Lifecycle and techno-economic assessment for carbon dioxide mineralization using Nordic rocks

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Abstract:

This paper presents lifecycle and techno-economic assessments of three carbon dioxide mineralization processes with the final objective of finding the best rock and process for large-scale mineralization. The two process routes consist of dry (thermal) or wet (aqueous) extraction of magnesium from rock, with purification and carbonation downstream in the process, processing nesquehonite $MgCO_3·3H_2O$. For the recovery of chemicals, removal of water or conversion of alkali sulfate by-product is needed. The best mineralization process was found to be Route 2, requiring about 6 tons of rock to capture 1 ton of CO_2 with an internal rate of return of 9.9 %. The most profitable process follows Route 4B, where an IRR of 29.9 % was reached. This route is not feasible, however, since it leads to more than 20 tons of CO_2 released for 1 ton of CO_2 mineralized. Another process capable of capturing CO_2 was Route 4A, where about 5 tons of rock is needed for every 1 ton of CO_2 captured. However, Route 4A was found to be financially unviable, due to the extraordinarily high costs of bipolar membrane electrodialysis for alkali salt conversion. For Routes 2 and 4A, the market price of nesquehonite product and equipment cost was found to determine profitability. For Route 4B, the market price of potassium hydroxide used, and sulfate produced were the most important for profitability, selling the by-products. Recycling chemicals in the process is imperative due to the associated carbon footprint of purchased chemicals. Use of mining waste rock rather than rock mined for the purpose of CO_2 mineralization is essential. Using electricity from renewable energy sources such as wind power is a must, due to the sometimes large carbon footprint of market electricity. For Route 2 to be economically viable, a market for nesquehonite must exist at a price of around 500 € per metric ton, representing a 2.7 billion € market for capturing 1 million tons CO_2 per year. An operational expenditure of 947 €/ton CO_2 and revenue of 3 090 €/ton CO_2 (yielding a positive cash flow of 2 143 €/ton CO_2) is reached for the best performing process Route 2 with Serp-P. Mineralization Routes 4A and 4B are concluded to be unviable due to cost of chemicals regeneration (R4A) and environmental pollution (R4B).

Keywords:

Life cycle assessment; Techno-economic assessment; Sustainability; Carbon capture and storage by mineralization.

1. Introduction

With the rising carbon dioxide (CO_2) levels in the atmosphere, global temperatures are rising. To mitigate further damage, carbon capture solutions such as carbon capture and storage by mineralization (CCSM) have great potential [1,2]. In CCSM, CO_2 is captured in magnesium carbonate or calcium carbonate, which are thermodynamically more stable than CO_2. Here, an indirect (stepwise) mineralization process consisting of extraction of Mg, removal of metals, Mg carbonation and lastly chemicals recovery will be investigated through life cycle assessment (LCA) and techno-economic assessment (TEA), highlighting both the environmental and economical dimensions of sustainability.

Two optional routes developed at Åbo Akademi University (ÅAU) will be assessed, and referred to as Routes 2 and 4, see Figure 1. Route 2 consists of a dry (thermal) extraction step and wet (aqueous) carbonation step. Routes 4A and 4B consist of wet (aqueous) extraction of Mg and wet carbonation of Mg, where either a bipolar membrane electrodialysis (BPMED) unit is used for chemicals recovery (R4A) or chemicals are bought and sold (R4B). Details for five alternative routes for mineralization developed at ÅAU are given elsewhere [3].

The chemical reactions involved are for Route 2, with extraction at 400-440°C (R.1), purification at room temperature and carbonation at around 35 °C (R.2):

$$3MgO \cdot 2SiO_2 \cdot 2H_2O\ (s) + 3(NH_4)_2SO_4(s) \leftrightarrow 3MgSO_4(s) + 6NH_3\ (g) + 3H_2O(g) \tag{R1}$$

$$MgSO_4(aq) + 4H_2O(l) + 2NH_3(aq) + CO_2(g) \leftrightarrow MgCO_3 \cdot 3H_2O(s) + (NH_4)_2SO_4\,(aq) \tag{R2}$$

where instead of aqueous ammonia (NH_3) as in Route 2 also potassium hydroxide (KOH) can be used for the pH raise during purification and the carbonation step after that, as in Routes 4, the by-product then being potassium sulfate (PS, K_2SO_4).

For Routes 4, extraction is conducted using sulfuric acid (H_2SO_4) at 80°C instead (R.3)

$$3MgO \cdot 2SiO_2 \cdot 2H_2O\ (s) + 3H_2SO_4(aq) \leftrightarrow 3MgSO_4(s) + 3H_2O(l) \tag{R3}$$

For chemicals recovery the ammonium sulfate (AS, $(NH_4)_2SO_4$) can be processed for re-use by mechanical vapor recompression (MVR) crystallization while PS (aq) can be converted into KOH and H_2SO_4 for re-use using BPMED (Route 4A) or sold, requiring purchase of make-up H_2SO_4 and KOH (Route 4B).

$$K_2SO_4(aq) + 2H_2O(l) + electricity \leftrightarrow 2KOH(aq) + H_2SO_4\,(aq) \tag{R4}$$

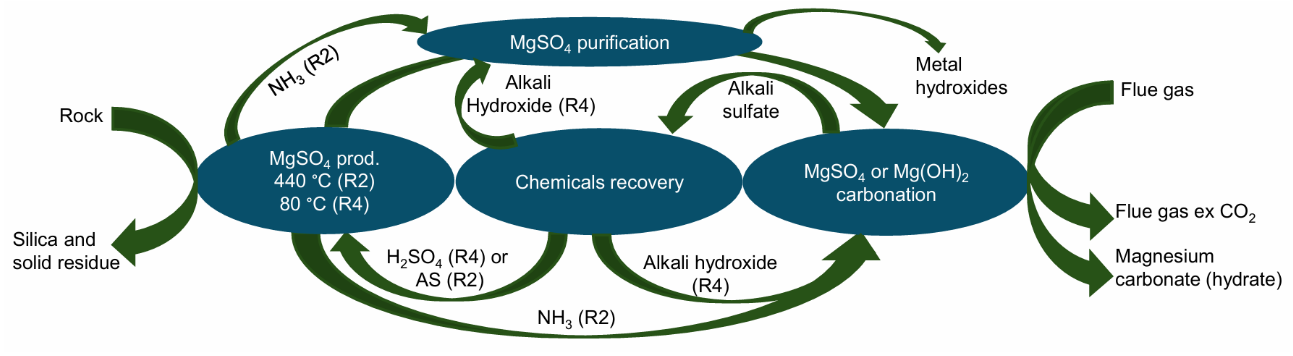


***Figure 1.** ÅAU Routes 2 (R2) and 4 (R4) process description.*

In the LCA study by Ostovari et al. [4], five indirect (serpentine, olivine and steel slag) and direct (serpentine) mineralization routes were studied. For direct mineralization, pre-treatment of the rock and for indirect mineralization, the reagent recovery are the most energy intensive steps. In the LCA and cost analysis by Giannoulakis et al. [5], it was found that CO_2 emissions for power plants in Europe could be reduced by 15-64% through mineralization. Implementing mineralization with power generation increased cost of electricity by 209-370%. In the technical and economic study by Pasquier et al. [6], 234 kg of CO_2 could be captured per ton of rock, requiring 7.8 GJ/ton CO_2 of energy. By producing valuable by-products from the process, the revenues of the process reached 644 \$/ton CO_2 captured, while without such revenues a cost of 144 \$/ton CO_2 captured was obtained. In the LCA study by Nduagu et al. [7], ÅAU process Route 1 was studied, capturing 90% of the CO_2 emissions from a power plant, releasing 433 kg of CO_2 equivalents for every ton CO_2 captured. Net power production efficiency was reduced by 30% while 51% of the life cycle CO_2 emissions were avoided.

2. Methodology

The chosen CCSM processes are (from the five routes in [3]) Route 2 using rock Serp-P, Route 4A using Serp-H and Route 4B using Serp-P, see also [8]. The location of the CCSM plant is assumed to be in Finland. The functional unit for the assessments will be 1000 kg/h of external CO_2 capture, similar to [8], accounting for CO_2 release from carbonate in the rocks during processing. In this paper, the LCA analysis will consider the final tons of rock to capture 1 ton of external CO_2.

2.1. Life cycle assessment

To determine the environmental impact of CO_2 mineralization by the ÅAU mineralization routes, an LCA was carried out. The system boundaries are given in Figure 2, including mining of the rock, transportation of the rock and all the inputs/outputs to/from the CCSM process.

Rock transportation will be assessed in this work, with the complete CCSM plant located at the CO_2 source. If extraction of Mg occurs where the rock is located and carbonation of Mg occurs where the CO_2 source is located, magnesium hydroxide ($Mg(OH)_2$) or magnesium sulfate ($MgSO_4$) could be transported for both Routes 2 and 4. Considering the mass differences, for every 1 kg of rock processed, 0.87 kg of $MgSO_4$ (dry) and 0.42 kg of $Mg(OH)_2$ (dry) would be transported for Route 2. For Route 4, transporting $MgSO_4$ (dry) would lead to 0.86 kg (R4A) and 0.48 kg (R4B); for $Mg(OH)_2$ transportation (dry), 0.41 kg (R4A) and 0.23 kg (R4B). Note that transporting $Mg(OH)_2$ would be preferable as this involves half the mass of $MgSO_4$ to be transported. (Another benefit for transportation of $Mg(OH)_2$ versus $MgSO_4$ is the fact that $Mg(OH)_2$ is insoluble in water and can be filtered off before transportation. However, this feature falls outside the scope of this work). More detail is given elsewhere [9].

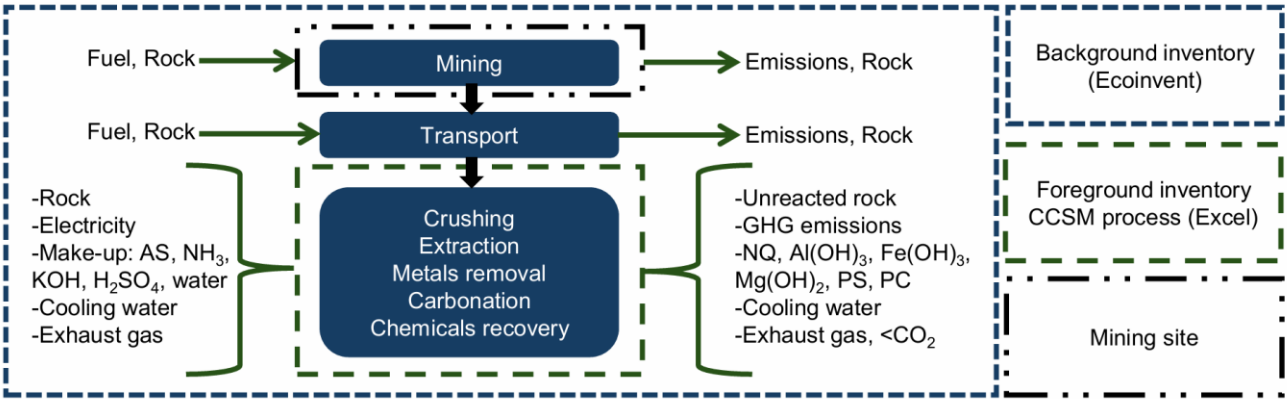


Figure 2. *Life cycle assessment boundaries, showing background and foreground inventory.*

For the background inventory data, SimaPro 9.4 software with the Ecoinvent v3.5 (released 2018) database was used, using the system model “allocation cut-off by classification”. The system process approach was chosen as it is recommended over Unit process, giving faster calculations. For the impact assessments, “ReCiPe 2016 Midpoint (H)” method was chosen from the Methods library to estimate CO_2 equivalent emissions per ton CO_2 captured.

Table 1. *Life cycle inventory for the selected rocks, foreground data taken from [8], where 1 000 kg/h of external CO_2 is captured (without LCA accounted for).*

Flows:	**R2 Serp-P**	**R4A Serp-H**	**R4B Serp-P**	**Units:**
		Input data:		
Uncertainty	±1.5	±0.3	±9.6	
Rock	3 894	3 541	13 382	kg/h
Make-up $(NH_4)_2SO_4$	93			kg/h
Make-up KOH		34	10 801	kg/h
Make-up H_2SO_4		52	7 816	kg/h
Water make-up	1 990	2 056	6 216	kg/h
Electricity	8.811	14.302	9.656	MW_{el}
Cooling water	4.996	7.309	7.323	$MW_{20°C}$
Cooling water	1 018	1 270	1 213	m^3/h
		Output data:		
$MgCO_3 \cdot 3H_2O$	3 522	3 169	6 638	kg/h
Captured CO_2	1 121	1 009	2 113	kg/h
$Al(OH)_3$	13	2	19	kg/h
$Fe(OH)_{3+2}$	133	392	251	kg/h
$Mg(OH)_2$	144	111	232	kg/h
K_2SO_4			13 858	kg/h
K_2CO_3			2 520	kg/h

Table 1 lists the foreground inventory for the CCSM processes assessed. Uncertainty ranges are taken from [8], based on uncertainty in Mg extraction analyses and CO_2 release analyses from the rock. The inputs that will be considered in the LCA will be rock, electricity, make-up chemicals and cooling water. For the background data, SimaPro will be used. For the assessment of emissions from mining, the Ecoinvent data for chrysotile (chemically identical to serpentine) rock (GLO, global) will be used. For the assessment of electricity consumption, the electricity market mix for Finland is used (market, medium voltage (FI) from 2014) and wind power from Finland (transformation, >3 MW_{el} turbine onshore (FI) from 2014).

Impacts from chemicals such as AS and KOH are assessed using European transformation data (RER) and H_2SO_4 market data (RER). Water is considered using market data (Europe without Switzerland). For the transportation of rock, both the mining location and CO_2 source are assumed to be close to the train tracks. For the assessment, freight trains for Europe are used (market, Europe without Switzerland) with a transportation distance of 500 km. Among output products are nesquehonite (NQ, $MgCO_3 \cdot 3H_2O$), aluminum and iron (iii) hydroxide ((Al, Fe)$(OH)_3$), magnesium and iron (ii) hydroxide ((Mg, Fe)$(OH)_2$), potassium sulfate (PS) and potassium carbonate (PC, K_2CO_3), see Table 1.

2.2. Techno-economic assessment

To determine how the different CCSM routes perform financially/economically, a TEA was carried out. Table 2 gives the data for the TEA for process equipment that were sized in [8]. From these flows, area, volume data and so forth, different cost estimation methods will be used.

For most process equipment, the capital expenditure (CAPEX) will be determined by purchased equipment cost correlations from [10]. The costs for the rotary kiln thermal extraction (R2) and rotary dryer equipment for product drying were estimated from [11], giving a cost of ~ 400 k$ for 200 tpd (tons per day) operation. Other minor cost items such as infrastructure, operating and labor cost will not be used. The cost of the kiln will be used as the purchased equipment cost. The cost for a vacuum membrane degasser (VMD) unit as part of recovered chemicals dewatering was estimated in price per m^2 from [12], at about 200 $/$m^2$ (for a whole assembled module). The costs for the ion exchange resin (IER) unit (needed for removing; Mg^{2+} ions prior to the BPMED, preventing $Mg(OH)_2$ precipitation was estimated from [13]), at 40 to 200 $/$ft^2$ was given for strong acid cation resins. A density value of 800 kg/m^3 resin and 100 $/$ft^2$ were used to estimate resin cost per kg, giving 4.46 $/kg resin material.

The costs for a scaled-up BPMED unit were estimated based on the MSc thesis of Hägglund (2024) [14], For the bipolar membranes and cationic/anionic membranes costs of 3 000 and 600 €/m^2 were given, respectively. The needed membrane area was then calculated to be 385 and 598 m^2/kmol for PS processing with bipolar membranes and cationic and anionic membranes, respectively. From the throughput of PS, the BPMED membrane area and costs can be calculated. Bag filter costs were estimated from [15], with a typical unit cost of 20 k$ to 50k$ for a maximum flow 8 500 m^3/h. For Route 2 a needed flow of 1.9 m^3/s (about 6 700 m^3/h), an average cost of 35k$ will be assumed. Finally, the costs for the heat pump used were estimated from [16], at an industry-scale average value of 400 €/kW thermal. Caution is needed with this estimate as cost ranges 300 - 900 €/kW thermal and as low as 200 -250 €/kW thermal (in China) were given as well (for $MW_{thermal}$ scale heat pumps).

Table 2. *Parameters for cost estimation of process equipment for the techno-economic assessment where 1 000 kg/h of external* CO_2 *is captured (without LCA accounted for). [8]*

Equipment	R2 Serp-P	R4A Serp-H	R4B Serp-P	Unit	Source:
Ball mill	3.9	3.5	13.4	Flow, t/h	10
Belt conveyor	225.0	200.0	200.0	Length, m	10
Bucket elevator	18.0	3.0	3.0	Height, m	10
Rotary kiln	244.8	-	-	Flow, tpd	11
Centrifugal pump	546.3	885.7	532.7	Flow, L/s	10
Gas blower	21.8	3.2	4.2	Flow, m^3/s	10
F&P filtration	1.4	1.3	3.3	Volume, m^3	10
Agitated reactor	245.0	419.4	577.1	Volume, m^3	10
BPMED tanks	-	916.0	-	Volume, m^3	10
S&T heat exchanger	173.4	314.5	569.6	Area, m^2	10
Plate heat exchanger	2 808	888.5	1 380	Area, m^2	10
VMD degasser	20 423	-	-	Area, m^2	12
IER	-	80.5	145.9	Volume, m^3	13
BPMED	-	82 672	-	Area, m^2	14
MVR unit	1 093	852.0	2 902	Area, m^2	10
Vacuum rot. Dryer	91.8	89.1	173.0	Flow, tpd	11
Bag filter	1.9	-	-	Flow, m^3/s	15
Refrigeration	0.101	-	-	Elec., MW_{el}	10
Heat pump	1.826	1.701	4.430	Heat, $MW_{105\,°C}$	16

Using the cost estimation methods and sources seen in Table 2, a CAPEX estimate can be made for the total investment needed to build a CCSM plant. The estimation method used follows [10]. Total equipment costs include corrections for geographical location, cost escalation and material of construction. The cost correlations are corrected from January 2010 using Chemical Engineering magazine CEPCI values up to June 2024. To account for inflation in equipment cost, EUR = 1.08USD is used (2024) where needed. The material of construction chosen for all equipment is 316 stainless steel, as corrosive chemicals are handled – see [10]. Cost for the rotary kiln, VMD, IER, BPMED and bag filter were taken from 2024 and forward with 2024 prices. The cost estimates provided here can be categorized into a class 4 estimate (based on the scale by The Association for the Advancement of Cost Estimating International) with a +/- 30 % accuracy (using [10]).

Besides purchased equipment costs, costs for installation, offsites, design and so forth are needed as well. The inside battery limit (ISBL) includes costs such as installing equipment, piping, electrical work, labor, rental of equipment, insurance, import duties etc. The outside battery limit (OSBL) costs include costs reflecting changes in the site's infrastructure surrounding the plant. In this work, it is assumed that the CCSM plant is built near existing infrastructure requiring a moderate amount of OSBL work. Engineering costs include the detailed design of the process equipment, piping systems and control systems. Administrative costs are also included for project management, travel and inspection. Contingency charges are meant to be used if there are changes in project scope, in prices, currencies and labor disputes. With all these cost estimations, the total plant investment can be estimated as given in section 3.2. For all ISBL, OSBL, design and contingency estimation values, see [10], where values used are the balanced values for solid-liquid processes (moderate modifications).

For the TEA analysis, costs and prices of consumables and products are needed as well, see Table 3. The NQ selling price is assumed to be 500 €/t and while for mineralization avoided costs of CO_2 80 €/t [17] emitted will be used. Make-up water is assumed to cost 2 €/m^3 and electricity price is assumed to cost 50 €/MWh (the average spot price for Finland in 2025). All other costs and prices were found online (imarcgroup.com). Plant operational hours are assumed to be 8760 h per year.

Table 3. *Costs for make-up chemicals and product prices per metric ton.*

Costs:	Value:	Unit:	Source:	Prices:	Value:	Unit:	Source:
$(NH_4)_2SO_4$	250	€/t	Imarc	$MgCO_3{\cdot}3H_2O$	500	€/t	Assumed
NH_3	560	€/t	Imarc	$Al(OH)_3$	560	€/t	Imarc
KOH	715	€/t	Imarc	$Fe(OH)_{2+3}$	835	€/t	Imarc
H_2SO_4	145	€/t	Imarc	$Mg(OH)_2$	700	€/t	Imarc
Water	2	€/t	Assumed	K_2SO_4	500	€/t	Imarc
Electricity	50	€/MWh	Assumed	K_2CO_3	1630	€/t	Imarc
				CO_2	80	€/t	[17]

3. Results and discussion

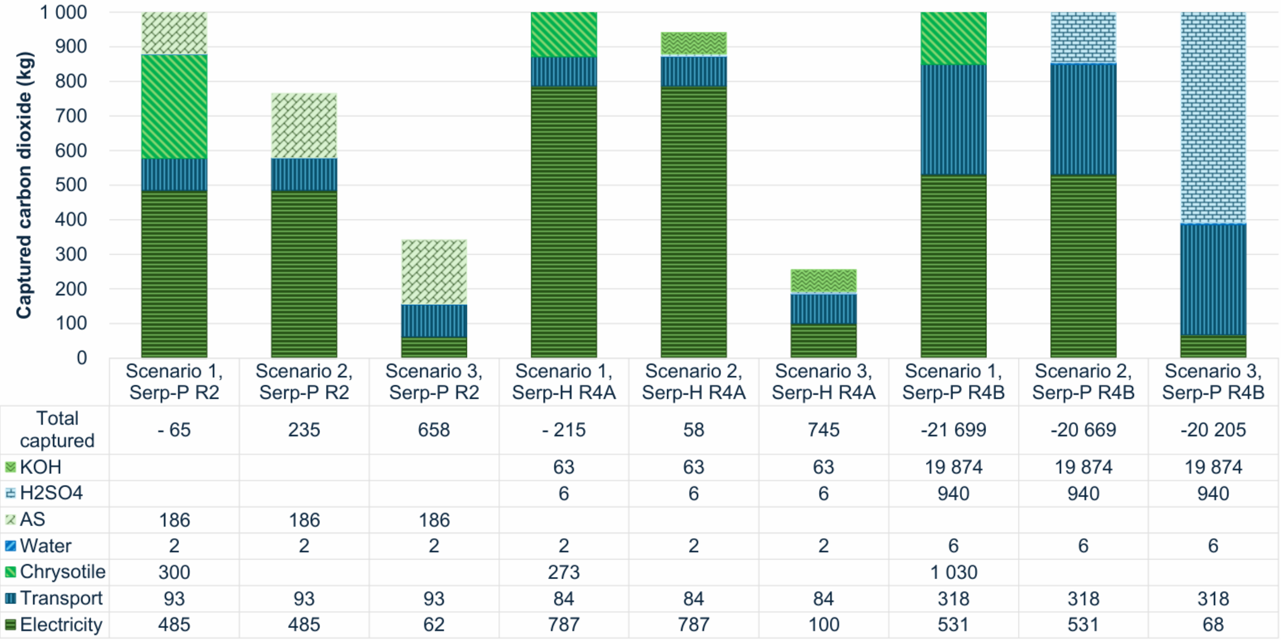
3.1. Life cycle assessment

The CO_2 equivalent emissions for the processes calculated using SimaPro can be seen in Figure 3. Three scenarios were modelled:

scenario 1 accounting for mining of chrysotile and using the electricity from the market mix in Finland,

scenario 2 accounting for electricity from the market mix in Finland without chrysotile mining, and

scenario 3 accounting for wind power from Finland without chrysotile mining.



	Scenario 1, Serp-P R2	Scenario 2, Serp-P R2	Scenario 3, Serp-P R2	Scenario 1, Serp-H R4A	Scenario 2, Serp-H R4A	Scenario 3, Serp-H R4A	Scenario 1, Serp-P R4B	Scenario 2, Serp-P R4B	Scenario 3, Serp-P R4B
Total captured	- 65	235	658	- 215	58	745	-21 699	-20 669	-20 205
KOH				63	63	63	19 874	19 874	19 874
H2SO4				6	6	6	940	940	940
AS	186	186	186						
Water	2	2	2	2	2	2	6	6	6
Chrysotile	300			273			1 030		
Transport	93	93	93	84	84	84	318	318	318
Electricity	485	485	62	787	787	100	531	531	68

Figure 3. *CO_2 equivalent emissions from SimaPro for three scenarios for Routes 2, 4A and 4B.*

The different scenarios highlight the impact of electricity sources (market mix or renewables) and the impact on mining specifically for CCSM (instead of using waste from mining activities). For all scenarios, transportation, make-up water and chemicals are accounted for. In Figure 3, the electricity CO_2 equivalent emissions values have been changed to reflect the current development of the electricity grid in Finland. In SimaPro, the value for the electricity mix is about 247 g CO_2 equivalent/kWh (from 2014) and about 27 g CO_2 equivalent/kWh (from 2014) for wind power. Finnish electricity mix values are in 2025 about 37 to 72 g CO_2 equivalent/kWh, see [18] and [19], respectively. In Figure 3, an average of 55 g CO_2 equivalent/kWh is used.

In Finland, large amounts of wind power have been installed the last decade, effectively decarbonizing the electric grid alongside nuclear power for base load purposes, see [19]. For wind power, 7 g CO_2 equivalent/kWh is used, see [20]. To be clear, only Figure 3 electricity CO_2 equivalent emissions have been changed, all other figures and tables follow section 2.1 methodology. Furthermore, AS data in SimaPro was checked to equal 2 kg CO_2 equivalent per kg AS, meanwhile sources such as [21] give 1 kg CO_2 equivalent per kg AS. In Figure 3, the SimaPro value is used, however, note that for Route 2 scenario 3 the total captured value could approach about 750 kg CO_2 captured using 2026 data for AS, see [21].

Route 4A is the best performing route, effectively capturing 745 kg CO_2 when feeding 1000 kg external CO_2 to the process when using wind power and mining waste (offsetting CO_2 emissions on other mining activities). Including the mining of serpentine (~ chrysotile) for Route 4A, lowers the CO_2 capture potential by 273 kg. Route 2 can capture 658 kg of CO_2 when using wind power and mining waste. The worst process is Route 4B, where purchasing KOH and H_2SO_4 and selling the by-product K_2SO_4 leads to more than 20 tons of CO_2 equivalent emissions when capturing 1 ton of CO_2. For Route 2 using electricity from the market mix rather than renewables, 235 kg of CO_2 can be captured, meanwhile for Route 4 only 58 kg can be captured.

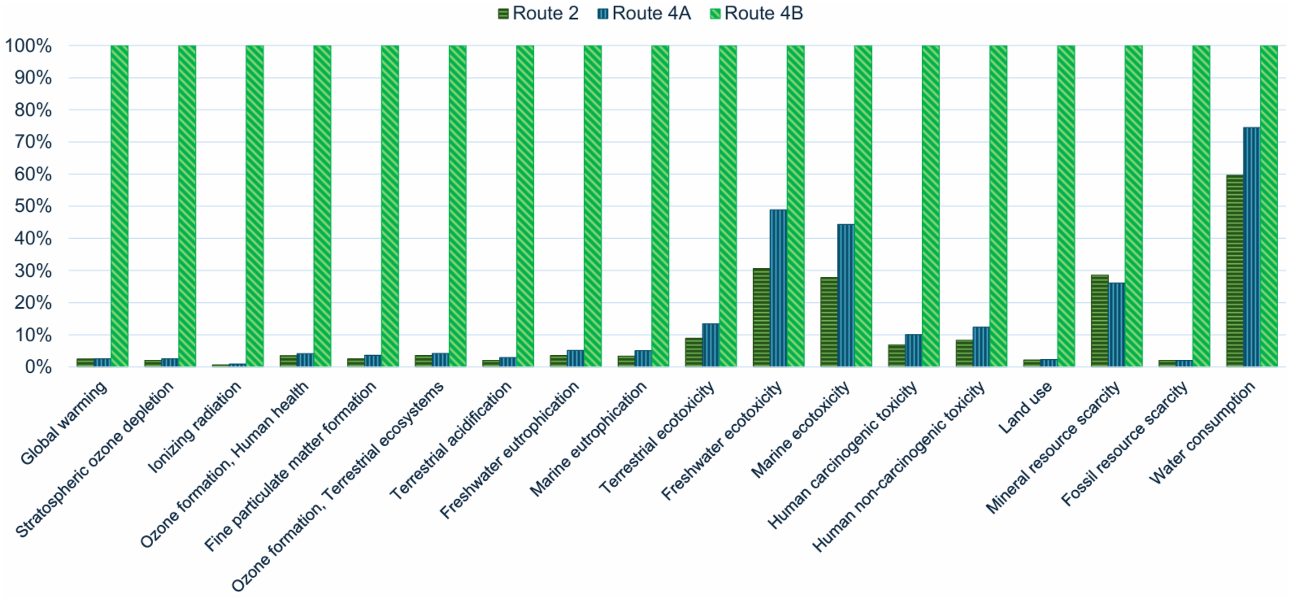


Figure 4. *Routes 2, 4A and 4B damage categories comparison.*

The different routes were compared in terms of damage to the environment, see Figure 4. Route 4B is the most polluting and damaging process route. When it comes to midpoint categories where the two other process routes are the closest damage wise are in water consumption, freshwater ecotoxicity and marine ecotoxicity. The least damaging CCSM route for both midpoint and endpoint damage categories is Route 2. The reason why Route 4B performs so poorly lies in the production of KOH (at an external facility), produced by electrolysis of potassium chloride, consuming large amounts of electricity. Another problem is the production of H_2SO_4, which releases almost 1 ton of CO_2 when mineralizing 1 ton of external CO_2 in NQ.

The different sources of damage on midpoint indicators are shown in Figures 5 and 6. For Routes 2 and 4A (Figures 5 and 6 top), electricity consumption can be seen to have the largest impact on most impact categories. For Route 4B (Figure 6 bottom), KOH and H_2SO_4 make-up are the most important impact categories. A clear challenge for Route 4B can therefore be identified, which is that chemicals in the CCSM process need to be recycled since otherwise, the process will result in much more CO_2 emitted than what is captured. For Routes 2 and 4A, the CO_2 footprint from the use of electricity is the most important in terms of CO_2 binding capacity. Using wind power or other renewable electricity sources is crucial for being able to capture significant amounts of CO_2. For Routes 2 and 4A, to a lesser extent, the make-up chemicals and transportation CO_2 footprint must be lowered as well, through cleaner production sources and/or through lower losses in the process. Washing process steps are already at a maximum in Route 2, thus the only way to minimize the AS losses is through outside water use and using MVR to evaporate the excess water to avoid dilution in the process. This will however require electricity.

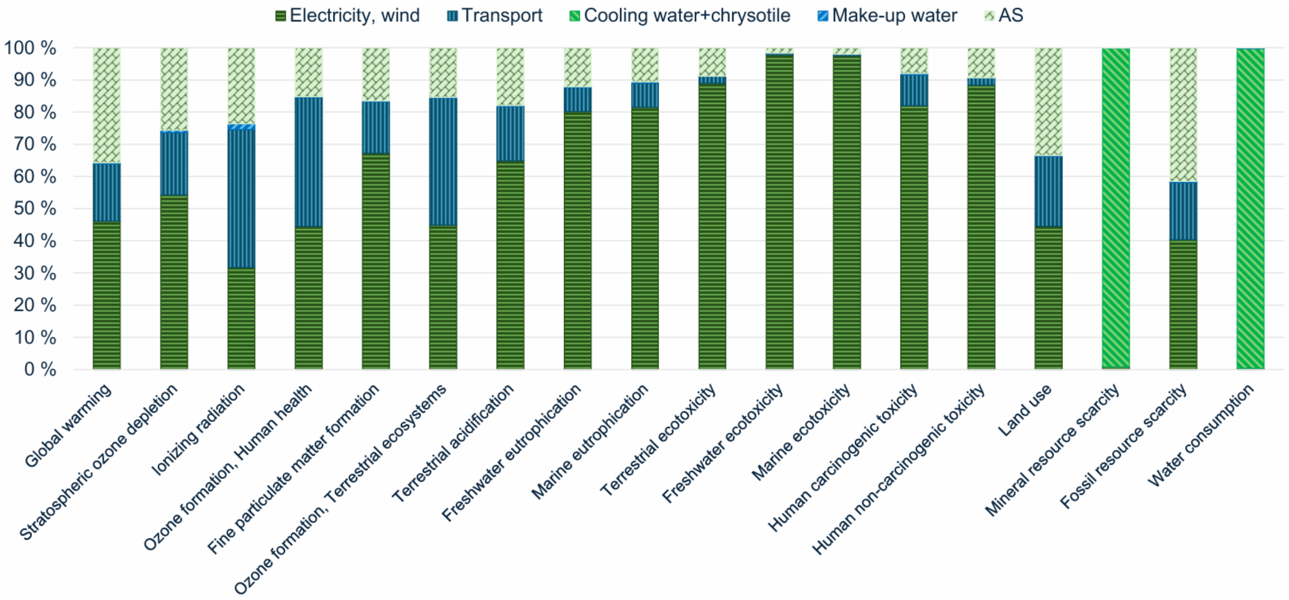


Figure 5. *Route 2 midpoint categories damage assessment, showing cooling water and chrysotile, AS, make-up water, transportation and electricity consumption.*

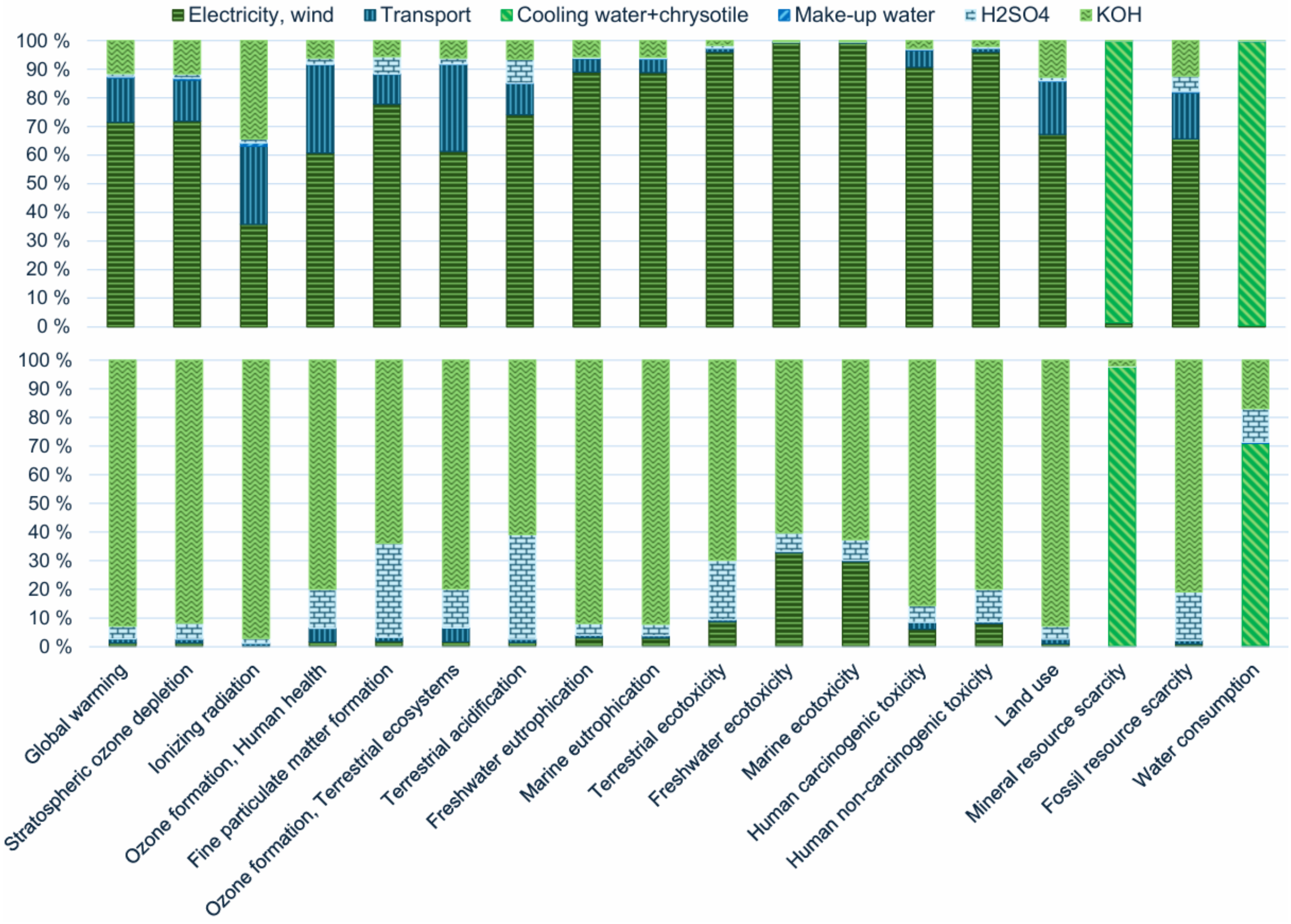


Figure 6. *Routes 4A (top) and 4B (bottom) midpoint categories damage assessment, showing cooling water and chrysotile, KOH, make-up water, transportation, H_2SO_4 and electricity consumption.*

3.2. Techno-economic assessment

Table 4 shows the cost breakdown for equipment in the process, ISBL, OSBL, design and contingency. Also given are total investment costs, CAPEX and the yearly operational expenditure (OPEX), revenues and cash flow. The total investment for all three processes is at around 110 million €, without accounting for LCA. For Route 4A the total investment cost would be 495 million € if the full BPMED costs were considered as well. As this would lead to enormous financial losses, the BPMED costs would have to be significantly reduced by about 93 %, reaching an internal rate of return (IRR) of 0 % (breakeven) after 20 years of process facility operation (inflation not accounted for). Route 4A can therefore be considered financially unviable, unless the BPMED CAPEX cost is reduced drastically, membrane lifetime (currently at 3 years) is extended and/or less membrane area is needed.

Table 4. *CAPEX, OPEX and revenues, where 1 000 kg/h of external CO_2 is captured (without LCA accounted for). For cost estimation sources, see Table 2.*

Routes:	**R2 Serp-P (€)**	**R4A Serp-H (€)**	**R4B Serp-P (€)**	**Cost estimation source:**
Ball mill	566 612	544 245	949 530	10
Belt conveyor	75 139	37 827	104 129	10
Bucket elevator	29 130	2 632	9 804	10
Rotary kiln	521 308	-	-	11
Centrifugal pump	353 042	2 375 636	318 061	10
Gas blower	1 033 322	152 416	187 347	10
F&P filtration	790 077	788 077	921 143	10
Agitated reactor	3 263 324	3 248 766	5 854 429	10
BPMED tanks	-	1 194 300	-	10
S&T heat exchanger	115 914	148 210	221 118	10
Plate heat exchanger	695 995	242 288	334 615	10
VMD degasser	4 349 359	-	-	12
IER	-	215 778	391 088	13
BPMED	-	28 498 227	-	14
MVR unit	3 789 094	3 376 878	5 936 460	10
Vacuum rot. Dryer	195 558	189 752	368 382	11
Bag filter	37 269	-	-	15
Refrigeration	701 620	-	-	10
Heat pump	1 030 225	959 835	2 499 197	16
Total equipment cost:	17 546 988	42 974 868	18 095 303	
Equipment erection	8 773 494	6 738 320	9 047 652	10
Piping	10 528 193	8 085 984	10 857 182	10
Instrument. & control	5 264 096	4 042 992	5 428 591	10
Electrical	3 509 398	2 695 328	3 619 061	10
Civil	5 264 096	4 042 992	5 428 591	10
Structures & buildings	3 509 398	2 695 328	3 619 061	10
Lagging & paint	1 754 699	1 347 664	1 809 530	10
OSBL cost	26 652 705	20 470 118	27 485 559	10
Design & Engineering	16 657 941	12 793 824	17 178 474	10
Contingency	6 663 176	5 117 530	6 871 390	10
Total investment cost:	106 124 183	111 004 949	109 440 393	
Cash flow analysis:				
OPEX cost	5 459 474 947	12 403 927 1 901	82 032 321	€/year €/ton CO_2
Revenue	17 812 545 3 090	17 952 818 2 751	114 942 964	€/year €/ton CO_2
Cash flow	12 353 071 2 143	5 548 890 850	32 910 642	€/year €/ton CO_2

Analysis for Routes 2, 4A and 4B shows that the most expensive process equipment for the processes are VMD (Route 2), BPMED (Route 4A) and MVR (Route 4B), with the BPMED in a price class of its own. The agitated reactors are also relatively expensive equipment units. For Route 2, a cash flow of 2 143 €/ton CO_2 is obtained (all emissions included), with an OPEX cost of 947 €/ton CO_2 and an obtained revenue of 3 090 €/ton CO_2.

For Route 4A, if the BPMED costs can be reduced by 93 %, a cash flow of 850 €/ton CO_2 is reached, with an OPEX cost of 1 901 €/ton CO_2. The effect of replacement membranes cost, and the higher electricity consumption is evident compared to Route 2. Thus, with today's costs no CO_2 capture potential exists for Route 4A (see also [14]). For Route 4B no cost and revenue per ton CO_2 captured was calculated as it releases much more than is captured.

As most process equipment costs are class 4 estimates with a +/- 30 % estimation accuracy, a sensitivity analysis has been carried out, for the IRR, see Figure 7. Starting with costs in the processes, it can be noted that equipment costs make the IRR vary quite a lot, as all other (ISBL, OSBL, design and contingency) costs are calculated from the total equipment cost. The BPMED costs do not change the IRR much as the costs already had to be reduced by 93 %.

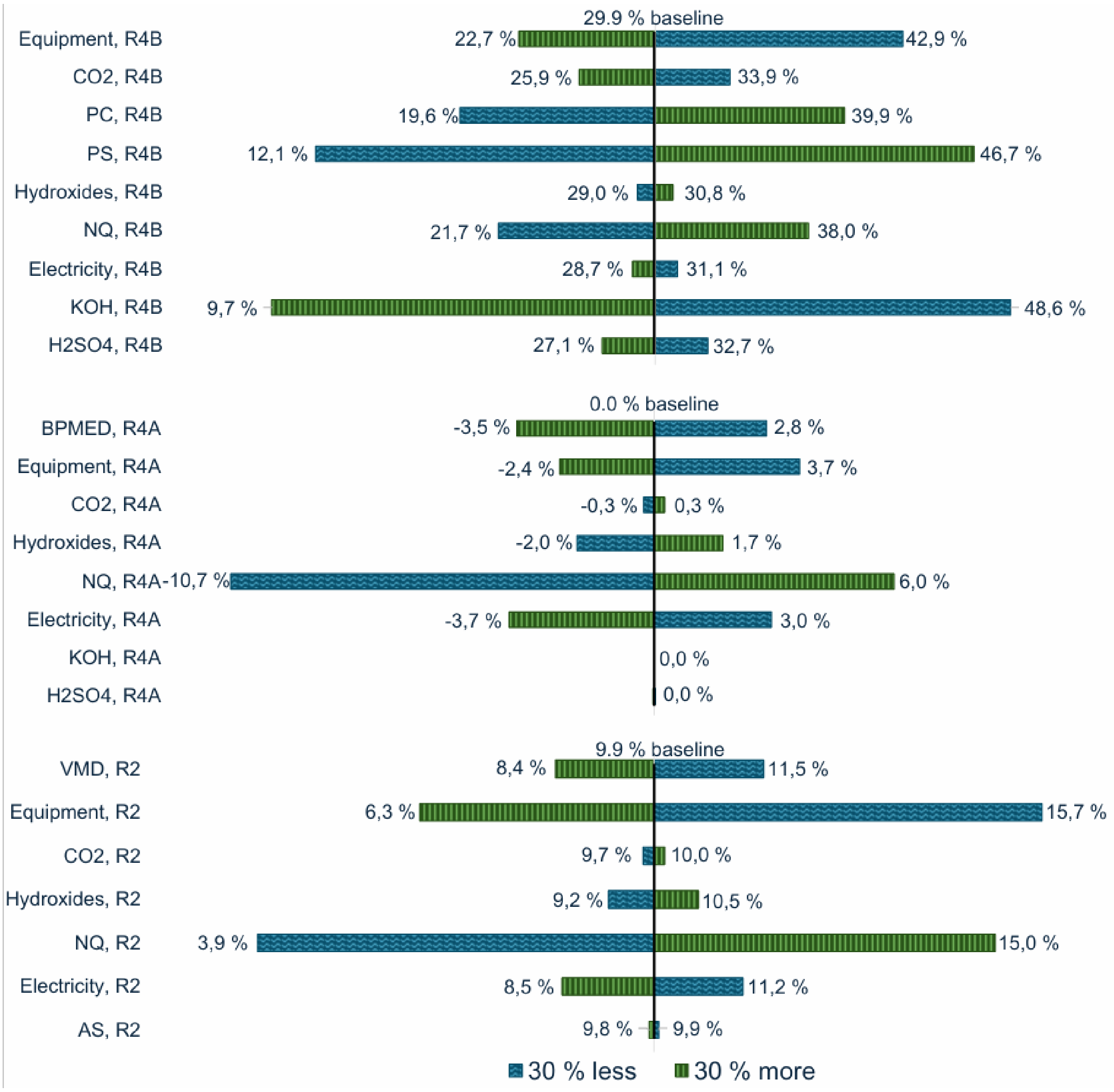


Figure 7. *Sensitivity analysis of the IRR, increasing and decreasing costs and prices by 30 % for all three routes, where 1 000 kg/h of external* CO_2 *is captured (LCA accounted for).*

For Route 2, the costs of the VMD impacts the profitability quite a lot but even if the cost of the VMD increases by 30 %, the process is still profitable with an IRR of 8.4 %. The electricity costs are not the most important variable, with an extremely low impact on Route 4B. Electricity costs, when increased by 30 %, start to impact Routes 2 and 4A, where profitability can be reduced by 1.4 % in Route 2 to an IRR of 8.5 %. For make-up chemicals, a variation in costs of 30 % will have a negligible effect for Route 2 and 4A, meanwhile for Route 4B the swings are large but still lead to profitable outcomes.

Moving on to revenues of products from the process, the NQ price is one of the more important factors. For Route 4B, the NQ price has less impact as PS and PC already have larger markets with higher or equal prices. The price of CO_2 emissions has a negligible impact on the process for Routes 2 and 4A, as the quantities captured are low and the low price of 80 €/t lead to practically no revenue. However, for Route 4B, a higher CO_2 emissions cost leads to a lower IRR due to the emissions resulting from the process itself.

Inputs and outputs for mineralizing 1 million tons of CO_2 per year can be seen in Table 5. The process routes would increase in size by factors of 173× (R2), 153× (R4A) and 228× (R4B), respectively based on the different CO_2 capture potential (see Figure 3). As Route 4B releases more CO_2 than what is captured, it will here be assumed that 500 kg of CO_2 can be captured to be able to show how much material input is needed for the process to work.

For the rock input to the routes, all emissions are included, consisting of carbonate CO_2 release from the rocks, sulfate losses via filtration moisture and resource consumption (from LCA study here). Routes 2 and 4A require around 6 and 5 tons of rock to capture 1 ton of CO_2, respectively. Around 4 to 5 million tons of NQ is produced when capturing 1 million tons of externally supplied CO_2. For Route 4B, 14 million tons of NQ is produced, due to the large carbonate CO_2 release from the rock. For Routes 2 and 4A, the inputs of make-up chemicals are at a manageable level of around 100 k to 200 k metric tons of chemicals per year. For Route 4B, the amounts of make-up chemicals needed and produced PS and PC may exceed market supply and demand (especially KOH and PC). For water make-up and cooling, around 3 million and 1.6 billion m^3 per year is needed for Routes 2 and 4A, respectively. The amounts of metal hydroxides produced will be significant but won't flood markets (see also [2]).

Table 5. *Tons per year of inputs and outputs, assuming capture of 1 million metric tons of CO_2 per year, LCA accounted for.*

Inputs	R2	R4A	R4B	Products	R2	R4A	R4B
	Inputs				Outputs		
Rock	5.92 M	4.75 M	26.8 M	$MgCO_3 \cdot 3H_2O$	5.35 M	4.25 M	13.8 M
$Water_{20\,°C}$	1.55 B	1.71 B	2.43 B	$Al(OH)_3$	19.8 k	2.69 k	38 k
$(NH_4)_2SO_4$	141 k	-	-	$Fe(OH)_{2+3}$	202 k	526 k	502 k
KOH	-	45.6 k	21.6 M	$Mg(OH)_2$	218 k	149 k	464 k
H_2SO_4	-	69.8 k	15.6 M	K_2SO_4	-	-	27.7 M
Water	3.02 M	2.76 M	12.4 M	K_2CO_3	-	-	5.04 M

4. Conclusions

In this paper, three different process routes were compared with LCA and TEA analyses, to find the most suitable process for CO_2 mineralization using serpentine-based rock from environmental and economical dimensions of sustainability. Based on the LCA and TEA analyses that have been presented in this work, Route 2 is the only process route that performs well both environmentally and financially. For Route 2, about 6 tons of rock is needed to capture 1 ton of CO_2 leading to an IRR of 9.9 %, with a production cost of 947 €/ton CO_2 and revenue of 3 090 €/ton CO_2, the process generates a positive cash flow of 2 143 €/ton CO_2 captured (including LCA). Route 4B is the most profitable process with an IRR of 29.9 % but releases about 20 tons of CO_2 equivalent to every 1 ton of CO_2 captured in nesquehonite. For Route 4A, about 5 tons of rock are needed for every 1 ton of CO_2 captured but will suffer financially due to the high BPMED costs. For CO_2 capture potential, renewable electricity, recycling of chemicals and waste rock are a must, due to the associated carbon footprints otherwise. To capture 1 million tons of CO_2 per year with Route 2 (best process), about 5 million tons of nesquehonite is produced. For the process to work nesquehonite must be sold at about 500 € per metric ton, otherwise the process is barely profitable, representing a market value of 2.7 billion € per year.

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Nomenclature

AS $(NH_4)_2SO_4$	Ammonium sulfate
BPMED	Bipolar membrane electrodialysis
CAPEX	Capital expenditure
CCSM	Carbon capture and storage by mineralization
CEPCI	Chemical Engineering Plant Cost Index
IER	Ion exchange resin
IRR	Internal rate of return
ISBL	Inside battery limits
MVR	Mechanical vapor recompression
NQ, $MgCO_3 \cdot 3H_2O$	Nesquehonite (magnesium carbonate trihydrate)
OPEX	Operational expenditure
OSBL	Outside battery limits
PC, K_2CO_3	Potassium carbonate
PS, K_2SO_4	Potassium sulfate
VMD	Vacuum membrane distillation

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