/h CO_2
- 2022-2025 Academy of Finland ”*Viable magnesium ecosystem: Exploiting Mg from magnesium silicates with carbon capture and utilization*”(MAGNEX) (Uni. Oulu., ÅA, Uni. Tampere) circular economy use of products from ÅA AMC (e.g. TES)
- 2022-2025 Formas (se) ”*Koldioxavskiljning, användning och lagring med anrikningssand i Sverige - Möjligheter och utmaningar*” (KALAS) (RISE, Chalmers UT, ÅA) Deployment of ÅA approach in Sweden
- 2021→ Second dr thesis work on use of magnesium carbonate for thermal energy storage (TES) in building applications
- Being considered: bioenergy + CCU with ACM: BECCU

Questions & answers

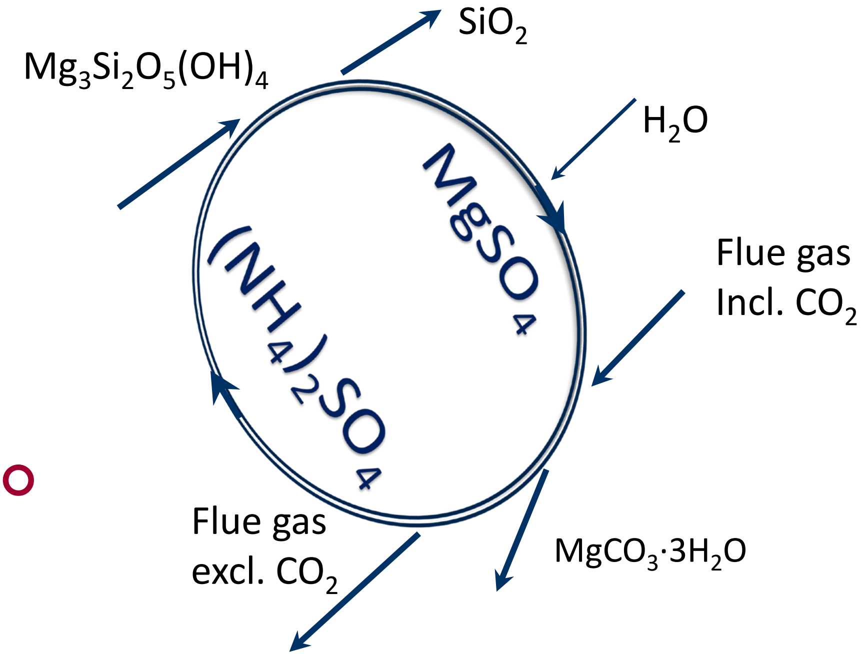
see also GHGT-16 later this year

ÅA approach: five routes

$Mg_3Si_2O_5(OH)_4$ + $3(NH_4)_2SO_4$
(+ heat 440°C) ←→
$3MgSO_4 + 2SiO_2$
$+ 5H_2O + 6NH_3$

$MgSO_4$ $+ 3H_2O + 2NH_3 + CO_2$ (g)
←→ $(NH_4)_2SO_4$ + **$MgCO_3 \cdot 3H_2O$**
(+ heat 500°C)

No heat effects when using aqueous solution process stages



Zevenhoven, ACEME2021 conference

ÅA approach: five routes

	Mg extraction	Intermediate salt	Mg salt carbonation
1 2012	Thermal with AS / ABS	$Mg(OH)_2$ (s)	Gas/solid press. fluid. bed
2 2014	Thermal with AS / ABS	$MgSO_4$ (aq)	Aqueous with NH_3 (aq)
3 2017	Thermal with AS / ABS	$MgSO_4$ (aq)	Aqueous with NH_3 (aq)
4 2019	Aqueous with AS / ABS	$MgSO_4$ (aq)	Aqueous with NH_3 (aq)
5 2021	Aqueous with AS / ABS	$Mg(OH)_2$ (s)	Gas/solid press. fluid. bed

Routes 3, 4, 5 include membrane separation and membrane electrodialysis

AS = ammonium sulphate, ABS = ammonium bisulphate