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Beneficial reuse or end-use options for brine from the Narrabri Gas Project region

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We acknowledge the Traditional Custodians whose ancestral lands we live and work upon and we pay our respects to their Elders past and present. We acknowledge and respect the deep spiritual connection and the relationship that Aboriginal and Torres Strait Islander people have to the Country. We also pay our respects to the cultural authority of Aboriginal and Torres Strait Islander people and their nations, in particular the Kamilaroi people in Narrabri, NSW.

Executive summary

The Narrabri Gas Project (NGP), which was granted development consent by the NSW government in 2020, is expected to generate large volumes of produced water (PW) requiring treatment for its beneficial reuse. Treatment of PW by reverse osmosis will lead to a highly saline by-product – brine, a concern in the local community. Development conditions for the management of PW include maximising the beneficial reuse of brine and salt and disposing of salt that cannot be beneficially reused, or other end-use options.

This project aimed to review beneficial reuse or end-use options for brine from the NGP region. The project objectives were to:

- Collate data and knowledge on brine in the NGP region;
- Undertake a review of existing and emerging innovative technologies and solutions for beneficial reuse or end-use options for brine;
- Conduct techno-socio-economic analysis (identify pros and cons) for the options identified in the objectives 1 and 2 above; and
- Communicate and engage with key stakeholders about the beneficial reuse or end-use options for brine.

The options evaluated for the beneficial reuse of brine included recovery of salts, critical minerals and other important elements, microalgae cultivation, acid mine drainage (AMD) neutralisation, and energy harvesting and storage. A 30-year techno-socio-economic assessment revealed varying financial performances. The selective salt recovery (SSR) via the Solvay process exhibited an annual revenue of A$5.92 million with A$58 million capital expenditure (CAPEX) and operating expenditure (OPEX) of A$8 million/year, yielding a negative net present value (NPV) of -A$107.1 million. The Sal-Proc SSR process presented a comparable revenue with lower CAPEX (A$9.1 million) and OPEX (A$2.1 million/year), yielding a positive NPV of A$17 million. The recovery of critical minerals and other important elements was not shown to be economically viable. The osmotic energy production, which harnesses the salinity gradient between two water bodies of different salinities to produce energy, showed a negative NPV (-A$1 million). AMD neutralisation and microalgae cultivation displayed potential annual revenues of A$5 million and A$32 million, respectively, albeit with varying CAPEX and OPEX. Hydrogen production from treated RO water exhibited substantial CAPEX and OPEX requirements, generating significant annual revenue and positive NPV, albeit constrained by water diversion from irrigation. A social assessment highlighted the significance of integrating brine reuse options with community co-benefits, emphasising contributions to local economies, employment, and training opportunities, managing scarce water resources carefully, and communicating environmental and public health standards to maintain public trust.

Abbreviations

AACE	-	Association for the Advancement of Cost Engineering
ACS	-	Annualised cost of the system
AEM	-	Anion exchange membrane
AMD	-	Acid mine drainage
AWE	-	Alkaline water electrolysis
AWG	-	Atmospheric water generation
BESS	-	Battery energy storage system
CAPEX	-	Capital expenditure
CapMix	-	Capacitive mixing
CATL	-	Contemporary Amperex Technology Co. Ltd.
CCS	-	Carbon capture and storage
COW	-	Cost of water
CSG	-	Coal seam gas
CWP	-	Combined water and power production
DCF	-	Discounted cashflow
ED	-	Electrodeionisation
EROEI	-	Energy return on energy invested
ESS	-	Energy storage system
FC	-	Fuel cell
HC	-	Hard carbon
IEX	-	Ion exchange
LCOE	-	Levelised cost of electricity
LCOS	-	Levelised cost of storage
LIB	-	Lithium-ion battery
MD	-	membrane distillation
ME	-	membrane electrolysis
NF	-	nanofiltration
NGP	-	Narrabri Gas Project
NPV	-	Net present value

O&G	-	Oil and gas
OPEX	-	Operational expenditure
PBP	-	Payback period
PEM	-	Proton exchange membrane
PRO	-	Pressure retarded osmosis
PV	-	Photovoltaic
PW	-	Produced water
RED	-	Reverse electrodialysis
RES	-	Renewable energy source
RO	-	Reverse osmosis
SGE	-	Salinity-gradient energy
SIB	-	Sodium-ion battery
SMR	-	Steam methane reforming
SOE	-	Solid oxide electrolysis
SSR	-	Selective salt recovery
SWRO	-	Seawater reverse osmosis
TEA	-	Techno-economic assessment
TOEC	-	Thermo-osmotic energy conversion
ZLD	-	Zero liquid discharge

1 Introduction

The Narrabri Gas Project (NGP) involves coal seam gas (CSG) extraction from the Narrabri region in the Gunnedah Basin of NSW. Highly saline ‘produced water’ (PW) will be generated while extracting CSG and require treatment through a reverse osmosis (RO) process, which is highly effective in removing salt from solutions with up to 99% reduction in total dissolved solids (TDS) concentrations. The RO treatment includes forcing solution under pressure through a membrane to remove ions from the solution with the formation of a purified permeate solution and a concentrate solution, or brine, containing the membrane-rejected salts. The waste brine can vary in concentration and composition of salts, metals, TDS, and other contaminants that will influence its reuse and other end-use options, which are socially, environmentally and economically acceptable. The NGP and the associated activities and processes including the generation of large quantities of brine as a result of CSG extraction activities have been a cause for concern in the local community.

Previous research found that 63% of respondents in the Narrabri Shire believed their community would adapt or transform into something better (McCrea and Walton, 2023). To help maintain the wellbeing and function of communities, it is important to provide impacted communities with information on the environmental, economic and social impacts associated with gas extraction. Therefore, a thorough assessment including the pros and cons of all potential options for the management of brine needs to be conducted and shared with the community.

The brine produced through the RO process can be diverted to storage ponds; concentrated via passive evaporation; or via, salt crystallisers or enhanced evaporation systems, which require additional energy. However, brine can also be used as a feedstock for chemical production, such as sodium hydroxide. Further, the concentration of brine to produce salt containing minimal to no liquid can make it considerably easier for the beneficial reuse opportunities arising from a solid salt material. The primary salts present in PW include sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3) and sodium chloride (NaCl). Each of these can be used in processes for a range of industrial applications, such as the production of glass, detergents, animal feeds (algae) and sodium hydroxide, and for mine site rehabilitation (Hayes, 2020).

The Development Consent for the NGP published by the Independent Planning Commission of NSW has a preference for undertaking beneficial reuse options, where this is feasible. The waste disposal of brine or salts produced from brines is also an (undesirable) option as long as this meets regulatory requirements, such as using suitably licenced waste management facilities (NSW DPIE, 2020). However, the extent of beneficial reuse options for brine or salt needs to consider a range of factors to examine the feasibility of the proposed options, such as technical, economic, social, environmental and safety factors.

The use, disposal, and reuse of water associated with oil and gas (O&G) production has been a topic of interest for decades to O&G operators, regulators, water users, and researchers for decades. Previous studies have also considered the beneficial reuse and disposal of CSG brines in

Australia, with a number of technically viable options identified (APPEA, 2018; Hayes, 2020; Khan and Kordek, 2014; Ly et al., 2016).

Beneficial reuse options for brine include:

- Selective salt recovery (SSR) of high-purity salts (Na_2CO_3, $NaHCO_3$, NaCl) for industrial applications
  - Carbonation route for sodium bicarbonate
  - Sodium carbonate monohydrate ($Na_2CO_3.H_2O$)
  - Sodium carbonate decahydrate ($Na_2CO_3.10H_2O$)
  - 'Gossage' process with recycling of lime reagent
  - Trona / nahcolite solar evaporation
  - Solvay and other modified Solvay processes
  - Chlor-alkali processes
  - Hydrochloric acid (HCl) addition to create NaCl salt
  - Continuous or standard ion exchange (IX) processes
- Recovery of critical minerals and other important elements
- Acid mine drainage neutralisation
- High-value algae cultivation
- Harvesting energy (e.g. osmotic power or salinity gradient power)
- Regeneration of solvent extraction organics

1.1 Aims and objectives

The aim of this project was to review beneficial reuse or end-use options for brine from the NGP region. The project objectives were to:

- Collate data and knowledge on brine and salt management in the NGP region
- Undertake a review of existing and emerging innovative technologies and solutions for beneficial reuse or end-use options for brine
- Conduct techno-socio-economic analysis (identify pros and cons) for the options identified in the objectives 1 and 2 above; and
- Communicate and engage with key stakeholders about the beneficial reuse or end-use options for brine.

2 Narrabri Gas Project

The Narrabri Gas Project (NGP) covers about 950 square kilometres (95,000 hectares) with a footprint of about 1 % of that area (Onward Consulting, 2022). No salt will be produced during phases 1 and 2 exploration and appraisal activities of the NGP. All PW generated through phases 1 and 2 will be stored in the PW and brine ponds at Leewood and treated through the existing RO water treatment facility (Onward Consulting, 2022). The water management infrastructure approved under Phase 2 of the Project consent includes an additional 300-megalitre storage pond at Leewood and a water treatment plant with a capacity of up to 12 megalitres per day. The brine from the RO facility will be returned to the ponds. Storing the PW and brine until Phase 3 will provide larger volumes of concentrated brine, which will be more attractive and economically feasible for commercial salt extraction. However, the potential downsides of storing produced water and brine for commercial salt extraction include significant environmental risks, such as soil and water contamination due to high salt concentrations, and potential harm to local vegetation and ecosystems (North Dakota State University, 2023). Process modelling results predict that the brine produced from the new Phase 3 RO treatment process will have a high concentration of beneficial salts, comprising (by weight) approximately 64 % sodium carbonates and approximately 12 % sodium chloride (Onward Consulting, 2022). The strategy to maximise the beneficial reuse of salt includes combining more than one of the beneficial reuse options.

2.1 Composition of produced water

The PW composition can vary depending on age, depth and the type of geological formation. As part of the approved water quality monitoring program, many representative samples from NGP appraisal wells were collected to characterise the PW composition. A summary of the PW composition is provided in Table 1 (Onward Consulting, 2022). At an average total dissolved solids (TDS) value at the wellhead of 11,675 mg/L, the estimated volume of salt held within the produced water during the Phase 1 and 2 appraisal activities, including existing pilot wells, is approximately 14.44 tonnes per day. The total salt estimate over a predicted 5-year period to be held within the existing produced water and brine ponds is approximately 26,360 tonnes. This is in addition to the approximately 8,600 tonnes from existing exploration and appraisal activities.

Table 1 Produced water composition at the NGP wellhead (Onward Consulting, 2022)

PARAMETER	UNIT	NO. OF SAMPLES	MEAN	10^{TH} PERCENTILE	90^{TH} PERCENTILE
Physicochemical parameters					
pH	-	321	8	7.2	8.7
Electrical conductivity	µS/cm	319	14836	10426	19400
Solids (dissolved)	mg/L	255	9765	6500.5	14400
Solids (dissolved) @180ºC	mg/L	82	11675	7259	15090
Ion balance	-	166	3.76	0.135	9.57

PARAMETER	UNIT	NO. OF SAMPLES	MEAN	10TH PERCENTILE	90TH PERCENTILE
Biochemical oxygen demand (5 day)	mg/L	51	7	2	20
Chemical oxygen demand	mg/L	51	1788	2	3810
Dissolved organic carbon	mg/L	221	5.83	1	19.32
Dissolved anions					
Alkalinity (CO_3)	mg/L $CaCO_3$	231	715	152.5	1846
Alkalinity (HCO_3)	mg/L $CaCO_3$	335	8518	4374	12314
Alkalinity (OH)	mg/L $CaCO_3$	198	<1	<1	<1
Alkalinity (total)	mg/L $CaCO_3$	135	8972	4308	12960
Bromide	mg/L	207	4.44	2.73	5.55
Chloride	mg/L	335	1396	830	1794
Fluoride	mg/L	75	4.86	2.12	6.73
Iodide	mg/L	51	0.13	0.025	0.206
Sulfur (total)	mg/L	34	4.15	0.1	9.75
Cyanide (total)	mg/L	43	0.004	0.004	0.004
Dissolved cations					
Calcium (total)	mg/L	284	19	4	43
Magnesium (total)	mg/L	166	6.48	2.67	11
Potassium (total)	mg/L	335	213	30.1	230
Sodium (total)	mg/L	334	4360	2621	6257
Hardness (total)	mg/L $CaCO_3$	115	88	22	211
Silica as SiO_2	mg/L	24	19.8	16.7	24.7
Silicon (total)	mg/L	35	10.9	10.04	11.66
Silicon (acid soluble)	mg/L	17	8.38	6.86	9.28
Nutrients					
Ammonia-nitrogen	mg/L	57	9.6	3	16.4
Nitrate-nitrogen	mg/L	192	3.03	0.05	5
Nitrite-nitrogen	mg/L	251	0.05	0.01	0.04
Nitrogen (TKN)	mg/L	220	25.6	4.93	54.9
Nitrogen (total)	mg/L	226	23.6	4.4	47.8
Phosphorus (total)	mg/L	34	0.28	0.032	0.6
Total metals & trace elements					
Aluminium (total)	mg/L	226	3.52	0.02	7.67
Antimony (total)	mg/L	226	0.0008	0.0001	0.00206
Arsenic (total)	mg/L	226	0.011	0.0029	0.0225
Barium	mg/L	226	8.53	3.42	15.4
Beryllium (total)	mg/L	224	0.001	0.001	0.001
Boron (total)	mg/L	226	0.64	0.2	1.3

PARAMETER	UNIT	NO. OF SAMPLES	MEAN	10TH PERCENTILE	90TH PERCENTILE
Cadmium (total)	mg/L	226	0.0109	0.0001	0.03494
Chromium (total)	mg/L	226	0.0118	0.0006	0.03608
Chromium (VI)	mg/L	57	<0.01	< 0.01	< 0.01
Cobalt (total)	mg/L	224	0.0018	0.0001	0.00559
Copper (total)	mg/L	226	0.053	0.00452	0.137
Iron (total)	mg/L	223	18.4	0.26	25.9
Lead (total)	mg/L	17	0.02	0.0004	0.033
Lithium (total)	mg/L	17	1.69	1.252	2.16
Manganese (total)	mg/L	225	0.27	0.0017	0.256
Mercury (total)	mg/L	226	0.0006	0.0001	0.0015
Molybdenum (total)	mg/L	226	0	0.0001	0.01321
Nickel (total)	mg/L	226	0.0065	0.0001	0.0167
Selenium (total)	mg/L	226	0.02	0.0005	0.0514
Strontium (total)	mg/L	226	2.61	0.6	4.76
Thallium (total)	mg/L	17	0	0.0005	0.0009
Tin (total)	mg/L	17	0	0.0005	0.00318
Uranium	mg/L	226	0	0.0001	0.0009
Vanadium (total)	mg/L	55	0.01	0.005	0.0184
Zinc (total)	mg/L	226	0.05	0.00292	0.162

2.2 Feed pond water composition

The PW extracted during phases 1 and 2 will be treated via the 1.5 ML/day RO water treatment facility at Leewood (Onward Consulting, 2022). No salt will be produced during this period and all brine will be stored in the brine ponds until Phase 3 of the project. Although it is expected that there will be adequate capacity in the existing ponds, the infrastructure includes an additional 300 ML storage pond at Leewood, with two cells of approximately 150 ML capacity (Onward Consulting, 2022).

With continued treatment of the stored produced water, and due to evaporation and the addition of legacy brine, it is expected that the salinity in these ponds will increase over time. A number of physical, chemical, biological and climatic/environmental processes may also lead to a change in the concentrations of some parameters in the stored water. The predicted quality of the water from the feed pond to the water treatment plant is provided in Table 2.

Table 2 Predicted feed water composition (Onward Consulting, 2022)

PARAMETER	UNITS	MEAN	90^{TH} PERCENTILE
Physicochemical parameters			
pH	-	9.37	9.45
Electrical conductivity [2]	µS/cm	16,690	20,620
Solids (dissolved) - sum of ions [2]	mg/L	14,540	18,060
Total suspended solids (TSS)	mg/L	19.4	37.3
Biochemical oxygen demand (5 day) [1]	mg/L	N/A	N/A
Chemical oxygen demand [1]	mg/L	N/A	N/A
Dissolved organic carbon	mg/L	6.03	19.14
Dissolved anions			
Alkalinity (CO_3)	mg/L $CaCO_3$	2,692	4,156
Alkalinity (HCO_3)	mg/L $CaCO_3$	5,014	5,097
Alkalinity (OH)	mg/L $CaCO_3$	1.36	2.42
Alkalinity (total)	mg/L $CaCO_3$	8,630	11,140
Bromide [1]	mg/L	N/A	N/A
Chloride [1]	mg/L	1,697	2,185
Fluoride [1]	mg/L	N/A	N/A
Iodide	mg/L	0.13	0.21
Sulfate (total) [1]	mg/L	N/A	N/A
Cyanide (total) [1]	mg/L	N/A	N/A
Dissolved cations			
Calcium (total)	mg/L	16.8	21.3
Magnesium (total)	mg/L	6.51	11.07
Potassium (total)	mg/L	214	231
Sodium (total)	mg/L	4,896	6,349
Nutrients			
Ammonia-Nitrogen [1]	mg/L	N/A	N/A
Nitrate-Nitrogen	mg/L	0.02	0.53
Nitrite-Nitrogen	mg/L	0.01	0.01
Phosphorus (total)	mg/L	0.057	0.37
Total metals & trace elements			
Aluminium (total)	mg/L	0.056	0.05
Antimony (total) [1]	mg/L	N/A	N/A
Arsenic (total) [1]	mg/L	N/A	N/A
Barium	mg/L	2.35	3.76
Beryllium (total) [1]	mg/L	N/A	N/A
Boron (total)	mg/L	0.64	1.3
Cadmium (total) [1]	mg/L	N/A	N/A

PARAMETER	UNITS	MEAN	90TH PERCENTILE
Chromium (total) [1]	mg/L	N/A	N/A
Hexavalent chromium [1]	mg/L	N/A	N/A
Cobalt (total) [1]	mg/L	N/A	N/A
Copper (total) [1]	mg/L	N/A	N/A
Iron (total)	mg/L	0.18	0.26
Lead (total) [1]	mg/L	N/A	N/A
Lithium (total) [1]	mg/L	N/A	N/A
Manganese (total)	mg/L	0.054	0.052
Mercury (total) [1]	mg/L	N/A	N/A
Molybdenum (total) [1]	mg/L	N/A	N/A
Nickel (total) [1]	mg/L	N/A	N/A
Selenium (total) [1]	mg/L	N/A	N/A
Silica as SiO_2	mg/L	19.9	24.9
Silicon (total) [1]	mg/L	N/A	N/A
Silicon (acid soluble) [1]	mg/L	N/A	N/A
Strontium (total)	mg/L	1.97	2.48
Thallium (total) [1]	mg/L	N/A	N/A
Tin (total) [1]	mg/L	N/A	N/A
Uranium [1]	mg/L	N/A	N/A
Vanadium (total) [1]	mg/L	N/A	N/A
Zinc (total)	mg/L	0.05	0.082

[1] These values were not calculated as part of process chemistry modelling across the pond. Note that only parameters important for RO performance were modelled through the feed pond and the water treatment facility. Typically, a value of 0% removal for highly soluble analytes and 50% removal were used for the remaining parameters (Onward Consulting, 2022).

[2] Values for major analyte ratios (i.e. the Na to Cl ratio which is a measure of the sodium chloride to sodium carbonate ratio) align with the mean values presented in Table 1. To maintain the ion balance, chloride is modified. Additionally, the value of TDS (sum of ions) is based on individual analyte values (Onward Consulting, 2022).

2.3 Treatment of produced water

Up to 37.5 gigalitres (GL) of produced water will be extracted during Phase 3 at a peak rate of 10 ML/day (Onward Consulting, 2022). The RO water treatment facility at the Leewood site is expected to treat up to 12 ML/day of PW. The four key stages of the water treatment process that will influence the brine and salt volumes produced from the treatment of produced water are as follows (Figure 1) (Onward Consulting, 2022).

- Stage 1: pre-treatment to RO to remove dissolved solids, oils and hydrocarbons and membrane cleaning processes
- Stage 2: removal of salt using RO technology. Approximately 83% of the PW feed to the RO plant would leave this treatment stage as treated water (permeate), with the remaining 17% being brine

- Stage 3: treatment of brine to recover treated water (distillate) by thermal technologies, thereby reducing the brine volume and increasing its concentration. The distillate would be added to the treated water (permeate) produced from the RO plant; and
- Stage 4: removal of a solid salt product from concentrated brine using salt crystallisation technology. Residual distillate would be recovered during the salt crystallisation process and added to the treated water (permeate) produced from the RO plant.

Figure 1 provides an overview of the proposed Phase 3 PW treatment process showing the four stages listed above and the relative volumes produced from each treatment stage (Onward Consulting, 2022). The volume of brine produced from the RO process is expected to be approximately 17 % of the produced water inflows to the water treatment process, and the rate of brine production will vary over the life of the NGP based on a number of factors, including PW rates from the field and pond levels.

The total volume of salt that will be produced from the brine generated through the treatment process is dependent on the chemistry of the PW (feed water) and the recovery rate achieved through the water treatment process. Based on the modelling, the combined treated water stream (permeate plus distillate) is expected to have a salinity of 231 mg/L (Onward Consulting 2022). Therefore, a small amount of salt would be contained in the treated water while the remaining salt would be contained in the brine stream, which in turn is processed through the salt crystalliser.

The quantity contained within the treated water is approximately 2% of the total salt volume which remains within the treated water specification. This treated water can then be amended and stored, for beneficial uses including dust suppression, construction, drilling, crop irrigation and stock watering, with the latter subject to a Resource Recovery Order and Exemption (RROE) application, or alternatively released to Bohena Creek (subject to certain restrictions and limitations).

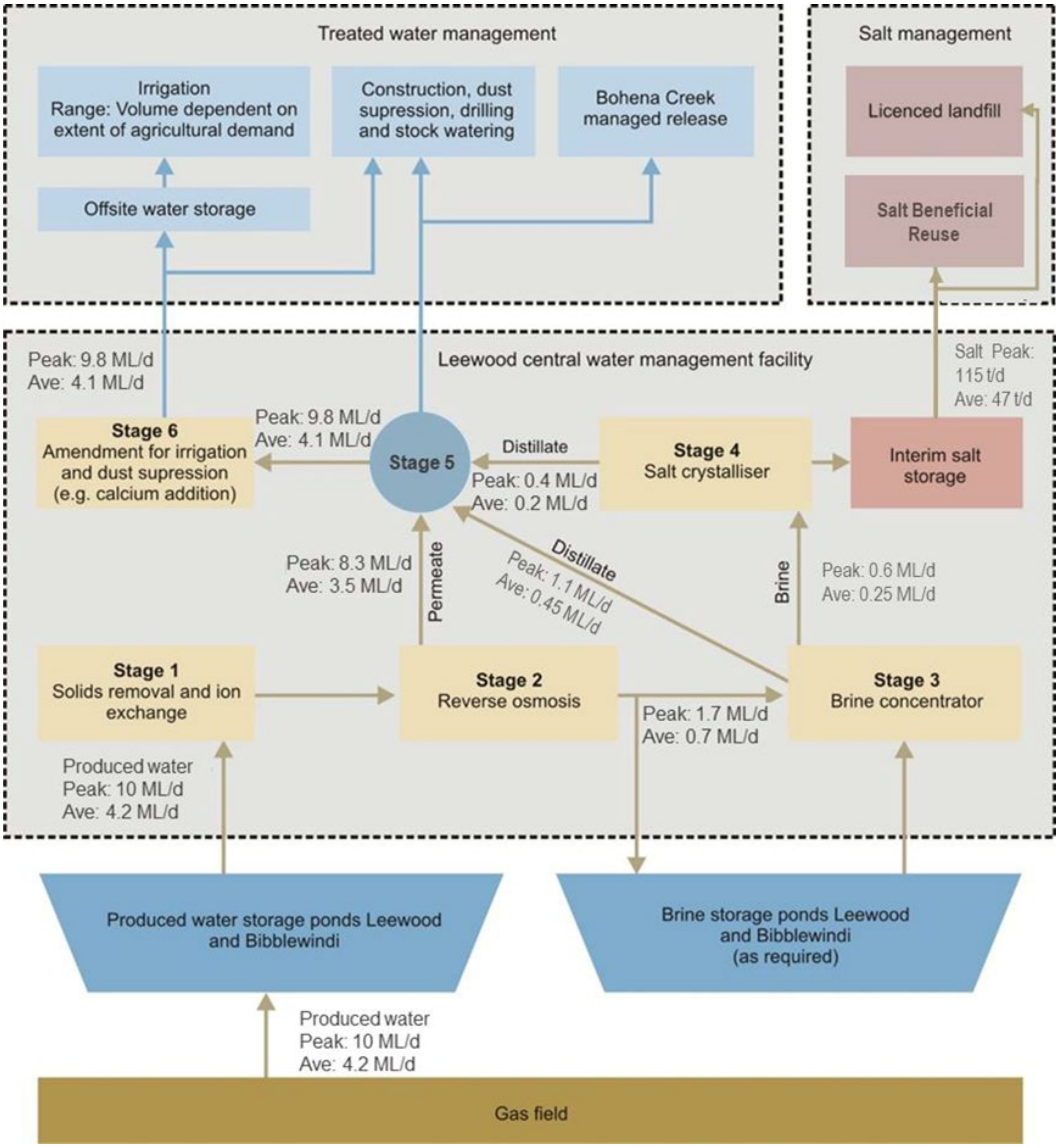


Figure 1 Overview of the Phase 3 produced water treatment process (Onward Consulting, 2022)

2.4 Predicted brine composition

The analytical results of the PW samples collected from exploration and appraisal wells through the approved monitoring program were used to develop a feed specification for the Phase 3 water treatment plant. The expected brine composition, which will be produced through the treatment process and predicted through the water process modelling, is provided in Table 3 (Onward Consulting, 2022).

The dominant ions predicted in the brine are bicarbonate, carbonate and sodium, demonstrating that the dominant salts expected to be present in the brine are sodium carbonate and sodium bicarbonate(Onward Consulting, 2022).

Table 3 Expected brine composition predicted through the water process modelling (Onward Consulting, 2022)

PARAMETER	UNITS	MEAN	90TH PERCENTILE
pH	pH	8.9	9
Electrical conductivity	µS/cm	64,060	77,220
Solids (dissolved) [1]	mg/L	83,220	102,400
Total suspended solids	mg/L	0	0
Alkalinity (CO3) [1]	mg/L	15,380	25,240
Alkalinity (HCO3) [1]	mg/L	28,500	29,570
Alkalinity (OH)	mg/L	2.6	5.3
Alkalinity (total) [1]	mg/L	49,130	66,490
Dissolved organic carbon	mg/L	32	101
Total organic carbon	mg/L	32	101
Aluminium	mg/L	0.04	0.04
Barium	mg/L	4.6	4.5
Boron	mg/L	2.5	5
Calcium	mg/L	25	24
Chloride [1]	mg/L	9,646	9,796
Iron	mg/L	1.1	1.5
Magnesium	mg/L	38	64
Manganese	mg/L	<LOR	<LOR
Total nitrogen	mg/L	0.17	3
Total phosphorus	mg/L	0.003	1.8
Potassium	mg/L	1,208	1,284
Silica	mg/L	113	140
Sodium [1]	mg/L	27,980	35,930
Strontium	mg/L	10	10
Sulfate	mg/L	11.1	8.2
Zinc	mg/L	0.05	0.162

[1] Values for major analyte ratios (i.e. Na to Cl ratio which is a measure of the sodium chloride to sodium carbonate ratio) align with the mean values presented in Table 1. To maintain the ion balance, chloride is modified. Additionally, the TDS (sum of ions) is based on the individual analyte values (Onward Consulting, 2022).

2.5 Predicted salt composition

The expected chemical composition of the salt which will be produced from the processing of brine through a crystalliser predicted via process modelling is provided in Table 4 (Onward Consulting, 2022).

Table 4 Expected salt composition predicted through the water process modelling (Onward Consulting, 2022)

PARAMETER / SUBSTANCE	UNITS	90^{TH} PERCENTILE
Moisture content	% total mass	15
Liquid phase pH	-	9.5-10.7
Sodium carbonate monohydrate	% total mass	64
Sodium chloride	% solid mass	12
Aluminium	mg/kg	0.0038
Arsenic	mg/kg	0.69
Barium	mg/kg	49
Beryllium	mg/kg	0.06 (LoD) [1]
Boron	mg/kg	27
Cadmium	mg/kg	1.1
Calcium	mg/kg	257
Chromium as CrO_4^{2-}	mg/kg	1.1
Chromium (VI)	mg/kg	0.6 (LoD) [1]
Cobalt	mg/kg	0.18 (LoD) [1]
Copper	mg/kg	4.2
Fluoride	mg/kg	410
Iron	mg/kg	16
Lead	mg/kg	1
Lithium	mg/kg	66
Magnesium	mg/kg	685
Manganese	mg/kg	0.000016
Mercury	mg/kg	0.046
Molybdenum	mg/kg	0.4
Nickel	mg/kg	0.51
Potassium	mg/kg	13,855
Selenium	mg/kg	1.5
Silica as SiO2	mg/kg	1,508
Strontium	mg/kg	111
Zinc	mg/kg	4.9
Bromide	mg/kg	338
Sulphate as SO_4^{2-}	mg/kg	88
Uranium	mg/kg	0.02 (LoD) [1]
Vanadium	mg/kg	0.56

[1] These values are overestimates as the limit of detection (LoD) is used. Note that the ratio for major analytes aligns with the mean values presented in Table 1 in order to maintain the ion balance while the raw water TDS (sum of major ions) is based on the 90^{th} percentile values. The sodium carbonate to sodium chloride ratio as presented in Table 1 is based on the mean value for each well sample. This will be different to a flow-weighted average which may vary between 60-80% sodium carbonate monohydrate depending on which wells are producing at the time (Onward Consulting, 2022).

As shown in Table 4, it is estimated that the salt produced from the processing of brine through a crystalliser consists of approximately 64% (by weight) of sodium carbonate, with a further 12% as sodium chloride, both of which are potential beneficial salts. The remaining 24% is comprised of approximately 15% entrained moisture, with the remaining 9% a variety of other non-commercial salts (Onward Consulting, 2022).

Although the predicted salt composition is based on modelling, the composition of the produced salt will be monitored over the life of the project once salt production commences during Phase 3 (Onward Consulting, 2022).

2.6 Predicted salt mass

During Phase 3 of the NGP, the brine stream which is primarily composed of sodium carbonate and sodium bicarbonate, will be converted to salt, predominantly sodium carbonate. Based on a mean produced water TDS value at the wellhead of 11,675 mg/L and a total produced water volume of up to 37.5 GL over the life of the project, the total mass of salt that will be produced is approximately 435,000 tonnes (Onward Consulting, 2022).

3 Beneficial reuse options for brine

A number of potential beneficial reuse options for the brine and salt produced at the NGP were explored in this research. These include, but are not limited to, the following:

- Selective salt recovery
- Recovery of critical minerals and other important elements
- Harvesting energy
- Energy storage
- Acid mine drainage neutralisation
- High-value algae cultivation

This section describes each of the above options and summarises the literature on various processes applicable to NGP. Subsequently, a techno-economic assessment and the social acceptability of each of these options are presented.

3.1 Selective salt recovery

Selective salt recovery (SSR) employs technologies to generate salt products from brine for potential beneficial uses. The process typically involves concentrating stored brine through solar evaporation or alternative mechanical methods, followed by conveying the concentrated brine via a pipeline to an SSR facility to induce crystallisation (Panagopoulos, 2022). This process yields various products, such as table salt (sodium chloride ($NaCl$)) and soda ash (sodium carbonate (Na_2CO_3)). The purity of the salts produced through SSR can exceed 99%, with yields depending on the initial brine concentration and the efficiency of the evaporation and crystallisation processes, typically resulting in a recovery of 70-90% of the target salts (Panagopoulos, 2022).

The NGP brine has a high potential for commercial salt extraction, with sodium carbonate and sodium chloride being the dominant salts predicted to be present (Nghiem et al., 2015). To optimise the SSR process, the volume of CSG RO brine must be reduced, further concentrating the brine near saturation to minimise downstream processing expenses.

Soda ash is produced via natural or synthetic processes, with 30% coming from natural sources and 70% from synthetic processes globally (Adham et al., 2018). The primary use of soda ash is in glass manufacturing, with additional applications in chemical manufacture, soap and detergents, flue gas desulfurisation, pulp and paper processing, and water treatment. Australia imports all soda ash used within the market.

Sodium bicarbonate ($NaHCO_3$), commonly known as 'baking soda' or 'bicarb of soda', is manufactured by reacting aqueous soda ash with carbon dioxide (CO_2), with 1 tonne of soda ash producing approximately 1.6 tonnes of sodium bicarbonate (Simon et al., 2014). The predominant uses of sodium bicarbonate include food, personal care, pharmaceuticals, stock feed, and water treatment. Australia has no domestic production of sodium bicarbonate, but there is a potential opportunity to use waste CO_2 from gas-processing facilities to produce sodium bicarbonate.

Multiple processes have been reported in the literature for deriving high-purity salts from brine, including nanofiltration (NF), ion exchange (IEX), chemical precipitation, membrane electrolysis (ME), and membrane distillation (MD) (Panagopoulos, 2022). These processes are primarily dependent on thermal energy and can be readily integrated with solar thermal collection systems. Hybrid systems, such as tri-hybrid RO-wind-aided intensified evaporation (WAIV)-membrane crystallisation (MCr) and RO-MD-MCr, have demonstrated the extraction of various salts, including NaCl, $CaCO_3$, $CaSO_4$ and KCl, at competitive costs (Adham et al., 2018; Nghiem et al., 2015).

Simon et al. (2014) investigated the feasibility of using ME to produce sodium hydroxide (NaOH) from CSG brine, evaluating and comparing the ME of $NaHCO_3$, Na_2CO_3 and NaCl. The study found that the efficiency of the ME cell remained consistent regardless of the brine solution used as the feedstock, but using $NaHCO_3$ resulted in lower NaOH solution strength compared to using NaCl, likely due to the lower osmotic pressure and electrical conductivity of $NaHCO_3$.

Effectively recovering resources from brine solutions presents opportunities for a circular economy and long-term sustainability. Synergistically integrating technologies and processes is essential for success, which can be achieved through process-based design and system-based optimisation models (Panagopoulos and Haralambous, 2020). Brine treatment via membrane and thermal technologies faces various challenges including fouling, scaling, and corrosion. Addressing these obstacles involves modifying membranes, developing novel membranes, employing corrosion-resistant materials, and implementing pre-treatment methods (such as chemical or biological processes), among others. Some strategies can increase treatment costs, yet they help mitigate fouling and scaling issues. Reusing spent membranes as ultrafiltration or microfiltration membranes can reduce treatment costs (Khaless et al., 2021). Commercially exploiting recovered products, including fresh water and salt solids, can make brine treatment profitable (Panagopoulos and Haralambous, 2020). Nonetheless, resource recovery through minimal liquid discharge (MLD)/zero-liquid discharge (ZLD) frameworks has raised concerns regarding high energy consumption. While membrane-based technologies generally require less energy than thermal ones, desalinisation remains an energy-intensive process. Transitioning to renewable energy sources, such as solar, wind, geothermal, or tidal power, would decrease carbon footprints and support carbon neutrality goals (Kalogirou, 2018). Integrating renewable energy helps reduce energy demands and carbon emissions and offers possibilities for extracting energy from brine effluents to aid in the recovery of salts and minerals (Panagopoulos and Haralambous, 2020).

The Solvay process, also known as the ammonia-soda process, is a well-established method for producing sodium carbonate and sodium bicarbonate by reacting sodium chloride (salt), ammonia, and carbon dioxide in water.

This process involves several steps, including the absorption of carbon dioxide in an ammonia solution to form ammonium bicarbonate, which then reacts with sodium chloride to precipitate sodium bicarbonate. The sodium bicarbonate is subsequently heated to produce sodium carbonate.

Recent advancements have integrated selective salt recovery techniques into the Solvay process to enhance efficiency and environmental sustainability. For example, a method has been developed to remove carbon dioxide from process gases by chemical absorption, which is then reused in soda production, thereby improving the overall carbon footprint of the process (Bessenet and Rittof, 2018).

Additionally, processes for treating wastewater or waste brines containing sodium, sulfate and chloride ions have been incorporated, where the brine is concentrated and directed to various crystallisers to recover salts such as sodium sulfate and sodium chloride (Bessenet and Rittof, 2018; Skowron et al., 2018). Another approach involves the use of nanofiltration devices to separate and recycle streams within the process, further optimising salt recovery (Rittof and Rieke, 2012).

The traditional Solvay process has been modified to eliminate ammonia and incorporate alternative buffering agents like $Ca(OH)_2$, KOH, and NH_4HCO_3. Studies have demonstrated that using NH_4HCO_3 and KOH yields higher purity $NaHCO_3$ compared to $Ca(OH)_2$, with desalination brine and NH_4HCO_3 producing the highest purity $NaHCO_3$ (Ali et al., 2023).

The calcium-oxide-based modified Solvay process has also been explored, showing a sodium removal efficiency of up to 43% from real desalination brine under optimal conditions, with the process kinetics fitting a second-order model (Setayeshmanesh et al., 2022). Additionally, a KOH-based Solvay process has been effective in reducing brine salinity and capturing CO_2 at higher temperatures, achieving significant removal rates of various ions and producing valuable by-products like $NaHCO_3$ and $KHCO_3$ (Mourad et al., 2021). The integration of electrocoagulation with the Solvay process has been proposed to remove chloride and ammonium ions, enhancing the overall efficiency of brine treatment (Ahmad et al., 2021). Furthermore, the use of nanofiltration and membrane distillation in conjunction with the Solvay process has been investigated for pure single-salt recovery, showing potential for large-scale applications and economic viability (Qiao et al., 2022). These advancements highlight the potential of modified Solvay processes in both mitigating the environmental impact of brine discharge and in recovering valuable salts, thereby contributing to sustainable water and resource management (Bazedi et al., 2014; Kieselbach et al., 2020; Orestov et al., 2019; Wang et al., 2019).

The Sal-Proc process for selective salt recovery is a comprehensive, multi-step method designed to treat wastewater or waste brines containing various ions such as sodium, chloride, and sulfate, and to recover valuable salts. The process begins with the concentration of the brine, which is then directed to a Mirabilite crystalliser to produce hydrated sulfate salt crystals and a first solution. The hydrated crystals are melted to form an aqueous sulfate solution, which is further processed in a sodium sulfate crystalliser to produce sodium sulfate salt crystals.

The first solution from the Mirabilite crystalliser undergoes nanofiltration, resulting in a permeate stream directed to a sodium chloride crystalliser to produce sodium chloride crystals, while the reject stream is recycled back to the Mirabilite crystalliser (Bessenet and Rittof, 2018). Additionally, the process can be integrated with supercritical water desalination to achieve ZLD and recover industrially essential materials, such as neodymium hydroxide, while producing freshwater (Yoon et al., 2021).

The method includes the use of superheated steam and absorption chillers to create chilled water, which aids in the recovery of minerals like potash, washing soda, nahcolite, and Glauber's salt through a cooling crystalliser system (McEwan et al., 2017). Electrochemical desalination with capacitive deionising cells can selectively remove bromide and iodide ions from seawater, enhancing the overall efficiency of the process (Izaak et al., 2019). The process also involves the recovery of sodium chloride and sodium carbonate decahydrate crystals from concentrated brine, with the brine being pre-concentrated and carbon dioxide removed to convert sodium bicarbonate to sodium carbonate (Goldman, 2012; Rittof and Rieke, 2012). Ion exchange techniques are employed to exchange all ions in the concentrate stream for sodium and chloride, facilitating further treatment and freshwater recovery (Rittof and Rieke, 2012). Additionally, metal-selective sorbents and membranes, along with electrodialysis and forward osmosis, are used to recover metals from solutions, making the process environmentally friendly with minimal industrial waste (Sean et al., 2020). Finally, the process includes the treatment of an initial aqueous solution to generate a solid mix of NaCl and KCl, which is then separated to yield a depleted aqueous solution primarily containing Ca and Cl ions (Yariv, 2016). This multi-faceted approach ensures efficient and selective recovery of various salts and valuable materials from waste brines.

The Sal-Proc process involves various innovative techniques aimed at minimising environmental impact and maximising resource recovery. One approach employs osmotic membrane distillation in a hollow fibre membrane contactor, effectively recovering salts from concentrated brine by optimising key process parameters such as feed concentrations and flow rates (Ahmad et al., 2021). Spray dry technology is also used to isolate minerals from brine, achieving zero liquid discharge by repeatedly concentrating and separating mineral salts (Bhadrachari et al., 2022).

The HighCon project developed a ZLD process that integrates NF, ED, and MD to recover pure single salts from industrial wastewater (Kieselbach et al., 2020). Additionally, liquid-liquid extraction using an organic phase containing ethanol, cyclohexane, and sunflower oil has been shown to reduce brine salinity by 27%-64% in a single stage, offering a simple and environmentally friendly solution (Panagopoulos and Haralambous, 2020). Static freeze crystallisation has also been explored, achieving significant salt rejection and water recovery by controlling the cooling rate and employing a sweating process (Zhang et al., 2021).

Finally, an integrated system combining monovalent selective electrodialysis and direct contact membrane distillation has demonstrated effectiveness in desalinating ion exchange spent brine and recovering NaCl for reuse, thus reducing the environmental impact of brine disposal (Darmaki and Hossain, 2022). These diverse methodologies highlight the potential of the Sal-Proc process in transforming brine from a waste product into a valuable resource, aligning with sustainable and decarbonised brine management strategies (Ahmed et al., 2021; Haddad et al., 2021).

The Sal-Proc process faces several challenges, primarily related to the complexity of handling and processing various types of brines and the efficiency of the recovery methods. One significant challenge is the fouling and scaling of membranes and crystallisers, which can reduce the efficiency of ion exchange and crystallisation processes (Rittof and Rieke, 2012). The need for pre-concentration and the removal of impurities such as carbon dioxide from the brine to convert sodium bicarbonate to sodium carbonate adds complexity (Bessenet and Rittof, 2018).

3.2 Recovery of critical minerals and other important elements

CSG brine contains a range of valuable minerals and salts that can be recovered using appropriate technologies and processes. In addition to common salts like NaCl, $CaCl_2$, $MgCl_2$ and Na_2SO_4, there is increasing interest in extracting critical minerals from brine, such as Li, Rb, In, Cs, Ga, Sc, and V (Nghiem et al., 2015). Mg has applications in robotics and fuel cells, with a significant portion of the supply originating from seawater and brine effluents in the United States. The demand for Li has risen sharply due to the increasing popularity of Li-ion batteries for electric vehicles, earning it the nickname 'new gold'. Rb finds applications in laser cooling and atomic clocks, while Cs is used in aeronautics, photoelectric cells, and other industries (Nghiem et al., 2015).

Various alternative technologies such as precipitation, ion exchange, liquid-liquid extraction, and electrodialysis have been proposed to reduce reliance on solar evaporation for Li recovery (Park et al., 2020). Park et al. (2020) studied a new membrane-based process for Li recovery and compared it to the traditional method of solar evaporation followed by chemical precipitation. The conventional techniques have limitations in meeting the increasing demand for large-scale Li production due to drawbacks associated with solar evaporation. Park et al. (2020) proposed a novel membrane-based process that combines MD and NF to concentrate Li-containing brine solutions and remove divalent ions. The proposed membrane-based process successfully concentrated a 100 ppm Li solution in artificial brine to 1200 ppm within a few days. Notably, it exhibited significantly higher water flux, with up to 60 times greater flux (22.5 L m^{-2} h^{-1}) compared to solar evaporation (0.37 L m^{-2} h^{-1} at 30 °C and 0.56 L m^{-2} h^{-1} at 50 °C) (Park et al., 2020).

Selective recovery processes have been developed for extracting Li from seawater using ion exchange methods. Nishihama et al. (2011) employed two successive ion exchange methods to selectively recover Li. The initial concentration process achieved a recovery efficiency of approximately 33% using a granulated λ-MnO_2 adsorbent. Subsequently, a novel separation process combining cation exchange resin and solvent-impregnated resin was employed to purify the concentrated Li liquor. The final product, Li_2CO_3, was obtained with a purity exceeding 99.9% and an overall yield of 56% (Nishihama et al., 2011).

To make the most of brackish water brine, Naidu et al. (2017) conducted a study using a hybrid system consisting of MD, RO and adsorption with potassium copper hexacyanoferrate. The results showed a moderate recovery rate of less than 65%, but a high extraction of Rb at approximately 97% was achieved (Naidu et al., 2017). In another study by Choi et al. (2019), a hybrid system combining submerged MD and adsorption was investigated for valorising seawater brine. The results demonstrated a high extraction of freshwater (>85%) and Rb (>98%) (Choi et al., 2019). Guo et al. (2019) explored a hybrid system involving ED and IEX with monovalent selective IEX membranes to extract Li from seawater brine. There was a successful extraction of Li in the form of $LiCl_2$ (Guo et al., 2019). More recently, Park et al. (2020) examined a hybrid system combining MD and NF to treat synthetic brine containing Li. The findings revealed a significant 12-fold increase in Li content (Park et al., 2020).

Membrane-based processes have significant advantages over conventional methods for Li recovery from brine, including higher water flux, lower capital costs, and comparable annual operating costs (Park et al., 2020). Park et al. (2020) demonstrated the effectiveness of a novel membrane-based process that combines MD and NF for concentrating Li-containing brine solutions and removing divalent ions. The process achieved a water flux that was 60 times higher than obtained from solar evaporation and reduced the need for excessive chemical usage required in conventional methods (Park et al., 2020). The advancements and benefits offered by membrane technology, including its scalability, small footprint, and weather-independent operation, make this new approach highly effective for Li recovery from brine (Park et al., 2020).

Choi et al. (2019) assessed the effectiveness of an integrated system combining submerged MD (S-MD) and adsorption for enhanced water recovery from brine while simultaneously extracting valuable Rb. The system successfully concentrated Rb (with 99% rejection) while producing fresh water using a thermal S-MD process at 55 °C and supplying Rb-rich SWRO brine continuously. The concentration of Rb in the thermal environment facilitated its extraction through granular potassium copper hexacyanoferrate (KCuFC), with an optimal dose of 0.24 g/L resulting in 98% Rb mass adsorption. The integrated S-MD-adsorption system demonstrated over 85% water recovery and efficient Rb extraction in a continuous feed supply over two cycles. A comparison of different forms of KCuFC (granular, particle, and powder) revealed that the particle form exhibited 10-47% higher capacity in terms of total adsorbed Rb mass and adsorption rate (Choi et al., 2019).

Recovering precious metals, like Li, Rb, and Cs, poses difficulties due to the intricate precipitation, crystallisation, and selective separation steps involved. Improving selectivity through advanced adsorbent designs can enhance the extraction of desired ions, such as Li^+, along with economically valuable metals such as Rb^+ and Cs^+ (Sui et al., 2017). Resource recovery from brine may provide significant benefits for a more sustainable future. By using innovative technologies and combining different approaches, it is possible to optimise treatment processes while minimising negative environmental impacts. However, challenges, such as the need for effective management of waste produced during treatment processes, must be overcome (Panagopoulos, 2022).

3.3 Harvesting osmotic energy

Osmotic energy, also known as salinity-gradient energy (SGE), is the energy released when waters with different salinities are mixed, such as rivers and oceans (Thorsen and Holt, 2009; Yip and Elimelech, 2012). Approximately 0.70–0.75 kWh of energy is released when 1 m^3 of freshwater flows into the sea (Thorsen and Holt, 2009; Yip and Elimelech, 2012). The maximum extractable energy from the mixing of 1 m^3 of fresh water with the Great Salt Lake and the Dead Sea is 10.4 and 14.1 kWh, respectively (Helfer et al., 2014).

Brine streams originating from the reverse osmosis of produced water in coal seam gas mining present opportunities for the development of innovative technologies that can convert their salinity gradients into usable energy (Panagopoulos, 2022). Several technologies have been employed for generating energy, including reverse electrodialysis (RED), pressure retarded osmosis (PRO), capacitive mixing (CapMix), thermo-osmotic energy conversion (TOEC), and combined water and power production (CWP) (Panagopoulos, 2022). While RED, PRO, TOEC, and CWP are membrane-based processes, CapMix operates on electrodes. Although these salinity gradient power technologies are still being explored at the laboratory scale, they have shown promising power densities of up to 38 W/m^2 (Panagopoulos, 2022).

The term 'osmotic pressure (π)' implies the potential of a solution to generate power (Panagopoulos, 2022). When two solutions of different salinities (or different chemical potential of the species) are separated by a semipermeable osmotic membrane, water is transported naturally from the low salinity solution (referred to as the feed solution) to the high salinity solution (referred to as the draw solution).

3.3.1 Pressure-retarded osmosis and reverse electrodialysis

Pressure retarded osmosis (PRO) is a technology that was conceptualised for producing salinity-gradient energy by Pattle (1954) in the 1950s and then reinvestigated in the mid-1970s due to the world's energy crisis (Loeb and Norman, 1975). Theoretical and experimental research was conducted on the feasibility of PRO, reporting that osmotic energy could indeed be harvested under the PRO principles (Loeb, 1976; Loeb and Mehta, 1978). However, due to the expensive and low-efficiency membranes available at the time, research was slowed down in the 1980s and 1990s. From the 1990s onwards, osmotic membranes for desalination and wastewater treatment have advanced rapidly and have been widely commercialised (Panagopoulos, 2022). In 2009, Statkraft in Norway built the first PRO prototype plant using commercial RO membranes (Skilhagen, 2010). The plant was shut down in 2013 partly due to the lack of effective commercial PRO membranes and partly due to the extensive pretreatment needed to minimise membrane fouling (Sikdar, 2014). Nevertheless, the Statkraft plant has proved that PRO can be used to generate electricity (Sikdar, 2014; Skilhagen, 2010).

The advancements in membrane technology and the increasing demand for renewable energy sources have renewed interest in PRO as a viable option for harvesting salinity-gradient energy (Panagopoulos, 2022). Ongoing research aims to develop more efficient and cost-effective membranes, as well as optimise pretreatment methods to minimise fouling and scaling issues (Panagopoulos, 2022). As these challenges are addressed, PRO has the potential to become a significant contributor to the global energy mix, particularly in areas with abundant sources of low-salinity and high-salinity water, such as river estuaries and seawater desalination plants (Panagopoulos, 2022).

SGE technologies, specifically PRO and reverse electrodialysis (RED), harness the chemical potential difference between salt and fresh water to generate renewable energy (Cheng and Chung, 2017; Straub et al., 2016b; Tufa et al., 2015). PRO operates by transporting freshwater across a semi-permeable membrane from a low-salinity feed solution to a high-salinity draw solution, driven by the difference in chemical potential. The resulting flow generates pressure, which is directed into a pressure exchanger to power a hydro turbine and generate electricity (Figure 2) (Bazhin, 2015; Straub et al., 2016a). In contrast, RED operates by flowing high-concentration and low-concentration solutions through a series of anion exchange membranes and proton exchange membranes (PEM). The chemical potential difference between the low and high concentration solutions drives the selective migration of positive and negative ions across the membranes, leading to the generation of electrochemical potential and voltage.

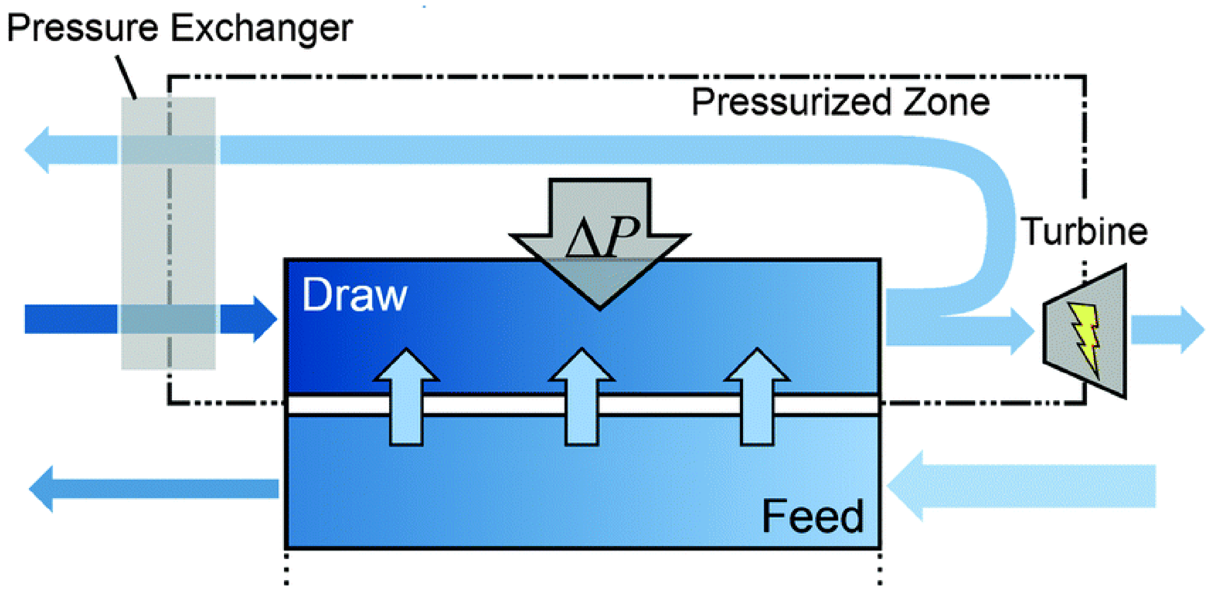


Figure 2 A schematic diagram of a constant-pressure, counter-current PRO system with energy recovery facilitated by a pressure exchanger. Darker colours indicate higher salinity levels, while the thickness of each arrow represents the relative flow rate (Straub et al., 2016a)

Several real-world SGE power plants have been successfully implemented, demonstrating the practical application and potential of PRO and RED technologies. Notable examples include the world's first osmotic power plant utilising PRO technology in Norway by Statkraft in 2009, the Redstack plant in the Netherlands, and the MegaTon Water System project in Japan (Kurihara et al., 2016). However, the performance of membranes poses a significant challenge in both PRO and RED technologies. Based on the experience of the Statkraft power plant, it is widely recognised that a membrane's power density should ideally exceed 5 W/m^2 for a PRO plant to be economically viable (Helfer et al., 2014; Logan and Elimelech, 2012). The MegaTon Water System project successfully developed a novel PRO hollow fibre membrane module that achieved a membrane power density of up to 13.5 W/m^2 during a year-long continuous operation (Kurihara et al., 2016).

In a case study by Salamanca et al. (2019), the Magdalena River mouth in Colombia was examined as a potential site for a renewable power plant utilising PRO technology. Simulations demonstrated that the power plant could generate nearly 6 MW of net power with a flow rate of 30 m^3/s, aligning with the scale of small hydropower plants. Sharma et al. (2022) conducted a comparative analysis between PRO and RED, revealing that PRO exhibits superior power densities, ranging from 22 to 32 times higher than RED for engineered salinity gradients. The study considered crucial factors such as membrane materials, modifiers, and essential parameters, concluding that PRO is the more favourable option in terms of power density and performance.

Ongoing research explores the use of PRO for oil recovery and the treatment of produced water from conventional oil sources (Adham et al., 2018; Gonzales et al., 2021). The high salinity levels in produced water make it a suitable choice as the draw solution in PRO, with seawater or desalination plant brine serving as the feed solution providing the salinity gradient is sufficient. This research focuses on identifying the pre-treatment requirements of produced water for effective use in PRO, developing membranes capable of withstanding high pressures, and integrating waterflooding with PRO. The combined process enables the reuse of diluted produced water, reduces pumping energy requirements, minimises waste streams, enhances injectivity, generates energy, and improves overall oil production.

Turek et al. (2008) studied the generation of electric energy through the mixing of CSG brine and low-salinity water using RED. The experimental analysis revealed that the maximum effective unit power was influenced by electric current density, flow velocity, and membrane resistance. The highest effective unit power recorded was 0.72 W/m^2 when using AMX and CMX membranes at 20 A/m^2 and a flow velocity of 0.58 cm/s. Low-resistance membranes achieved a maximum effective unit power of 1.040 W/m^2 at 30 A/m^2 and the same flow velocity. However, the high cost of implementing the RED technique at a large scale, particularly due to the costly low-resistance ion exchange membranes, hinders its practical application.

While PRO has shown better performance than RED, both technologies still require significant technological advancements before they can be used as viable sources of renewable energy. PRO necessitates high-performance pumps, pressure exchangers, turbines, and improved membranes to effectively convert the mechanical expansion of highly concentrated solutions into electrical energy. Additionally, a comprehensive analysis is necessary to identify and mitigate fouling issues in the input streams, and further case studies using working prototypes at various sources are required to assess the cost efficiency of these processes.

3.3.2 Hybrid systems

The salinity gradient between different water streams can be harnessed to generate power through hybrid systems combining RO and PRO technologies. Khasawneh et al. (2018) analysed the feasibility of three RO-PRO systems as part of the Red Sea-Dead Sea water conveyance project. The study aimed to harness the salinity gradient between water streams to generate power. Two proposed plants used Red Sea water and rejected brine from seawater reverse osmosis (SWRO) desalination plants as feed and draw solutions, while the third plant combined Red Sea water and Dead Sea water. While all three plants were technically feasible, only the third plant proved economically viable, with a capacity of 134.5 MW and a levelised cost of electricity (LCOE) of US$0.056/kWh. The power generated from this plant could fulfil around 24.7% of the energy requirements of the project and reduce electricity consumption by 49.3% for SWRO. Using the power from these PRO plants for desalination purposes can potentially reduce the cost of desalinated water produced by SWRO plants.

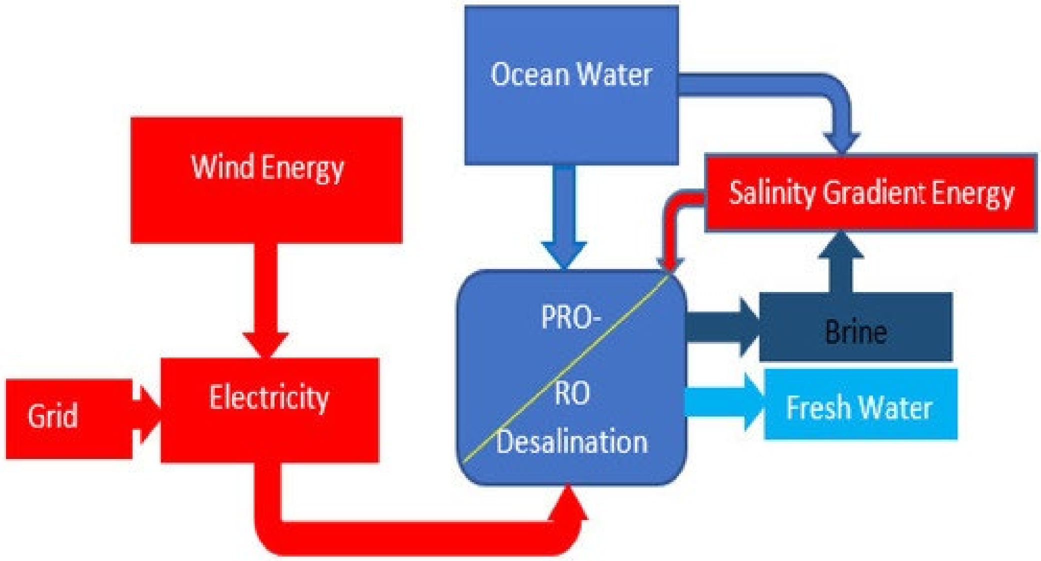


Figure 3 Integrated desalination process combining PRO and RO, which is powered by grid-tied offshore wind energy and uses the salinity gradient in the ocean (Okampo et al., 2022)

Okampo et al. (2022) investigated a PRO-RO desalination system for energy harvesting from seawater brine (Figure 3). The proposed hybrid model, powered by grid-tied offshore wind energy, was technically and economically viable, with an LCOE of US$1.11/kWh and an annualised cost of the system (ACS) of US$110,456. The study demonstrated that the PRO-RO system improves brine management by using the brine as a feed for the PRO unit to create a salinity gradient, allowing for water transfer through a membrane and generation of salinity gradient energy. The economic metrics assessed include LCOE, ACS, and Cost of Water (COW), while reliability was evaluated through the loss of energy probability. The results indicate an LCOE of US$1.11/kWh, ACS of US$110,456, COW of US$0.13/m³, loss of energy probability of 0.341, low total carbon emissions of 193,323 kg CO_2-e, and no brine production, demonstrating the economic viability, technical reliability, environmental friendliness, and overall sustainability of the proposed model.

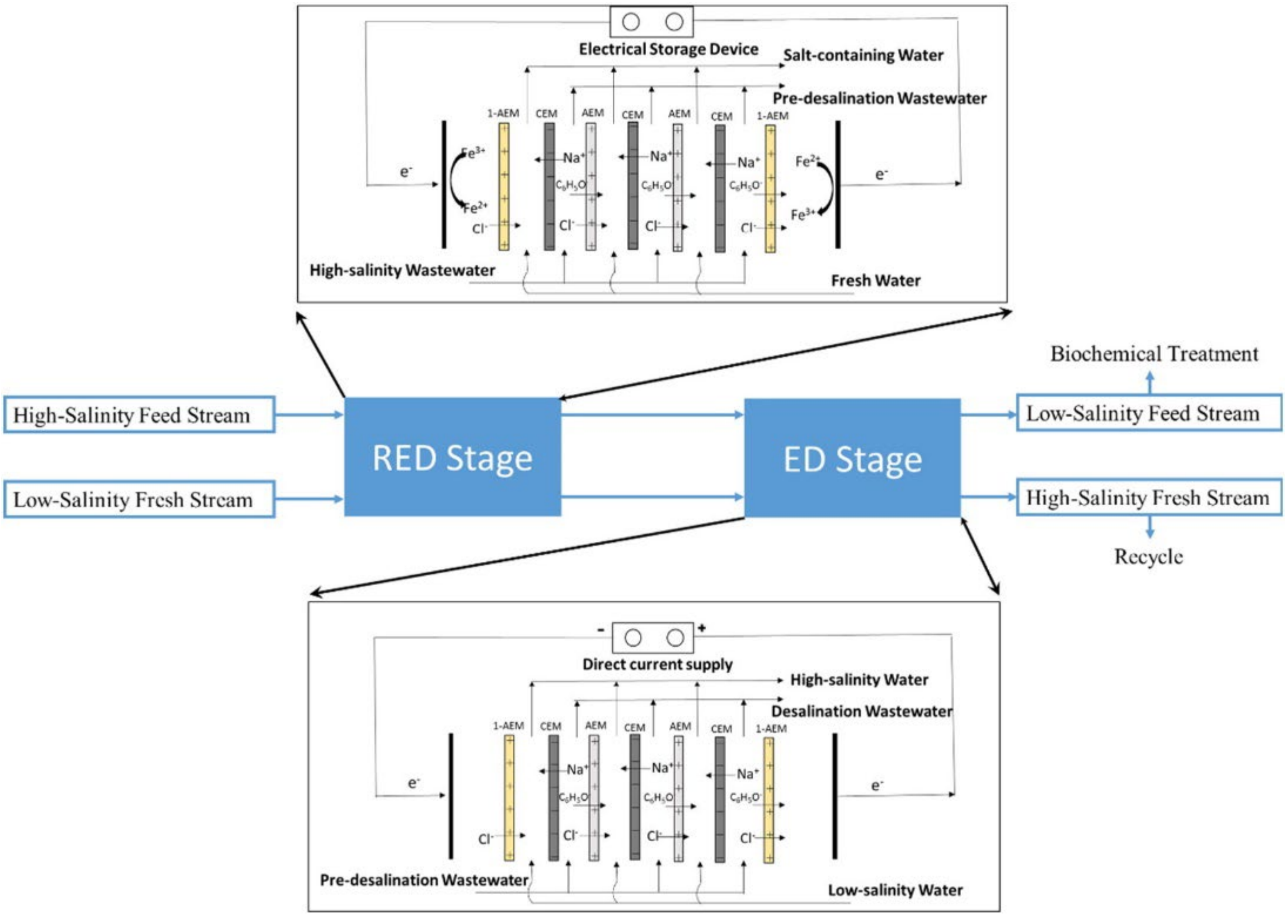


Figure 4 Schematic diagram of a hybrid RED/ED system designed for the simultaneous osmotic energy recovery and full desalination of high-salinity wastewater (Wang et al., 2017)

Wang et al. (2017) investigated a hybrid system that combines RED and ED for simultaneous osmotic energy recovery and desalination of seawater brine (Figure 4). The study demonstrated that the hybrid system could offer triple the benefits of using salinity energy, recovering high-value resources, and achieving low-energy desalination. In a similar vein, the study proposed a hybrid system that combines RED and ED for simultaneous osmotic energy recovery and complete desalination in phenol-containing wastewater treatment (Wang et al., 2017). The experimental investigation revealed that the stand-alone ED system had inefficient desalination performance due to salinity differences between the feed streams, which led to high stack resistance. This suggests the potential use of RED as a pre-desalination process to reduce the salinity difference and improve performance. The rate of pre-desalination is influenced by power generation in the RED stage and energy saving in the ED stage, with phenol-containing wastewater showing higher power generation compared to artificial seawater. Economic analysis highlights the average power generation and limiting wastewater treatment capacity as important factors for designing and improving the hybrid system. Control conditions are also crucial in selecting suitable wastewater systems for the hybrid setup. Overall, the hybrid RED/ED system offers advantages in using salinity energy, reclaiming high-valued resources, and achieving low-energy desalination in high-salinity wastewater treatment processes.

These studies demonstrate the potential of hybrid systems combining membrane-based technologies such as RO, PRO, RED, and ED to harness the salinity gradient between different water streams for power generation and desalination. By integrating these technologies, the systems can achieve multiple benefits, including energy production, brine management, resource recovery, and low-energy desalination. The technical and economic feasibility of these hybrid systems has been demonstrated although factors such as power generation, wastewater treatment capacity and control conditions. Membrane performance needs to be carefully considered for optimal design and operation.

3.3.3 Technical challenges, feasibility and future perspectives

The main challenge facing PRO is its feasibility. Researchers have acknowledged that the theoretical energy potential of PRO is flawed, and there are limitations in demonstrating the process's actual energy-harnessing capability, particularly when considering the energy required for pre-treatment, pressurisation, and delivery. Studies have shown that the maximum amount of energy extractable from the mixing of seawater and river water is only 0.26 kWh/m^3, and when accounting for the energy expended in pre-treatment, pressurisation, and pumping, the net energy obtained becomes fractional, potentially rendering the entire process futile (Gonzales et al., 2021). However, these findings are based on assumptions and economic analyses, as full-scale PRO power plants have not been operated to validate them.

The large-scale development and commercialisation of PRO membranes pose another challenge. The lack of commercially available membranes leads to high unit prices for each module, affecting the total capital cost of PRO operation. Membranes have a limited lifespan, requiring replacement, cleaning, and maintenance during continuous PRO operation. Furthermore, cheaper membranes may not offer better performance or longer lifetimes, potentially increasing operational costs. The performance of membranes is crucial in determining the feasibility of the PRO process, as membranes with low power density values necessitate larger sizes, increasing capital expenditure. High-performance membranes are expected to decrease energy costs by enabling greater energy production (Gonzales et al., 2021).

Recent research in the PRO field has focused on integrated hybrid processes that combine PRO with other applications, such as SWRO and MD. Integrating PRO installations into existing infrastructure and established processes can be more cost-effective than standalone PRO power plants. This approach leverages available infrastructure and reduces installation and operational costs. The challenges hindering full-scale implementation and commercialisation of PRO have persisted over the past five years, leading to a shift in recent research from pilot-scale applications to developing hybrid PRO processes and identifying niche applications for PRO (Gonzales et al., 2021).

Emerging trends involve advanced PRO configurations and niche applications, such as integrated processes that harness salinity gradient energy using different draw and feed solutions while enabling seawater desalination, wastewater treatment, heat recovery, and resource recovery. Dual-stage closed-loop PRO processes have demonstrated more efficient performance than single-stage processes. Future research should focus on hybrid processes and large-scale pilot plant installations, as projects like Mega-ton and GMVP in Japan and South Korea have provided valuable insights, showcasing the potential for high power density and reduced energy consumption in SWRO-PRO demonstration plants (Gonzales et al., 2021).

Pre-treatment strategies are essential for reducing PRO membrane fouling, chemical cleaning, and module replacement, thus extending membrane lifespan. The RO-NF-PRO hybrid process combines membrane processes to achieve higher extractable salinity gradient energy, feed pre-treatment, and energy harnessing. While feasibility studies have faced challenges in proving PRO as a commercially viable process, PRO still holds significant commercial potential (Gonzales et al., 2021). Integration with other membrane-based processes has shown promise, and with improved configurations and operating conditions, PRO can be further optimised. Continuous development of PRO processes, membranes, and modules may eventually achieve the economically feasible power density requirement of 5 W/m² set by Statkraft (Gonzales et al., 2021).

3.4 Energy storage (sodium-ion battery)

Energy storage systems (ESS) offer the possibility to integrate renewables such as wind and solar into electricity systems by mitigating the uncertainty that could be associated with the intermittency caused by variations in weather conditions. Currently, lithium-ion batteries (LIB) are among the most relevant electrochemical energy technologies and have dominated the portable electronics market and are also gaining ground in the application for large-scale ESS.

Sodium technologies of battery energy storage systems have attracted attention in recent years and it is considered as a supplementary technology to LIB. The wide abundance and low cost of sodium resources have created a possibility for the development of a sodium-ion battery (SIB) with chemical and electrochemical properties similar to LIBs. There has been advancement in the development of both cathode materials (e.g. ferrocyanides, polyanionic compounds and transition metals) and anode materials (e.g. hard carbon (HC), alloys and sulfides), as well as electrolytes for SIBs (Fang et al., 2018). SIBs also allow the use of aluminium instead of copper on the cathode side. This potential presents opportunities to explore suitable materials and understand the battery reaction required for efficient SIBs. Furthermore, sharing a similar operational mechanism as the LIBs makes SIBs easier to understand and more effective in the research context.

The working principle of SIBs is similar to that of the LIBs. The SIBs use an embedding and stripping process of sodium ions between the negative and positive electrodes to complete the charging and discharging cycles. The sodium ion (Na^+) is stripped from the cathode and embedded in the anode during charging and electrons are transferred to the anode through an external circuit to maintain the balance charge, and vice versa during discharge. The schematic illustration of the SIB working principle is presented in Figure 5.

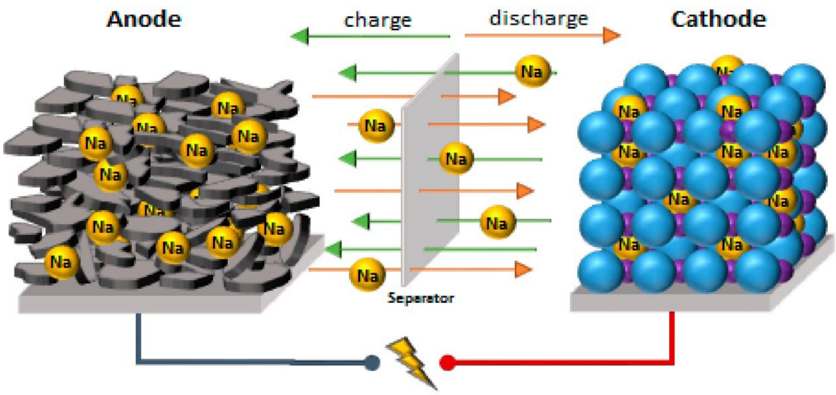


Figure 5 Schematic showing the working principle of sodium-ion battery (Peters et al., 2019)

Lithium and sodium are both ‘group 1’ elements of the periodic table. Both are alkali metals and possess one loosely held electron in their valence shell. Alkali metals are very reactive, and their melting point and first ionisation energy decrease down the group (Lu et al., 2021). The shared history between LIBs and SIBs is presented in Table 5. Furthermore, Table 6 shows some properties of both lithium and sodium, while Table 7 shows other similarities between the two.

Table 5 LIB and SIB shared-history illustrating the technological evolutions (Chayambuka et al., 2020)

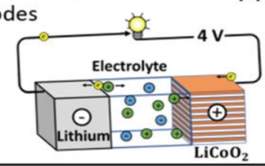
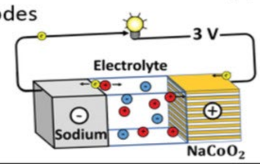
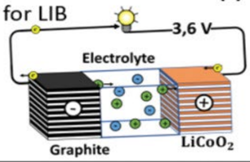
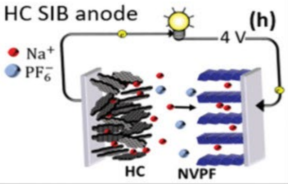
Period	Li-ion Batteries	Na-ion Batteries
1970 - 1980	(a) - Goodenough’s battery - $LiMeO_2$ cathodes *Applications:* Research 	(b) - Na/S batteries - $NaMeO_2$ cathodes *Applications:* Research 
1980-1990	(c) - The “rocking chair” battery - Graphite anode for LIB *Applications:* Research 	(d) - High temperature Na batteries - Lack of a suitable SIB anode *Applications*: e-Mobility, Grid 
1990-2000	(e) - First commercial LIB by SONY - Mixed metal oxides (research) *Applications*: Portable electronic devices 	(f) - SIB research decline - Development of ZEBRA cells *Applications*: Grid 
2000-2010	(g) - Si anodes - High energy density LIB *Applications*: e-Mobility 	(h) - Discovery of HC SIB anode *Applications*: Research 
2010-2020	(i) - Large scale LIB factories - Li supply concerns *Applications*: e-Mobility, Grid 	(j) - Revival of SIB research - SIB start-ups *Applications*: e-Mobility, Grid 

Table 6 Physical properties of lithium and sodium (Lu et al., 2021)

PROPERTY	LITHIUM	SODIUM
Atomic mass (g/mol)	6.94	22.99
Electron configuration	[He] $2s^1$	[Ne] $3s^1$
Cationic radius (Å)	0.76	1.02
Standard electrode potential (V)	-3.04	-2.71
Melting point (˚C)	180.5	97.7
Density (g/m^3)	0.971	0.534
First ionisation energy (KJ/mol)	520.2	495.8
Gravimetric capacity (mAh/g)	3861	1165
Volumetric capacity (mAh/cm^3)	2062	1131
Coordination preference	Octahedral/Tetrahedral	Octahedral/Prismatic
Cost of carbonates (US$/ton)	5000	150

Table 7 Key components of lithium-ion and sodium-ion batteries (Peters et al., 2019)

CHEMISTRY	ANODE	CATHODE	SEPARATOR	ELECTROLYTE	CELL HOUSING
LIB	Graphite on copper foil, organic or aqueous binder	Layered oxide on aluminium foil, organic binder	Polymer film (mostly PE)	Li salt ($LiPF_6$, LiTFSI) in organic solvent (EC/DMC)	Pouch, prismatic or round cells
SIB	Hard carbon on aluminium foil, organic or aqueous binder	Layered oxide on aluminium foil, organic binder	Polymer film (mostly PE)	Na salt ($NaPF_6$, $NaClO_4$) in organic solvent (EC/DMC)	Pouch, prismatic or round cells

However, SIBs also come with challenges and provide areas where further research could improve performance. Due to the higher specific weight of sodium in comparison to lithium and the higher irreversible capacity of the HC anodes, the theoretically achievable maximum energy densities of SIBs are lower than those of LIBs (Peters et al., 2019). Due to the large surface area requirements, the most relevant application for SIB will be for stationary applications using electrochemical battery technologies.

3.4.1 Sodium-ion batteries materials

Sodium is one of the most abundant and geographically spread resources on Earth, and it is found in rock salts and brines around the world. It is cheaper and more abundant than lithium, making it less susceptible to resource availability issues and price volatility. An explorable potential is to replace expensive lithium ions with sodium ions in battery technologies. This will imply changes to the cathode, anode and electrolyte to appropriately adapt to the SIB system. Over the years, cathode and anode materials for SIBs have been designed and developed with dramatic improvements in capacity and cycle life. SIBs can achieve energy densities greater than 100

Wh/kg, which is comparable to lithium iron phosphate batteries. By the end of 2022, the energy density achieved by SIBs was similar to that provided by some LIBs a decade ago as presented in Figure 6 (Crownhart, 2023).

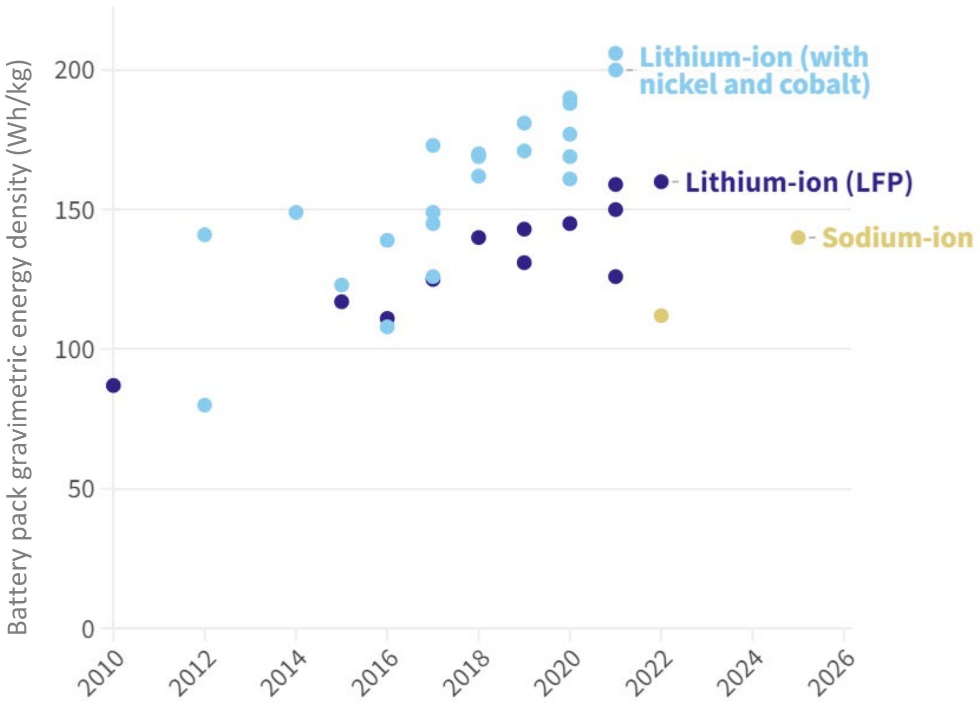


Figure 6 The energy density of lithium- and sodium-based batteries with projection to 2025

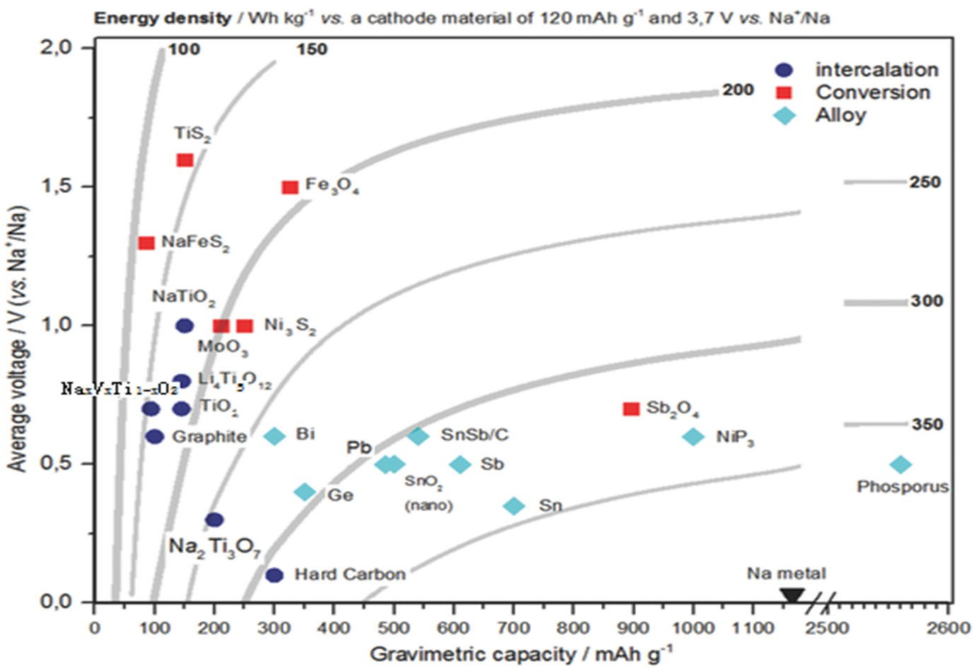


Figure 7 Average voltage versus discharge capacity of various SIB-based anode materials

3.4.2 Sodium sources and abundance

The surge in interest in energy storage and alternative battery material resources has placed a lot of attention on SIBs. A key attraction to SIBs in addition to similarities with lithium and its great electrochemical properties is the abundance of sodium. Over the years the production processes including extraction and purification of sodium from sodium carbonate, have become more efficient at lower costs. Sodium is the lightest metal and the second smallest after lithium, and when compared in terms of geographical abundance and availability, sodium is highly abundant. Sodium can be sourced from the earth's crust and water bodies (lakes, seas, etc.) (Nurohmah et al., 2022). Sodium can be obtained from various compounds including sodium carbonate, sodium acetate, sodium chloride and sodium nitrate. Sodium carbonate can be extracted from the mineral trona. Most of the sodium salts can be produced from saline water, and sodium compounds form from evaporation in lakes (Lwanyaga et al., 2020). Therefore, sea salt from seawater is an ideal candidate for the raw sodium materials required in SIB (Liu et al., 2020; Nurohmah et al., 2022). Brine from produced water from CSG mining represents a potential source of sodium that could be used for the development of the sodium ion battery industry, to provide cost efficiency. However, there was no study found in the literature where SIB production materials were sourced from recovered brine of CSG-produced water.

When compared to lithium which currently dominates the electrochemical energy storage battery technologies, sodium concentration in seawater could be as high as 10,800 mg/L as against 0.2 mg/L for lithium and when considering their abundance in the earth's crust, sodium makes up to 2.8% as against 0.006% for lithium (Yabuuchi et al., 2014). This comparison is further illustrated in Figure 8.

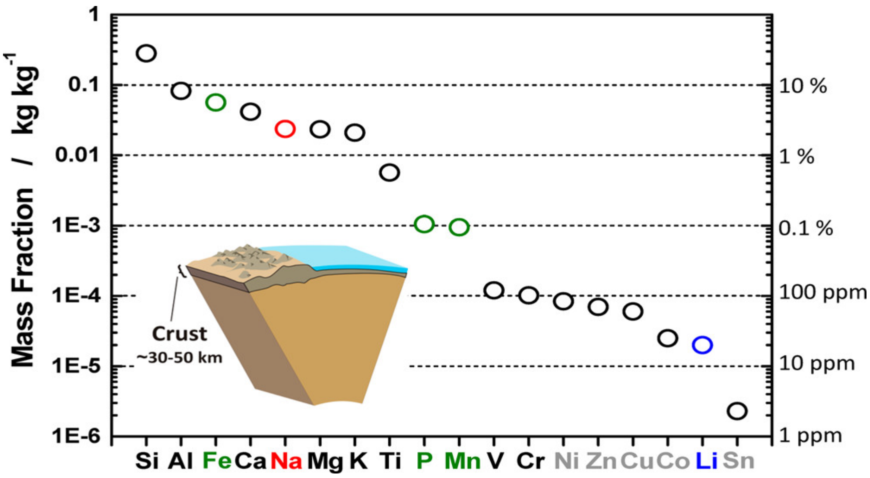


Figure 8 Comparison of the elemental abundance in the Earth's crust (Carmichael, 2017) (Y-axis represents a logarithmic scale, highlighting the mass fraction differences)

3.4.3 Opportunities

The abundance of sodium is key among the reasons why SIBs are being considered candidates for the future development of battery energy storage systems (BESS). The electrochemical properties are another consideration. The SIB's cycling ability and life duration also stand out. To illustrate the cycle life performance Figure 9 presents an example of a 75 Wh/kg cylindrical SIB with approximately 4,000 cycles at a 1C discharge rate (C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity) at room temperature and 100% depth of discharge (Chayambuka et al., 2020).

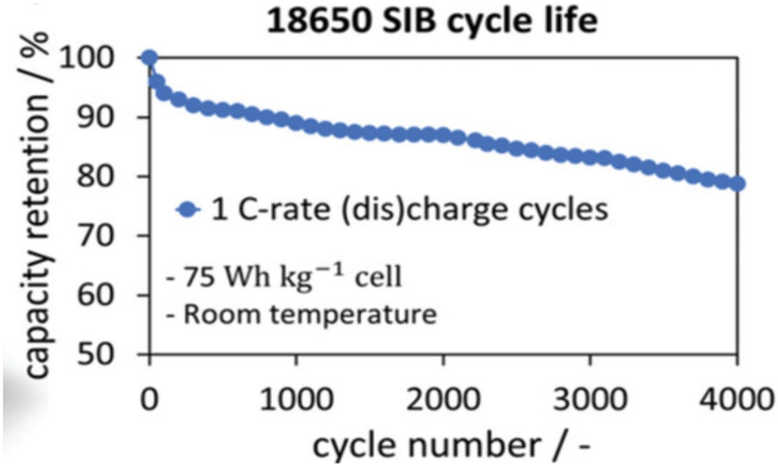


Figure 9 Extended cycle life test of SIB showing 4,000 cycles before the end of life (Chayambuka et al., 2020)

Additionally, as relatively large ions, sodium offers the possibility to increase the flexibility of materials design. Another merit of larger ionic radii is a weak solvation energy in polar solvents. This relatively low energy for desolvation is an important property useful for the design of high-power batteries. The high ion conductivity of sodium-based electrolytes increases the battery performance compared to lithium-ion electrolytes (Yabuuchi et al., 2014). The ability to discharge and store SIBs at 0 V, without degradation is also a highly safe characteristic (Chayambuka et al., 2020). Safety is a major consideration in the application of batteries for both mobility in electric vehicles and stationary energy storage.

3.4.4 Challenges

While the opportunities for SIB development seem promising, some challenges deserve attention that will lead to further research and development. Though the larger ionic radii offer some flexibility in terms of design, SIBs may not be suitable for portable electronic devices. The larger radius and heavier weight could affect phase behaviour and diffusion properties. Sodium ions also have larger electrode potential, limiting the energy density of SIBs (Lu et al., 2021).

Even though the cost of raw materials for the SIB is significantly cheaper than for lithium-ion batteries, the cost-effectiveness of the battery does not solely depend on material costs.

Battery cost analysis exceeds the simple approach of examining the unit cost of specific materials like lithium and sodium, but rather must be considered from a holistic perspective. Auxiliary features, also referred to as the balance of the systems from an engineering perspective, include aspects such as cell design, electrode coating thickness, porosity requirements and their impacts on battery chemistry as well as cost. The inclusion of auxiliary features as well as processing and overhead costs provides more representative costs of a technology or product.

In a study that applied an energy cost model to compare LIBs and SIBs, the material costs, processing costs and overhead costs were included in the evaluation to determine a battery cell cost of US$268/kWh for SIB and US$186/kWh for LIB both with 4C discharge rate (Schneider et al., 2019). This study showed that despite the cheaper sodium raw material costs compared to lithium in costing the kWh of battery cell capacity, SIB emerged more expensive than LIB due to higher other material, processing and overhead costs. This is illustrated in Figure 10.

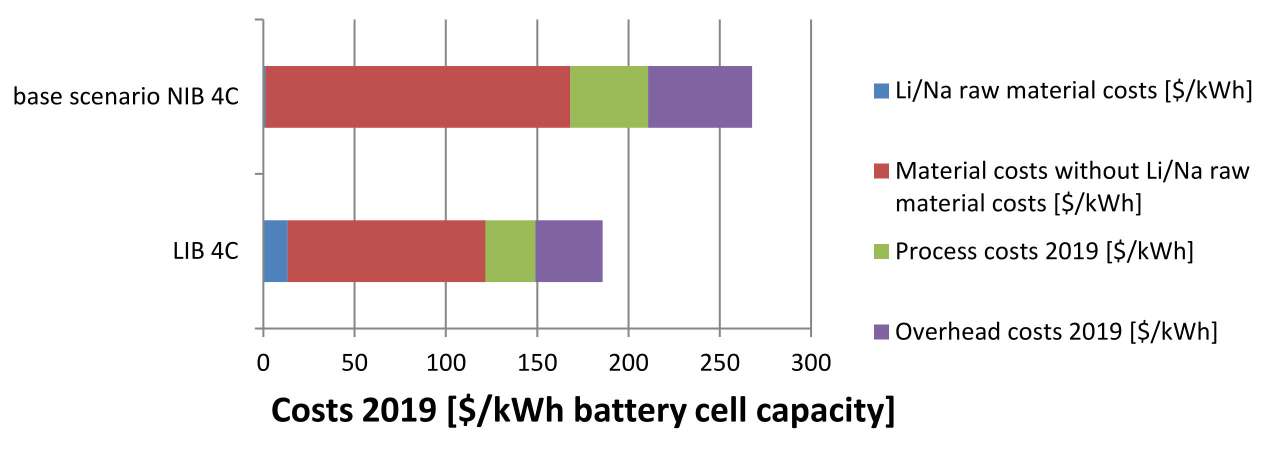


Figure 10 Manufacturing costs (US$) for LIB and SIB cells designed for 4C discharge rate (Schneider et al., 2019)

Another study used battery manufacturing cost estimation software *BatPac* to analyse SIB with layered oxide cathode of sodium-nickel-manganese-magnesium-titanate-oxide and LIB with lithium-iron-phosphate cathode and lithium-nickel-manganese-cobalt cathode (Peters et al., 2019). The results were €223/kWh for the SIB, €229/kWh for LFP-LIB and €168/kWh for the NMC-LIB. While the SIB cell was cheaper than the LFP-LIB, the NMC-LIB was the cheapest. These results highlight the potential energy density as another important factor for battery cost analysis. Materials that can provide higher energy density could significantly reduce the cell energy cost per kWh. NMC-LIB had the most expensive materials but also produced the highest energy density.

Finally, the SIB technology can, however, offer viable alternatives to complement LIB applications, the most promising being stationary storage applications, with limited applicability for mobile use.

3.5 Acid mine drainage neutralisation

Acid mine drainage (AMD), also known as abandoned mine drainage or acid rock drainage, occurs due to the oxidation of sulfide minerals (mainly iron-based pyrites) due to biological, geochemical and electrochemical processes (Dold, 2008). This involves a dual oxidation reaction, initially generating ferrous sulfur and sulfuric acid, followed by ferric hydroxide and additional sulfuric acid production (Akcil and Koldas, 2006). Other sulfide minerals such as chalcopyrite, pyrrhotite and sulfur-containing coal also have the potential to generate acid and heavy metals (Li et al., 2018). AMD processes occur naturally but are exacerbated by anthropogenic activity, which increases the exposure of sulfide minerals to oxygen, water and microorganisms. AMD effluents are strongly acidic (pH <4) with high concentrations of sulfate ions (1,000 – 130,000 mg/L), as well as trace metal ions to many times higher than water quality guidelines for human and ecosystem health (e.g. zinc and aluminium 20-800 mg/L; copper, nickel and manganese >250 mg/L) (Li et al., 2018). AMD effluent can cause chemical changes (e.g. increase in waterbody acidity, soluble metals, destruction of bicarbonate buffering system), physical changes (e.g. turbidity, sedimentation, reduced light penetration), biological changes (e.g. severe effects on behavioural, reproductive, osmoregulation processes, acute and chronic toxicity), and ecological damage (e.g. habitat destruction, niche loss, bioaccumulation in food chain, elimination of sensitive species, reduced primary productivity) (Ighalo et al., 2022). While AMD can become neutralised as effluent travels further from the source due to dilution and other chemical reactions, sulfate and metal ions can continue to remain in solution due to their high solubility (Naidu et al., 2019).

AMD poses serious ongoing environmental management problems in active and abandoned mine sites. In Australia, there are more than 380 mines in operation, while the number of abandoned mines could be as high as several thousand (Venkateswarlu et al., 2016). It has also been estimated that more than half of mining sites could consist of waste materials that have the potential to generate AMD (Naidu et al., 2019). AMD can be produced at both primary sources (mine rock dumps, tailings, open pit and underground mines, discharged underground water, seepage from replaced overburden in rehabilitated zones, rock used in constructing dams and roads) and secondary sources (rock cuts, stockpiles, emergency ponds, treatment sludge ponds, concentrated load-out and concentrate spills along the roadside) (Akcil and Koldas, 2006). While AMD production from active mines can be managed at lower costs compared to abandoned sites, approximately 70% of mine site closures between 1980 and 2005 were unplanned. Annual AMD management is therefore estimated to cost approximately A$150 million for active sites and more than A$500 million for abandoned sites (Naidu et al., 2019). Globally, it was estimated that AMD remediation from the four largest mining nations could be $US 32–72 billion (Cozzolino et al., 2018).

3.5.1 Acid mine drainage neutralisation – treatment options

AMD represents a significant undertaking for the mining industry worldwide due to the challenges associated with neutralising the acid heap leach within the containment structure while managing the risk of impacts to water and soil. The increasing drive towards sustainable mining and a circular economy has reinvigorated the consideration of AMD prevention and remediation technologies and processes. Prevention measures, such as limiting air and/or water from contacting pyritic minerals through soil, clay, geotextile and applications of other similar agents, present opportunities to avoid AMD production at the commencement of projects (Naidu et al., 2019).

Chemical neutralisation is the most common primary treatment for AMD through the application of alkaline materials, which have the capacity to resist acidification through buffering, increase the pH and precipitate the dissolved metals. More specifically, the term ‘alkalinity’ measures the capacity of a solution to neutralise acids to the so-called equivalence point of either carbonate or bicarbonate (~pH 4.5), and is equal to the sum of bases in solution (Dickson, 1981). An opportunity exists for produced water brines to be used as a treatment for AMD due to their high pH and alkalinity. The pH, alkalinity and sodium concentrations of common neutralisation products are comparable with the predicted PW brine composition from the NGP (Table 8).

Table 8 Predicted chemical composition of produced water brine compared to common chemical methods for AMD neutralisation. Different units are reported in italics where insufficient information was provided for conversion to mass per volume

				ALKALINITY (mg L^{-1})			
Source	**pH**	**EC (µS cm^{-1})**	**Sodium (mg L^{-1})**	**Total**	**CO_3**	**HCO_3**	**OH**
PW brine	8.9	64,060	27,980	49,130	15,380	28,500	2.6
Seawater	7.9-8.3	50,000	10,700		116		
Red mud (bauxite) liquor	13.14	116,100	7,447	38,300	16,239	6.4	3,794
Deep aquifer brine (to treat bauxite)	5.5	200,000	30-35,000	55,000 (with bauxite)			3.7 *(mol kg^{-1})*
Seawater neutralised bauxite	8.8	218,000	104,019 *(mg kg^{-1})*				
Lime	6	4,410	30	5			
Hydrated lime	11	2,180	54	57			
Limestone	6	4,330	40	354			
Caustic soda	13	1,635	5,836	3,565			
Soda ash	7	9,590	4,035	1,398			
Periclase	10	5,990	30	71			
Brucite	6	6,460	30	5			
Magnesite	9	6,190	30	56			
Paper mill waste	11.1 – 11.3		7,400 – 12,000 *(mg kg^{-1})*				

Source: (Bellaloui et al., 1999; Hanahan et al., 2004; Johnston et al., 2010; Madzivire et al., 2019; Masindi et al., 2017; Paradis et al., 2007)

3.5.2 Application of industrial by-products for acid mine drainage neutralisation

The neutralisation of bauxite residues with seawater increases its acid neutralisation capacity and the length of long-term neutralisation processes (Hanahan et al., 2004). A lifecycle analysis in Queensland, Australia found that seawater-neutralised bauxite residues generated 20% of carbon dioxide emissions and 44% of electricity use compared to lime applications for AMD treatment. However, fuel usage would be nearly 24 times greater than lime due to the need to transport materials long distances (Tuazon and Corder, 2008). The addition of natural brine from a deep aquifer to a bauxite residue converted bauxite basicity and highly soluble alkalinity to low soluble alkalinity (hydroxide, carbonate, hydroxycarbonate minerals), where the neutralisation potential was retained for longer following leaching compared to non-brine amended bauxite residues (Paradis et al., 2006; Paradis et al., 2007).

3.5.3 Co-treatment of acid mine drainage using produced water

Limited studies have directly examined the combination of produced water from natural gas extraction and AMD water. An Australian review identified the opportunity for highly alkaline CSG waters to be used for acid mine water neutralisation but did not elaborate on this potential (Ly et al., 2016). From a systems perspective, one study examined a co-treatment process for both produced water and 'abandoned' mine drainage in Pennsylvania by mixing both waste streams, after which the treated water can then be used for hydraulic fracturing operations with the additional benefit to offset freshwater use (Wang et al., 2018). A lifecycle analysis revealed that the feasibility of this process was dependent on electricity usage and transportation of the two wastewaters. Consideration must be given to the number of treatment sites as well as their location and proximity to the stationary treatment site, or to determine the viability of a mobile unit that could be transported between sites depending on the production volume of either waste stream.

Two studies examined the chemistry of the co-treatment of PW and AMD waters. The co-treatment of 'flowback' (produced) water with AMD was identified as a potential make-up water source to allow for flowback water reuse (He et al., 2016). One of the major identified issues was the precipitation of high sulfate and barium following the mixing of the two waste streams to form severe scaling and impairment of the well productivity, as well as the potential for high dissolved iron concentrations to interfere with reducing chemicals or cross-linking gels sometimes added to increase fracturing fluid viscosity (He et al., 2014). A pilot scale study showed that sulfate could be reduced to below 100 mg/L in the final water by adjusting the mixing ratio of the two streams, while ferric iron in AMD acted as a coagulant to remove suspended solids and co-precipitate ferric iron to remove it from the final treated water. Additionally, the solid waste precipitated as barite contained >99% of radium, showing a promising method for radioactive element remediation from the water itself. However, the approach does present an additional waste treatment challenge for disposal as identified through a review of the AMD and flowback water co-treatment process (He et al., 2014).

Santos has been collaborating with Aeris Resources Limited (Aeris), a Queensland mining and exploration company, to assess the potential to use the alkaline salt produced from the NGP to neutralise heap leach materials at one of its operational assets in central NSW, prior to covering the site with non-acid forming waste rock and rehabilitating to the final landform (Onward Consulting, 2022). Copper is extracted from the mined ore at the Murrawombie heap leach operation. The process to remove copper from the heap leach material is to leach the ore with acidic water. When the copper has been leached from the ore, the heap leach material has a low pH of 2 to 3 and contains elevated concentrations of water-soluble metal(oids) and major ions. Before a soil cover system can be placed over the heap leach material, the actual acidity must be neutralised. Neutralisation can be done with the alkaline brine to bring the material to pH 8. Increasing the pH of the heap leach material results in the immobilisation of water-soluble metal(oids), mainly as hydroxides. After the heap leach material is neutralised, an additional dose of fine limestone on the surface and an oxide waste rock/soil cover will be placed over the heap leach material. Geochemical assessment work has already been done to demonstrate that oxide waste rock materials (from Murrawombie) are geochemically benign and can be used as a cover material for the final rehabilitation of the heap leach material (Onward Consulting, 2022).

Santos and Aeris commenced a laboratory-scale neutralisation trial in 2017 on bulk samples of Murrawombie heap leach materials using brine produced during the NGP appraisal program (Onward Consulting, 2022). The laboratory trials showed that alkaline brine produced from the NGP could significantly reduce the acidity and concentrations of many of the dissolved metals/metalloids in seepage and surface runoff from the bulk heap leach materials (Onward

Consulting, 2022). The sodium carbonate-rich brine produced from NGP has demonstrated effectiveness at neutralising pH and significantly reducing the concentration of most metals and metalloids when compared with other conventional neutralising chemicals, such as sodium hydroxide, calcium hydroxide and calcium carbonate.

3.5.4 Summary

While the potential for PW and brine application for AMD neutralisation has been identified in the literature, only limited studies have investigated the chemical and techno-economic implications of this application. More data is needed to determine the efficacy of neutralising AMD with PW brines. Additionally, PW brines could be investigated for their properties to co-treat AMD through an initial reaction with bauxite red mud residues, as PW brines have similar properties to seawater treatments that have been applied in the industry. Moreover, the co-treatment of PW brines and acidic AMD wastewaters could provide for an additional 'freshwater' resource to reuse within the gas field operation and to offset the use of primary freshwater sources.

3.6 High-value algae cultivation

Microscopic algae, also known as microalgae or phytoplankton, are small unicellular photosynthetic organisms invisible to the naked eye. They occur in the water column and sediments of marine and freshwater systems, and can exist individually or in groups or chains (Spolaore et al., 2006). There are between 200,000 and 800,000 species of microalgae, from which over 15,000 novel chemical compounds have been identified, including a range of valuable metabolites such as oils and lipids (which can be converted to biodiesel or bioethanol), proteins, pigments (carotenoids, chlorophylls, phycobiliproteins), bioactive compounds (polyunsaturated fatty acids, antioxidants, vitamins) and biopolymers (Guedes et al., 2011). Therefore, the production of these compounds, in addition to the rapid biomass growth rates observed for many species, has created interest in the application of microalgal-based technologies for biofuels, food and feed ingredients and supplements, pharmaceuticals and nutraceuticals, and bioplastics for packaging, textiles and consumer goods (Chew et al., 2017; Spolaore et al., 2006). The need for developing next-generation bio-based liquid fuels is also critical as many economies seek to reach 'net zero' greenhouse gas emissions by 2050, where hard-to-abate sectors that are difficult to electrify (such as aviation) will require alternative sources of liquid fuels (Chisti, 2008). Microalgae can also be used for bioremediation applications by removing contaminants from wastewater and other environments through accumulation, adsorption or metabolism of toxic compounds (Priyadarshani et al., 2012). In Australia, it may cost up to A$100 million per year to repair damage to infrastructure caused by saline wastewater (Vo et al., 2020).

Microalgae are an attractive source of biomass as their cultivation requires less land area, faster growth rates (some species complete growth cycles within several days) and higher oil yield per acre compared to terrestrial crop-derived biomass when considering their potential for biofuel production (McHenry, 2013; Satputaley, 2012) (Table 9). Microalgae can also be cultivated on marginal land (reducing potential land use for food-fuel competition) and can be harvested continuously or semi-continuously. They have a lipid content of 5-50 % of biomass dry weight, do not require agricultural inputs such as pesticides and herbicides, and can potentially use nutrients from wastewaters to grow biomass as well as remediate or polish effluent (Jez et al., 2017). Some microalgal species are able to maintain rapid growth rates in saline, contaminated or low-quality waters, while others can withstand high temperatures (e.g. allowing for the introduction of flue-exhaust carbon from other industrial processes without pre-cooling) (Wang et al., 2008).

Table 9 Comparison of lower heating value, oil yields and land area for biodiesel production

SOURCE	LOWER HEATING VALUE (Mj/Kg)	OIL YIELD (L/ha)	LAND AREA (M ha)	EXISTING US CROPPING AREA (%)
Diesel	42.7	-	-	-
Jatropha	39.7	1892	140	77
Sunflower	39.6	952	-	-
Soybean	37.7 - 39.6	446	594	326
Karnja	37.4 - 38.8	-	-	-
Canola	38.5	1190	223	122
Corn	38.7	172	1540	846
Coconut	38.3	2689	99	54
Oil palm	39.8	5950	45	24
Microalgae	39.5	136,900 (70% oil by wt) 58,700 (30% oil by wt)	2 4.5	1.1 2.5

Sources: (Benjumea et al., 2008; Chisti, 2007; Demirbas and Fatih Demirbas, 2011; Hamawand et al., 2014; Lugo-Méndez et al., 2021; Satputaley, 2012)

An opportunity exists to use sources of saline water such as produced water and/or brine for algal production to reduce freshwater consumption or allow for its use in other sectors that are more sensitive to salinity (e.g. crop production).

Several water quality parameters can affect the growth and performance of algae in PW and brines. Salinities near or lower than seawater concentrations (approximately 35,000 ppm total dissolved solids) are optimal for algal growth, although at least 25 species have been identified as capable of surviving at high salinities within a PW context (Rahman et al., 2020). *Shewanella* spp. have the largest saline spectrum (between 0 – 7% salinity), although this species was not applied within the studies captured (Vo et al., 2020). While PW and brines can range from near freshwater to very saline (<1000 - >200,000 ppm TDS), studies have tended to focus on PW streams in the range of 2,650–8,090 ppm TDS in Australia to 7,744–38,422 ppm TDS in the south-western USA (Kinnon et al., 2010; Stephenson, 1992; Sullivan Graham et al., 2017). However, halophytic microalgae species such as *Scenedesmus* spp. showed promise for desalination applications in batch tests up to 20,000 mg/L salinity (Sahle-Demessie et al., 2019). Similarly, marine microalgal species showed high intracellular nitrate storage capacities under saline conditions (~20,000 mg/L), a potential application for nutrient remediation (Coppens et al., 2014). Higher salinities were also better for electricity generation and desalination in microbial desalination cells operating at 35,000 mg/L salinity, due to the higher internal resistance and conductivity (Ashwaniy and Perumalsamy, 2017; Gao et al., 2021; Khazraee Zamanpour et al., 2017).

Some researchers have suggested using other pre-processing technologies to reduce salt load (e.g. RO membranes) to then grow microalgae in lower salinity waters. However, this may not be feasible or cost-effective (Hamawand et al., 2014). CSG produced water showed the potential to support the growth of microalgal communities. However, biomass growth rate was 7-9 times slower than in other waters (Buchanan et al., 2013). Other studies also reported either low growth rates or no growth under very saline conditions except for a few species over 80,000 mg/L salinity (e.g. *Dunliella salina*, *Tetraselmis suecica*), with a polyculture showing low biomass accumulation (~0.15 g/L) over 21 days at a maximum salinity of 90,000 mg/L TDS (*Parachlorella kessleri* and cyanobacteria) (Hopkins et al., 2019; Parsy et al., 2022).

Algal community composition varied between dilute and concentrated CSG water, indicating that water quality may select for different algal species, although an algal consortium achieved ~20% removal rates for salinity and chloride and 44% chemical oxygen demand (COD) removal in PWs between 55,000 – 60,000 mg/L salinity (Buchanan et al., 2013; Hopkins et al., 2019; Nadersha and Aly Hassan, 2022). Similarly, biomass yields and oil and COD removal rates were high for *Nannochloropsis oculata* at PW loadings at 25% (~35,000 mg/L TDS), but decreased with increasing PW loading (Ammar et al., 2018). PW and brines are also commonly contaminated with a range of compounds from oil or gas extraction, such as trace metals, hydrocarbons, and other additives such as surfactants, metal salts, solvents and biocides that may induce ecotoxicological responses in algae, or may risk being adsorbed and transmitted to downstream consumers of algal-derived products (Sullivan Graham et al., 2017). Algae tend to sorb positively charged cations over anions due to their net negative surface charge (-7.5 to -40 mV). *Nannochloropsis salina* strongly sorbed Cd, Co, Cu, Pb and Zn trace metals under high salinity, while it was less effective at sorbing As, Cr, Ni and Se (Torres et al., 2017). Ni sorption also strongly decreased growth, while the other contaminants did not.

However, stress has been shown to vary microalgal lipid production quantities (Rawat et al., 2013). Halophiles, such as D. salina, can survive in environments like saturated brines (5 M NaCl) (Jeon et al., 2016). One study reported higher D. salina lipid production under higher PW:seawater ratios (~29% increase when 1:1 dilution, or 2,500 mg/L NaCl), while improving the removal of nitrogen, phosphorus and nickel (Talebi et al., 2016). Microalgal dry weight and lipid content peaked at a concentration of 50,000 mg/L NaCl for C. vulgaris, although the highest lipid accumulation was triggered by the near depletion of nitrate (<5 mg/L), producing a total lipid content of 40% (Shen et al., 2015). Additionally, high reef salt run-off wastewaters (43,800 mg/L) were reported to produce maximum lipid concentrations, with fatty acid composition indicating that more than half of the compounds were suitable for biofuel production (Devasya and Bassi, 2019). Stress induced by low-light conditions increased pigment content (87% increase in phycocyanin yield) (Wood et al., 2022).

3.6.1 Identified gaps

In summary, the literature review found that there are few studies on the application of high-value algae cultivation systems in PW and brines, with only 25 full-text research papers retrieved. There was a lack of studies conducted at the higher salinity concentrations that are predicted to occur in the brine. Additionally, the studies mainly focussed on bioremediation and the production of total biomass or lipids, with one paper reporting the production of a high-value pigment. While the focus on producing high-value compounds from microalgae is well documented in the broader literature for biopolymers or bioplastics, nutraceuticals, food, feed ingredients and supplements, and pharmaceuticals (Chew et al., 2017), there were no studies with this application in PW and/or brines.

While there are several viable design options for microalgal cultivation across open and closed systems, major bottlenecks remain at the harvesting and dewatering stages of processing. A recent review highlighted the potential role of genetic engineering technologies to enhance microalgal-based PW treatment, with a focus on CRISPR/Cas9 (Hassanien et al., 2023). Additionally, while capital expenditure and processing costs remain high for this technology, the development of a microalgal-based biorefinery to valorise multiple co-products such as biomass, lipids, pigments, nutrients, and other bioproducts could potentially provide a viable business model that integrates circular economy principles with the renewed market interest in emerging bio-based materials and products (Chew et al., 2017).

4 Techno-economic analysis

A techno-economic analysis (TEA) is a useful tool to estimate a proposed option's performance, emissions, and cost, and quantify economic costs, financial drivers, and associated environmental impacts.

Key assumptions and approaches made in this study are:

- The capital cost estimates were conducted to a Class 5 level (e.g. concept screening stage, very low project definition (i.e. 0-2%)), as defined by the Association for the Advancement of Cost Engineering International (Stephenson, 2015).
- A typical exponential methodology for capital cost estimation was used based on the correlations from publicly available references and proprietary databases.
- Estimated and calculated raw materials inputs, labour, utilities, consumables, maintenance, insurance etc. and cost of capital were used for operating cost estimate.
- Equations used for the TEA included cost adjustments to scale up or down using a base cost either found from a database or literature.
- Discounted cash flow (net present value or NPV) analysis was used to estimate the levelised cost of the product for each proposed brine reuse scenario. The levelised cost is a breakeven price of the product at the point where the NPV is 0, such that the project makes neither a loss nor a profit if the product is sold at the levelised cost of the product. Additionally, a payback period (the time for an investor to recover the project's initial cost) can be determined by assuming a potential price for the product.
- For identified brine reuse scenarios, the following assumptions were made:
- Company tax rate of 30%;
- Discount rate of 8.5%;
- Plant lifetime of 30 years; and
- All costs are in Australian Dollars (A$) unless otherwise specified.

The three key stages at the Leewood site present in the water treatment process that were of note in the TEA included:

- Stage 2 – Reverse osmosis of produced water (produces a brine output assumed as 0.7 ML/day)
- Stage 3 – Brine concentrator (produces a concentrated brine output assumed as 0.25 ML/day)
- Stage 4 – Salt crystalliser (produces a salt output assumed as 47 tonne/day)

4.1 Selective salt recovery using the Solvay process

4.1.1 Option description and assumptions

A techno-economic analysis was conducted to evaluate the performance of the Solvay process for selective salt recovery. The Solvay process uses brine, limestone, and ammonia to produce sodium carbonate.

The concentrated brine produced from the Stage 3 Brine concentrator unit was assumed as 10.4 m^3/h (250 m^3/day) and used as the input into the Solvay process.

The assumptions used to estimate the CAPEX of the selective salt recovery system utilising the Solvay process for brine reuse were taken from a case study on soda ash production conducted by Rumayor et al. (2020). The OPEX was calculated using the process modelling software Aspen HYSYS® to model the required utilities.

These values were escalated, scaled to the required plant capacity, and converted into A$, resulting in a CAPEX of A$58 million and OPEX of A$8 million/year. The Solvay process for selective salt recovery is assumed to produce two products:

- Calcium chloride as a by-product at a rate of 571 kg/h
- Sodium carbonate as the main product at a rate of 1,412 kg/h.

A block flow diagram of the process is presented in Figure 11.

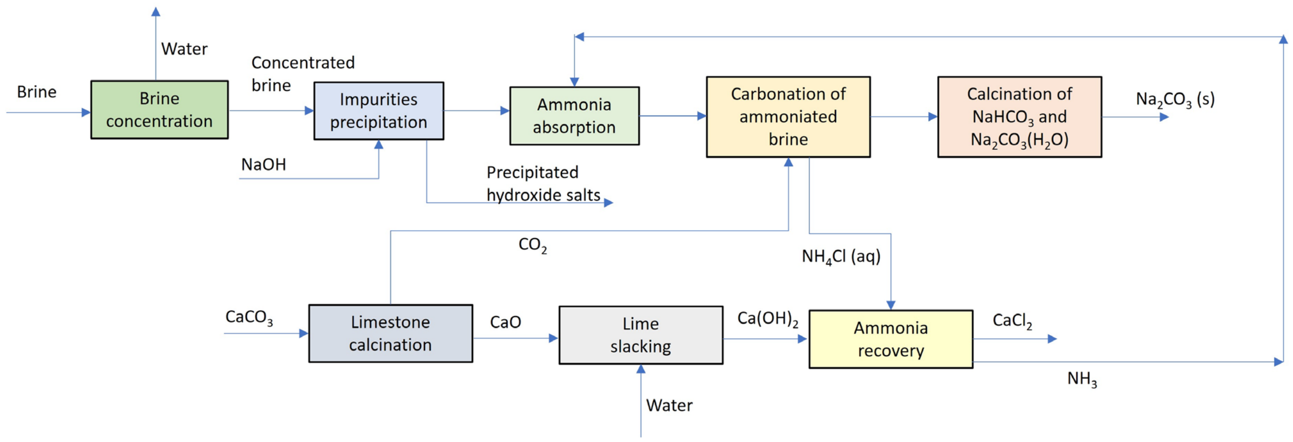


Figure 11 Block flow diagram of the Solvay process for selective salt recovery

4.1.2 Summary of results

A summary of the results of the TEA for the selective salt recovery using the Solvay process is presented in Table 10.

Table 10 Summary of TEA results for the selective salt recovery using the Solvay process

PARAMETER	VALUE
Concentrated brine input (m^3/h)	10.4
Production (tonne/year) Na_2CO_3 $CaCl_2$	 11,860 4,796
CAPEX (A$)	A$58 million
OPEX (A$)	A$8.1 million
Assumed selling prices for products (A$/tonne) Na_2CO_3 $CaCl_2$	 A$471 A$250
Sales revenue for Na_2CO_3 & $CaCl_2$ (A$/year)	A$5.92 million
NPV (A$)	-A$107.1 million
LCONa$_2$CO$_3$ (Levelised cost of Na_2CO_3 A$/tonne)	A$1,576

The levelised cost of sodium carbonate was determined as A$1,576/tonne of sodium carbonate produced. Alternatively, an NPV of -A$107.1 million was calculated, with an assumed market price for each product as:

- Sodium carbonate: A$471/tonne (Trading Economics, 2024)
- Calcium chloride: A$254/tonne (ECHEMI Digital Technology Co Ltd, 2024)

4.2 Selective salt recovery using the Sal-Proc process

4.2.1 Option description and assumptions

A techno-economic analysis was conducted to evaluate the economic performance of the Sal-Proc process for selective salt recovery. The Sal-Proc process is a patented technology developed by Geo-Processors USA, Inc. The Sal-Proc treatment process was designed to facilitate the production of specific dissolved salts from saline waters by sequential or selective precipitation. The process combines chemical reactions with evaporative cooling and crystallisation steps to enable sequential or selective precipitation for selective salt recovery. Since the chemical composition of the saline feed stream is unique in every case, is site-specific and the technology is patented, the exact requirements regarding energy and chemical reagent usage are not currently known. However, ranges for CAPEX and OPEX estimates were used to estimate the capital costs and operating costs for a proposed selective salt recovery system using the Sal-Proc process for brine reuse.

The brine produced from the Stage 2 Reverse osmosis unit was assumed as 29 m^3/h (700 m^3/day) and used as the input into the Sal-Proc process.

The assumptions used to estimate the CAPEX and OPEX of the selective salt recovery system using the Sal-Proc process for brine reuse were taken from a technical assessment of produced water treatment technologies by the Colorado School of Mines (Drewes et al., 2009) :

- CAPEX of US$5,838.2/$m^3$ per day
- OPEX of US$3.7/$m^3$

The above values were escalated, scaled to the required plant capacity, and converted into A$, resulting in a CAPEX of A$9.1 million and OPEX of A$2.1 million/year. The Sal-Proc process for selective salt recovery is assumed to produce two products:

- Sodium chloride as a by-product at a rate of 188 kg/h.
- Sodium carbonate as the main product at a rate of 1,176 kg/h.

A block flow diagram of the process can be observed in Figure 12.

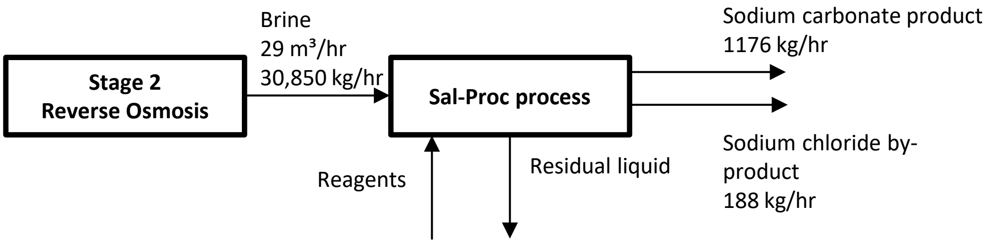


Figure 12 Block flow diagram of the selective salt recovery using the Sal-Proc process

4.2.2 Summary of results

A summary of the results of the TEA for the selective salt recovery using the Sal-Proc process is presented in Table 11.

Table 11 Summary of TEA results for the selective salt recovery using the Sal-Proc process

PARAMETER	VALUE
Brine input (m^3/h)	29
Mass brine input (kg/h)	30,850
Production of Na_2CO_3 salt (tonne/year)	9,881
Production of NaCl by-product salt (tonne/year)	1,575
CAPEX (A$)	A$9.1 million
OPEX (A$/year)	A$2.1 million
Assumed selling prices for products (A$/tonne) Na_2CO_3 NaCl	 A$471 A$387
Total revenue (A$/year)	A$5.3 million
NPV (A$)	A$17.0 million
LCONa_2CO_3 (Levelised cost of Na_2CO_3 salt) (A$/tonne)	A$201
Payback period (years)	4.2

The levelised cost of sodium carbonate was determined as A$201/tonne of sodium carbonate produced. Alternatively, an NPV of A$17.0 million and a payback period of 4.2 years were calculated, with an assumed market price for each product as:

- Sodium carbonate = A$471/tonne (Trading Economics, 2024)
- Sodium chloride = A$387/tonne (Breadon and Fox, 2023)

4.2.3 Sensitivity analysis

A sensitivity analysis was conducted to determine the effects that varying the OPEX would have on the LCOS, NPV and payback period of the selective salt recovery using the Sal-Proc process. The results are summarised in Table 12.

Table 12 Summary of sensitivity analysis by varying OPEX for the selective salt recovery using the Sal-Proc process

	-50%	Baseline	+50%
OPEX (A$/year)	A$1.0 million	A$2.1 million	A$3.1 million
LCONa_2CO_3 (A$/tonne)	A$154.4	A$274.2	A$393.9
NPV (A$)	A$27.3 million	A$17.0 million	A$6.6 million
Payback period (years)	2.0	4.2	10.1

When the OPEX was reduced by 50%, the levelised product cost was reduced by ~A$100 from A$274/tonne to A$154/tonne. The NPV also improved by A$10 million from A$17 million to A$27 million, while the breakeven point was achieved within half of the payback period (PBP) of the base case in 2 years. However, an increase in OPEX by 50% affected the economic viability of the process by reducing the NPV to below a quarter of the base case value at the end of the plant lifetime.

4.3 Recovery of critical minerals and other important elements

4.3.1 Description of process and assumptions

A techno-economic analysis evaluated the economic performance of recovering critical minerals and other important elements from concentrated brine. The analysis indicated that:

- Valuable minerals (e.g. Li, Rb, In, Ga, Sc, V, Cs) did not exist in reasonable concentrations in the brine.
- Minerals such as Ca, Mg and K were present in low concentration. The mineral with the highest potential for extracting value was potassium, with a concentration of 1,208 mg/L in the concentrated brine; however, while potassium chloride can be recovered from brine, it is not a simple process as brine typically contains a variety of different salts such as sulfates and chlorides of sodium, potassium and magnesium (Marx et al., 2019). When brine is concentrated, these other salts also precipitate out, making the separation of potassium chloride difficult. As such, the techno-economic analysis of the recovery of potassium chloride from brine could not be conducted.

- The salt produced from the Stage 4 – salt crystalliser process was stated to contain Li and Mg in low concentrations. Assuming 100% recovery of both minerals, the maximum value recovered would be approximately A$0.11 million per year.
- Observing a proposed recovery method for Li and Mg from brine indicates that the products would be lithium carbonate and magnesium hydroxide, requiring further processing.
- Thus, this method cannot effectively reuse the brine produced from Stage 2, the concentrated brine from Stage 3, or a potential salt product produced from Stage 4. A high-level TEA was performed using the concentrated brine from Stage 3 as an input, but no discounted cash flow analysis was conducted due to the low value available and the uncertainty in concentrated brine input quality.

The concentrated brine produced from the Stage 3 Brine concentrator process was assumed as 10.4 m^3/h (250 m^3/day) and used as the input into the recovery of minerals process.

The assumptions used to estimate the CAPEX and OPEX of the recovery of minerals process were taken from a process design and economic evaluation conducted by Lwanyaga et al. (2020).

The values were escalated, scaled to the required plant capacity, and converted into A$, resulting in a CAPEX of A$7.58 million and OPEX of A$0.63 million/year. The critical minerals recovery process is assumed to produce two products:

- Lithium metal at a rate of 0.13 kg/h
- Magnesium metal at a rate of 1.34 kg/h

A block flow diagram of the process is presented in Figure 13.

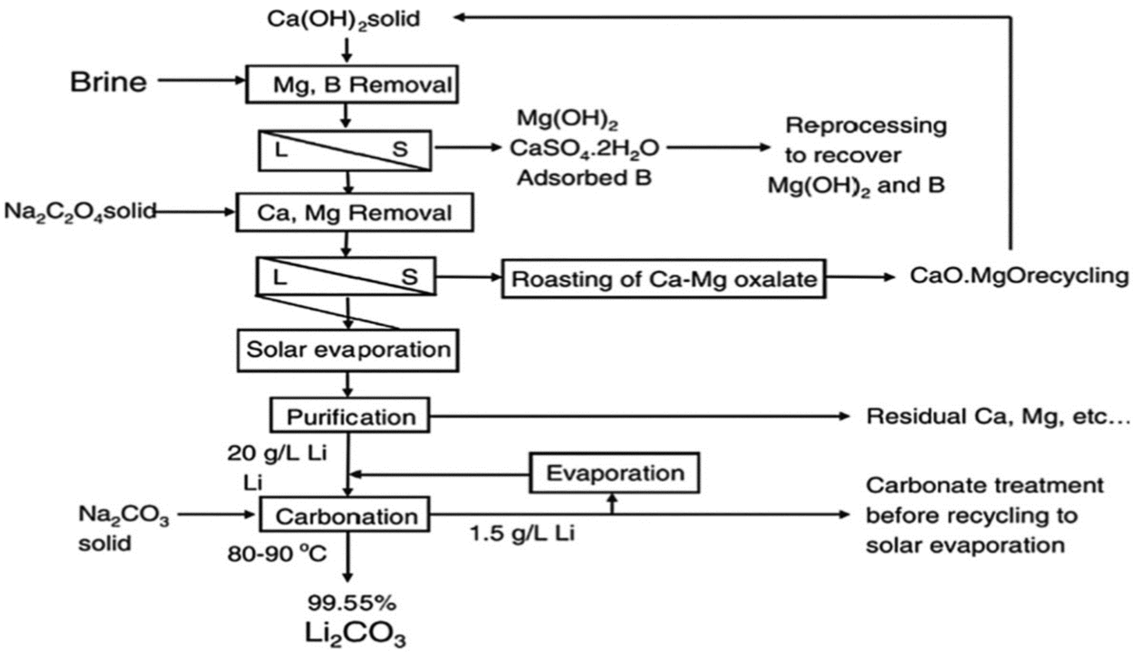


Figure 13 Block flow diagram of the critical minerals recovery from concentrated brine (An et al., 2012) (B: boron, Ca: calcium, Mg: magnesium, Li: lithium, L: liquid and S: solid)

4.3.2 Summary of results

A summary of the results of the TEA for the critical minerals recovery process from concentrated brine is shown in Table 13.

Table 13 Summary of TEA results for the critical minerals recovery process

PARAMETER	VALUE
Concentrated brine input (m^3/h)	10.4
Production (tonne/year)	
Li	1.13
Mg	11.8
CAPEX (A$)	A$7.58 million
OPEX (A$/year)	A$0.63 million
Total annual revenue (A$/year)	A$0.11 million

4.4 Harvesting energy – osmotic processes

4.4.1 Description of process and assumptions

Pressure retarded osmosis is a power generation process that harnesses the salinity gradient between two water bodies of different salinities. The higher salinity solution, called the draw solution, is the concentrated brine produced from Stage 3 of the NGP water treatment process. The less concentrated solution, called the feed solution, is the permeate produced from Stage 2 of the NGP water treatment process. The process involves placing a membrane between the two solutions. Due to the salinity difference between the draw and feed solutions, a salinity gradient energy is produced and released. This energy is encountered at the interface of the mixture. Theoretically, 2.5–2.7 MJ of energy could be released when 1 m^3 of the feed solution flows in contact with the draw solution. This energy, considering the losses, goes into a turbine for power generation.

The concentrated brine produced from the Stage 3 Brine concentrator unit was assumed as 10.4 m^3/h (250 m^3/day) and used as the input into the PRO process as the draw solution. Additionally, the permeate produced from the Stage 2 RO unit was assumed as 3,500 m^3/day, where 181.4 m^3/day of the RO water is used as the input into the PRO process as the less saline feed solution.

The assumptions used to estimate the CAPEX and OPEX of the PRO process for brine reuse were taken from a sustainability assessment of a PRO system (Mashrafi, 2021) , with a reference plant that was processing 1,067 m^3/h of brine.

The values were escalated, scaled to the required plant capacity, and converted into A$, resulting in a CAPEX of A$0.56 million and OPEX of A$0.038 million/year. The PRO process is assumed to produce approximately 26.5 MWh of electricity per year.

A block flow diagram of the process is presented in Figure 14.

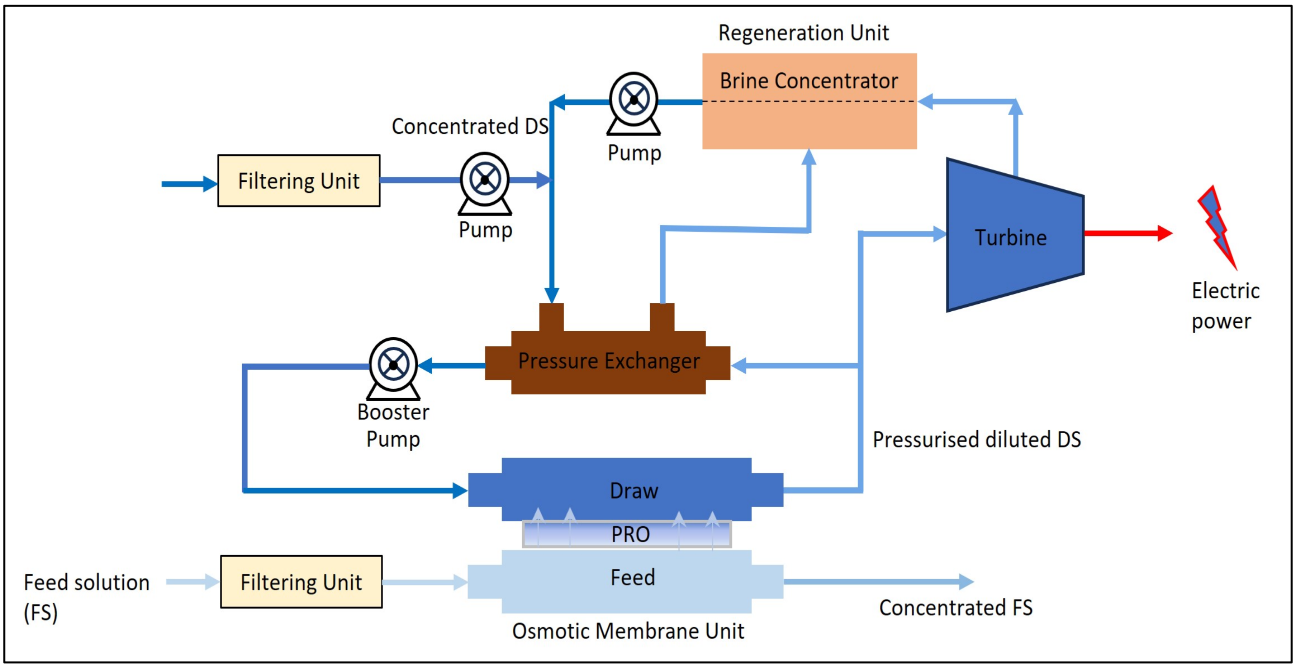


Figure 14 Block flow diagram of the PRO process. DS: draw solution, FS: feed solution

4.4.2 Summary of results

A summary of the results of the TEA for the harvesting of energy using the PRO process is presented in Table 14.

Table 14 Summary of TEA results for the PRO process

Parameter	Value
Production parameters assumed Concentrated brine input (m^3/h) Draw input (m^3/h)	 10.4 7.6
Electricity produced per year (kWh/year)	1.8 million kWh/year
CAPEX (A$)	A$8.35 million
OPEX (A$/year)	A$0.56 million
Assumed electricity selling price (A$/MWh)	A$90
Total revenue (A$/year)	A$3.3 million
NPV (A$)	-A$17 million
LCOE (A$/kWh)	A$1.75

The levelised cost of electricity was determined as A$1.75/kWh produced. Alternatively, an NPV of A$17 million with an assumed market price of A$0.09/kWh for electricity was calculated. Mashrafi (2021) recommended that the draw solution should be 0.215 m^3/s (~18,576 m^3/day) for the process to be technologically feasible. Therefore, this capacity was used to size the plan. This is an order of magnitude higher than the feed and draw solutions produced from the NGP, and likely explains both the high levelised cost of electricity and the negative NPV that have been calculated.

4.5 Energy storage (sodium-ion battery)

4.5.1 Description of process

The sodium ion battery energy storage system (SIB-BESS) was developed based on the operational characteristics of the SIB, such as rated power capacity, duration of discharge and the number of cycles. For a 60MW 4-hour BESS the economic model consists of costs for the system as presented in Figure 15, the electrical and mechanical balance of plant, fixed and variable OPEX.

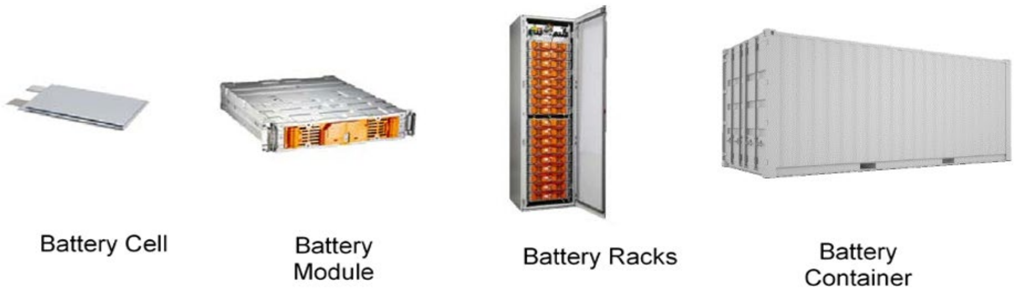


Figure 15 Battery system components (Ramasamy et al., 2022)

4.5.2 Summary of the results

The results from the analysis indicated that the sodium raw material required for the cathode and electrolyte constituted a minor part of the overall material cost for the sodium ion battery, at 0.61%, as shown in Figure 16.

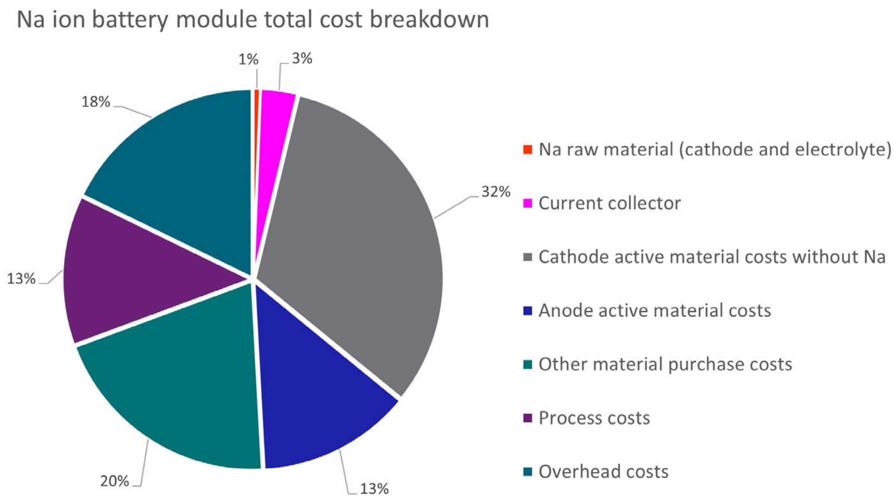


Figure 16 Sodium-ion battery module total cost breakdown

Furthermore, the product from the Stage 4 salt crystalliser would require further processing to be an appropriate feed into the sodium ion battery. Thus, this method does not effectively reuse the brine produced from Stage 2, the concentrated brine from Stage 3, or a potential salt product from Stage 4.

Therefore, further evaluation of SIB-BESS was not performed as only less than 1% of the inputs for the system could be provided by the brine from the NGP.

4.6 Acid mine drainage neutralisation

4.6.1 Description of process and assumptions

A techno-economic analysis was conducted to evaluate the economic performance of a salt crystallisation process for producing saline products for the neutralisation of acid mine drainage. It is also possible to use the brine in liquid form for AMD neutralisation; however, the transport cost for liquid brine will be much higher than that for crystallised salts, irrespective of the location of the AMD site.

The brine produced from the Stage 2 Reverse osmosis unit was assumed as 29 m^3/h and used as the input into the salt crystalliser process. A reference conventional concentrator-crystalliser ZLD system was used to estimate the CAPEX and OPEX of the salt crystalliser process for brine reuse (Poirier et al., 2022) .

The assumptions used to estimate the CAPEX and OPEX of the salt crystalliser process for brine reuse were:

- Reference plant of 345.5 tonnes of salt produced per year
  - CAPEX of US$235,396
  - OPEX of US$47,696/year

These values were escalated, scaled to the required plant capacity, and converted into A$, resulting in a CAPEX of A$3.6 million and OPEX of A$3.1 million/year. The salt crystalliser process is assumed to produce a single salt product for the neutralisation of acid mine drainage at a rate of 1,958 kg/h. A block flow diagram of the process is presented in Figure 17. The salt product for use in AMD neutralisation would have a predicted composition of 64% sodium carbonate monohydrate and 10.2% sodium chloride.

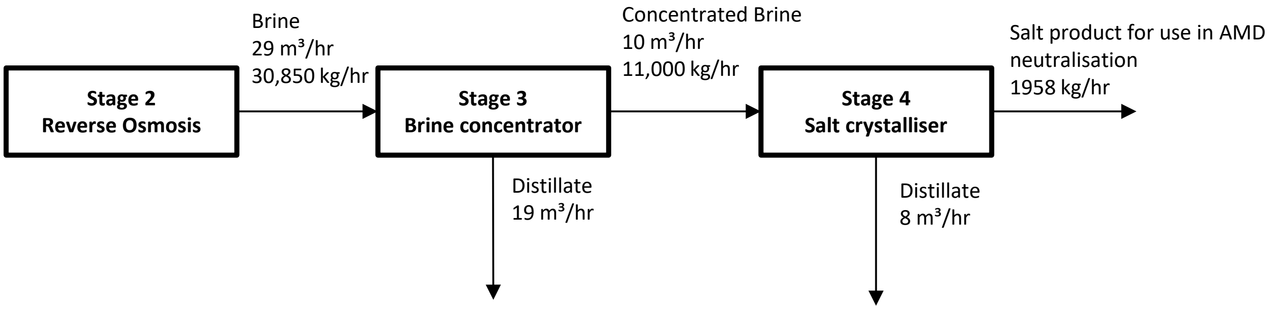


Figure 17 Block flow diagram of the salt crystalliser process

4.6.2 Summary of results

A summary of the results of the TEA to produce a saline product for the neutralisation of acid mine drainage using a salt crystalliser process is shown in Table 15.

Table 15 Summary of TEA results for the salt crystalliser process

Parameter	Value
Brine input (m^3/hr)	29
Mass brine input (kg/hr)	30,850
Annual production of salt (tonne/year)	16,450
CAPEX (A$)	A$3.6 million
OPEX (A$/year)	A$3.2 million
Bulk salt market price (A$/tonne)	A$301
Total revenue (A$/year)	A$5.0 million
NPV (A$)	A$8.1 million
LCOS (Levelised cost of salt A$/tonne)	A$245
Payback period (years)	5.8

The levelised cost of salt was determined as A$245/tonne of salt produced. Alternatively, an NPV of A$8.1 million and a payback period of 5.8 years were calculated, with an assumed market price of A$301/tonne for the single salt product, based only on the value of the sodium carbonate contained within the single salt (Trading Economics, 2024).

A breakdown of the CAPEX to produce a saline product for the neutralisation of acid mine drainage using a salt crystalliser process is shown in Figure 18.

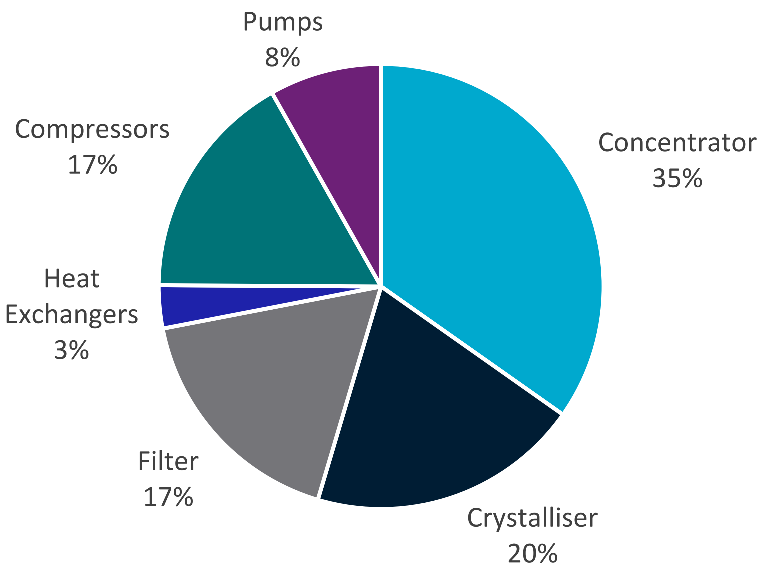


Figure 18 Breakdown of CAPEX of the salt crystalliser process

4.6.3 Sensitivity analysis

A sensitivity analysis was conducted to analyse the effects that varying the OPEX would have on the LCOS, NPV and payback period of the salt crystalliser process. The results are summarised in Table 16.

Table 16 Summary of sensitivity analysis by varying OPEX for the salt crystalliser process

	-50%	Baseline	+50%
OPEX (A$/year)	A$1.6 million	A$3.2 million	A$4.8 million
LCOS (A$/tonne)	A$133.9	A$244.6	A$355.4
NPV (A$)	A$24.0 million	A$8.1 million	-A$7.8 million
Payback period (years)	1.42	5.81	N/A

When the OPEX was reduced by 50%, the economic viability of the process improved, reducing the LCOS from A$245/tonne to A$134/tonne. The NPV also improved three-fold from A$8 million to A$24 million, while the process was able to attain a breakeven point within a PBP of less than 2 years. However, an increase in OPEX by 50% made the process non-viable with a negative NPV.

4.7 High-value algae cultivation

4.7.1 Description of process and assumptions

A techno-economic analysis was conducted to evaluate the economic performance of an algae growth-harvesting-extracting cultivation process for producing high-value algae products. Three main processing stages are required in the algae production system including algae production (cultivation), harvesting (culture dewatering), and cake and lipid extraction. The model considered the cultivation and conversion of microalgae into the three mentioned products (carotenoids, omega-3 and algae cake) using the brine at the NGP as an input, alongside other essential components required for the process. The production and cost parameters were drawn from literature and databases where appropriate. The microalgae biomass was modelled to be cultivated in open ponds. The NGP brine was supplemented with make-up nutrients and CO2. Another assumption was the reuse of effluent as a growth medium.

The harvesting comprised three stages. The first stage was gravity settling tanks that allowed up to 7% biomass concentration. This was followed by dissolved air flotation to get the biomass to 15-20% concentration. In the third stage, centrifugation provided a 30% concentrated biomass. At this concentration, the biomass is amenable to the fractionation process, while the solid algae cake obtained is further dried in a separate process.

The three stages considered in the production and conversion of microalgae are illustrated in Figure 17. The fractionation process was used to process the microalgal lipid products of interest, using molecular distillation. Fatty acids and carotenoids are the most prevalent components of the feed that go into the molecular distillation process. The main focus was to obtain high-purity carotenoids and omega-3 oil, which could also create additional value. The molecular distillation was performed using an agitated thin film evaporator with a revolving liquid film. The molecular distillation separates the two key products, namely carotenoids and fatty acids (significantly omega-3).

The concentrated brine produced from the Stage 3 brine concentrator unit was assumed as 10.4 m^3/h (250 m^3/day) and used as the input into the algae cultivation process.

The assumptions used to estimate the CAPEX and OPEX of the algae cultivation process for brine reuse were taken from a techno-economic analysis study on sustainable integrated microalgae biorefineries conducted by (Posada et al., 2016). The molecular distillation process used to produce high-value products was based on the industrial bio-fractionation process modelled by Mazzelli et al. (2019) and Mazzelli et al. (2022).

These values were escalated, scaled to the required plant capacity, and converted into A$, resulting in a CAPEX of A$65.9 million and OPEX of A$22.7 million/year. The algae cultivation process is assumed to produce three products:

- Algae oil-free cake for fish meal, as a by-product at a rate of 86.8 kg/h
- Microalgae oil for substitution of vegetable oil (omega-3) as a by-product, at a rate of 25.0 kg/h
- Carotenoids as the main product, at a rate of 8.3 kg/h.

A block flow diagram of the algae growth-harvesting-extracting cultivation process can be observed in Figure 19.

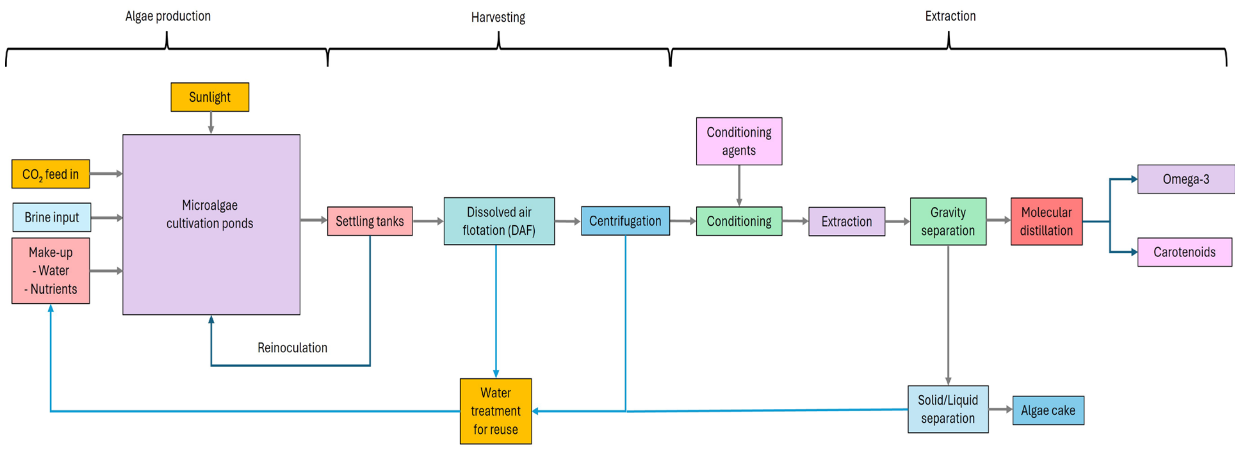


Figure 19 Block flow diagram of the algae growth-harvesting-extracting cultivation process

4.7.2 Summary of the results

The summary of the results of the TEA for the algae growth-harvesting-extracting cultivation process for producing a high-value algae product process is presented in Table 17.

Table 17 Summary of TEA results for the algae growth-harvesting-extracting cultivation process

PARAMETER	VALUE
Concentrated brine input (m^3/hr)	10.4
Pond area (ha)	24
Annual production of algae product (tonne/year) Algae cake Algae oil Omega-3 Carotenoids	 728.9 209.8 69.9
CAPEX (A$)	A$65.9 million
OPEX (A$/year)	A$22.7 million
Assumed selling prices for products (A$/kg) Algae cake Carotenoids Algae oil Omega-3	 A$0.76 A$455.89 A$0.55
LCOC (Levelised cost of Carotenoid A$/kg)	A$452
Total revenue (A$/year)	A$32.0 million
NPV (A$)	A$2.1 million
Payback period (years)	28.1

The levelised cost of carotenoid was determined as A$452/kg of carotenoid produced. Alternatively, an NPV of A$2.1 million and a payback period of 28.1 years were calculated, with the following assumed market price for each product:

- Algae cake, A$0.76/kg (Hassan El and Soha, 2016)
- Carotenoids, A$455.89/kg (Martínez-Cámara et al., 2021)
- Algae oil Omega-3, A$0.55/kg (Chauton et al., 2015)

A breakdown of the CAPEX for the algae growth-harvesting-extracting cultivation process for producing high-value algae products is presented in Figure 20.

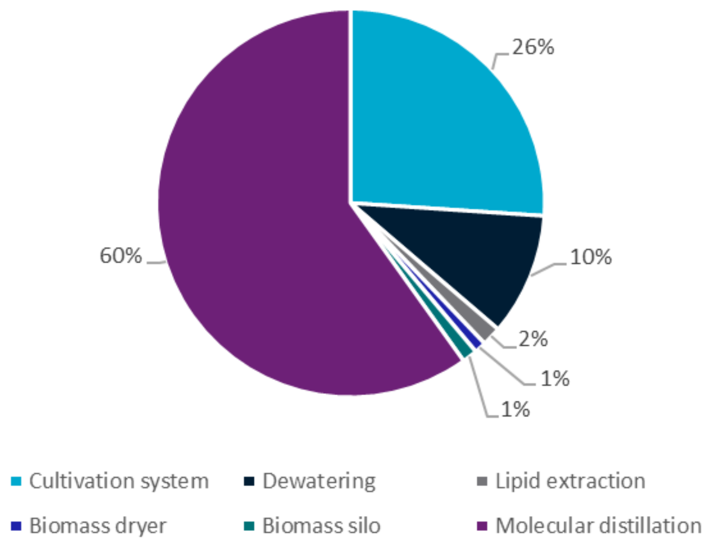


Figure 20 Breakdown of CAPEX of the algae growth-harvesting-extracting cultivation process

4.7.3 Sensitivity analysis

A sensitivity analysis was conducted to analyse the effects that varying the OPEX would have on the LCOC, NPV and PBP of the algae cultivation process. The results are summarised in Table 18.

Table 18 Summary of sensitivity analysis by varying OPEX for the algae growth-harvesting-extracting cultivation process

	-50%	BASELINE	+50%
OPEX (A$/year)	A$11.3 million	A$22.7 million	A$34.0 million
LCOC (A$/kg)	A$277.5	A$451.7	A$624.5
NPV (A$)	A$94.0 million	A$2.1 million	-A$104.9 million
Payback period (years)	6.4	28.1	N/A

When the OPEX was reduced by 50%, the economic viability of the process significantly improved, reducing the LCOC to A$278/kg from a base cost of A$452/kg. The NPV also improved significantly, from A$2 million to A$94 million, while the process was able to attain a breakeven point within a PBP of 6.4 years. However, an increase in OPEX by 50% made the process non-viable with a negative NPV.

4.8 Summary of TEA results for potential brine reuse options

High-level techno-economic analyses were conducted for the identified brine reuse options, with three options indicating potentially viable projects via positive NPVs (Table 19). These brine reuse options were:

- Selective salt recovery (Sal-Proc process) with an NPV of A$17.0 million and a payback period of 4.2 years
- AMD neutralisation (salt crystalliser process) with an NPV of A$8.1 million and a payback period of 5.8 years
- Algae cultivation process with an NPV of A$2.1 million and a payback period of 28.1 years.
  - Sensitivity analysis showed that the algae cultivation process could be a viable option with a lower OPEX, a A$94.0 million NPV and a payback period of 6.4 years both possible if the OPEX is reduced by 50%.

Table 19 Summary of TEA results for brine reuse options

PROCESS	CAPEX	OPEX (PER YEAR)	REVENUE (PER YEAR)	NPV	PAYBACK PERIOD (YEARS)	PRODUCTS/VALUE
Selective Salt Recovery (Solvay process)	A$58 million	A$8.1 million	A$5.92 million	-A$107.1 million	n/a	Two products were produced: Na_2CO_3 – 11,860 tonne/year $CaCl_2$ – 4,796 tonne/year LCONa_2CO_3 = A$1,576/tonne
Selective Salt Recovery (Sal-Proc process)	A$9.1 million	A$2.1 million	A$5.26 million	A$17.0 million	4.2	Two products were produced: Na_2CO_3 – 9,881 tonne/year NaCl - 1,575 tonne/year LCO Na_2CO_3 = A$0.201/kg
Osmotic energy	A$8.35 million	A$0.56 million	A$3.3 million	-A$17 million	n/a	Electricity produced - 1.8M kWh/a LCOE = A$1.75/kWh
AMD neutralisation (salt crystalliser process)	A$3.6 million	A$3.1 million	A$5.0 million	A$8.1 million	5.8	Single salt produced -16,450 tonne/year 64% Sodium carbonate monohydrate 12% sodium chloride LCOS = A$245/tonne
High-value microalgae cultivation	A$65.9 million	A$22.7 million	A$32.0 million	A$2.1 million	28.1	Three products: Algae cake, 728.9 tonne/year, Algae oil, 209.8 tonne/year, Carotenoids, 69.9 tonne/year LCOC = A$456/kg

n/a: not applicable

5 Social assessment

A social assessment was carried out for different beneficial reuse options for brine, with a focus on social acceptability considerations. Section 5.1 outlines the methods used and the main factors considered in the assessment. Section 5.2 lists the key points of social relevance identified from subject matter expert interviews regarding the different options. Section 5.3 summaries key themes raised in a workshop where community stakeholders provided feedback on the research findings. The final section summarises the assessment findings and conclusions.

5.1 Methods

The research design involved three steps:

- Develop social topics and interview questions to identify social acceptability considerations for each brine reuse option
- Conduct interviews with subject matter experts to understand potential social, economic, and environmental impacts and benefits associated with each option
- Socialise the preliminary findings with local community stakeholders.

Figure 21 provides an overview of the research design for assessing social acceptability factors for each brine reuse option.

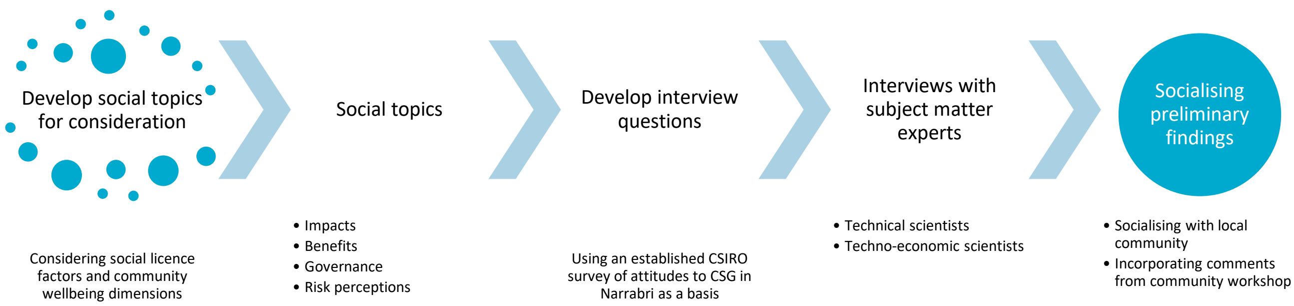


Figure 21 Overview of methods leading to the community workshop

As a basis for the social assessment, we considered factors in a social licence framework developed from previous survey work undertaken in coal seam gas communities (McCrea and Walton, 2023; Walton and McCrea, 2020). Figure 22 shows a range of factors affecting people's level of social acceptance towards new infrastructure development related to coal seam gas. The factors can be thought of as underlying drivers of social acceptance.

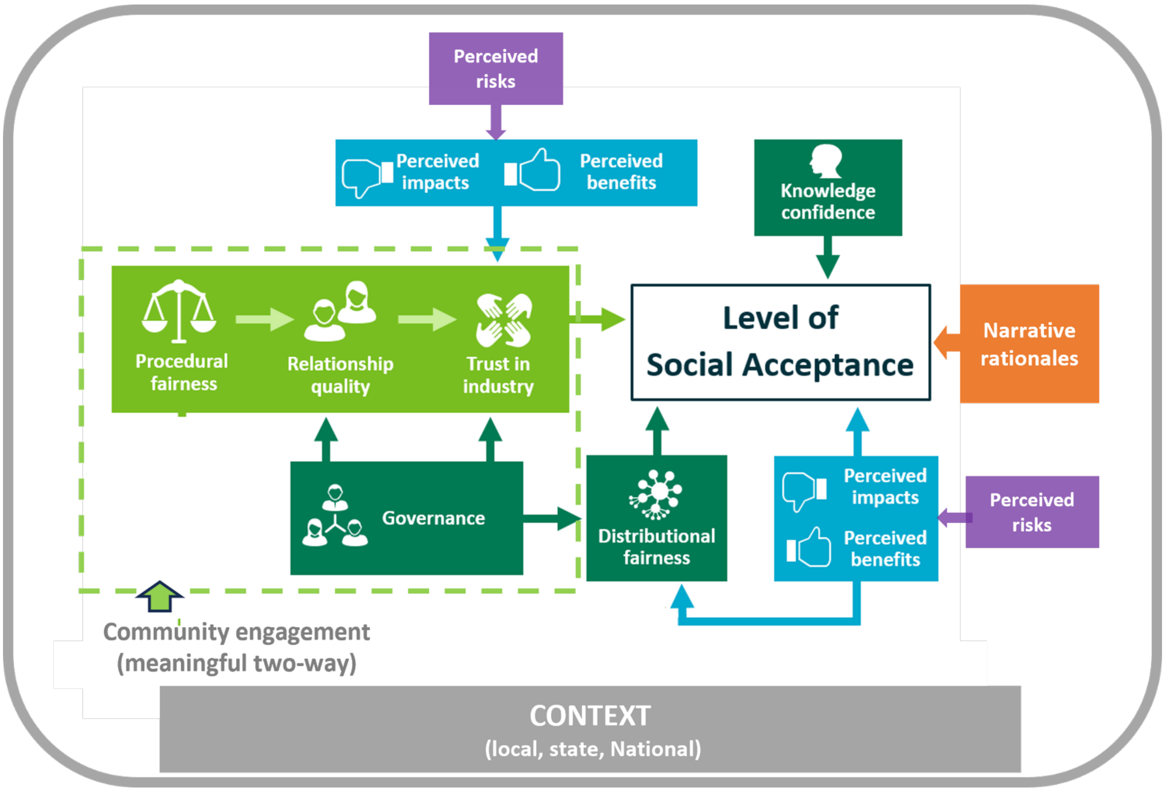


Figure 22 Social licence factors affecting social acceptance of new infrastructure developments (Adapted from (Walton and McCrea, 2020))

Of these factors, four were identified as relevant for a social assessment of emerging beneficial brine reuse options in the Narrabri context:

1. Perceived impacts - concerns people might have about immediate and future negative impacts on the social, economic, and environmental wellbeing of their local community.
2. Perceived risks - beliefs and feelings people might have about possible hazards.
3. Perceived benefits - perceptions of benefits to social, economic, and environmental wellbeing both local and wider benefits.
4. Governance and trust - expectations and perceptions of compliance activities and regulations, as well as trust and confidence in governing bodies to hold industry to account.

The CSIRO survey of community wellbeing and attitudes towards CSG in Narrabri (McCrea and Walton, 2023) was also reviewed with a view to targeting relevant items for assessing beneficial brine reuse options from a social perspective. These items then formed the basis for tailored interview questions put to technical and techno-economics experts about each brine reuse option. Figure 23 shows the four broad categories and sub-categories of questions used in the expert interviews. Appendix A presents all the interview questions.

Potential negative impacts	Potential benefits	Risk perceptions	Governance and trust
• Social • Environmental • Economic	• Social • Environmental • Economic	• Technology maturity • Manageability of risks • Severity of consequences	• Compliance and regulation • Monitoring • Approvals

Figure 23 Broad categories and sub-categories of questions used in expert interviews

Based on interviews with brine technology experts, key themes were identified for socialising at a local community workshop conducted in Narrabri on 24 November 2023. The selected stakeholders were familiar with CSG operations and had backgrounds in agriculture, community, government, and agricultural technologies.

5.2 Key points from expert interviews

Table 20 summarises the key points emerging from the interviews with technical and techno-economic experts relevant to social acceptability. These were used as discussion points when socialising the technologies in the community workshop and incorporating their feedback in the social assessment. Only the first five options were discussed at the community workshop, with a sodium-ion battery added for assessment after the workshop.

Table 20 Key points emerging from interviews with technical and techno-economic experts

BRINE REUSE OPTION	KEY POINTS RAISED FROM THE SOCIAL ACCEPTABILITY ASSESSMENT INTERVIEWS WITH SUBJECT MATTER EXPERTS
Selective recovery of high-purity salts for industrial use	Small to medium manufacturing plant - small spatial footprint; some heavy transport and delivery vehicles; minimal pressure on local services, facilities and housing A steady operation after construction – though long-term economic viability is uncertain and needs ongoing feedstock Employs 5-10 people ongoing - engineers, technicians, and semi-skilled 'Off the shelf' established technology No additional water used; minimal air, dust, and noise pollution Potential domestic market for soda ash – benefit to Australia
Recovery of critical minerals and other important elements	Unproven technology - no effective method identified Economic viability uncertain If established, small to medium plant Likely employs 5-6 people ongoing - engineers, technicians, and semi-skilled
Harvesting energy – osmotic processes	Energy generated used within the facility and likely only for onsite use Very small plant and largely automated - small spatial footprint 'Off the shelf' established technology Minimal jobs Uses additional water Creates a local circular system within the site - benefit Economic viability uncertain – potentially cheaper to buy electricity.
Sodium-ion battery	Small to medium manufacturing plant – small spatial footprint; some heavy transport and delivery vehicles; minimal pressure on local services, facilities and housing Not economically viable - sodium extracted from brine only 1% of battery input costs Employs approx. 10-20 people, if viable - engineers, technicians, and semi-skilled 'Off the shelf' established technology No additional water used; minimal air, dust, and noise pollution

BRINE REUSE OPTION	KEY POINTS RAISED FROM THE SOCIAL ACCEPTABILITY ASSESSMENT INTERVIEWS WITH SUBJECT MATTER EXPERTS
Acid mine drainage neutralisation	Small to medium manufacturing plant – small spatial footprint; some heavy transport and delivery vehicles; minimal pressure on local services, facilities and housing A steady operation after construction - long-term economic viability (dependent on brine supply) Employs 5-10 people ongoing - engineers, technicians, and semi-skilled 'Off the shelf' established technology Some additional water used when applying on mine sites; minimal air, dust, and noise pollution Domestic market for acid mine drainage neutralisation – benefit to Australia; established end use an alternative to lime
High-value algae cultivation	Ponds needed for growing algae - 24 hectares per 10 ponds Facility needed for processing algae - harvesting and drying algae within the one plant/facility; some heavy transport and delivery vehicles; minimal pressure on local services, facilities and housing A steady operation after construction Employs about 14 people ongoing - supervisor and semi-skilled workers Climate change benefit - removes CO_2 from the atmosphere Using the brine, rather than treating the brine with technologies - value-adding Algae farming well-understood and established Some additional water used; minimal air, dust, and noise pollution Domestic market for algae – benefit to Australia; used for high value proteins and biofuels

5.3 Feedback from community workshop

At a community workshop conducted in Narrabri in November 2023, the key points from Table 20 for each reuse option were presented to 10 invited stakeholders familiar with CSG operations in the region. The workshop involved presentations and discussions about each of the brine reuse options. The salient points from the workshop discussion are set out below. These have been grouped into three themes: the importance of providing context for comparison and transparency for trust in the information; perceptions of the social benefits and concerns around brine re-use options; and the similarities and differences between different options.

Providing context and transparency of information helps with sense-making and trust in the findings

- **Comparative analysis**: Understanding brine volumes by comparing them to volumes of other water sources or outputs (such as desalination plants or agricultural irrigation) helps contextualise the scale of brine production and its potential impact.
- **Public information**: Previous communications had suggested there was insufficient brine volume for commercial reuse options, highlighting a need for clear, transparent information about brine production and management options.
- **Publicly-funded research**: Emphasises the importance of research independent from industry interests, ensuring objectivity and credibility in findings on beneficial reuse options.

Social benefits and concerns

- **Community co-benefits**: Proposals for brine reuse should consider potential benefits for the local community, including contributions to community funds, partnerships with local services, and economic diversification.
- **Economic viability**: Assessing the ongoing economic feasibility of brine reuse technologies, including the brine volume requirements for their viability. The ongoing viability of brine reuse

developments is important for local regional communities because of associated local business, employment and training opportunities.

- **Circular economy considerations**: Highlights the value of integrating brine recovery into a circular economy, focusing on waste reduction and value addition through technologies such as energy harvesting and algae farming using brine. Circular economy considerations are additional to any savings from brine reuse incorporated into economic evaluations, such as brine transport and disposal costs with other brine options.
- **Environmental and public health**: Importance of keeping public perceptions in perspective to avoid undue concern, especially in the context of existing environmental and health standards. (e.g. presence of naturally occurring radioactive materials (NORM) levels in brine and how they compare to background levels in water).
- **Water use**: Recognises water as a scarce and contentious resource, emphasising the need for careful management of water and related issues like brine.

Similarities and differences

- **Manufacturing and employment**: Most reuse options involve small to medium manufacturing plants, with similar levels of employment and risks of environmental impacts, such as pond lining leaks.
- **Energy harvesting**: While energy harvesting from brine is a useful reuse option, energy harvesting does not directly address the issue of brine waste by reducing volumes for disposal. As such, it can be seen as an add-on technology.

5.4 Social assessment summary and conclusions

Each of the reuse options involves small- to medium-sized brine processing plants that would result in proportionally small- to moderate-level social and community opportunities and issues. Table 21 presents a summary of social assessment considerations for the seven beneficial reuse options for brine examined for Narrabri.

Table 21 Summary of social assessment of brine beneficial reuse options

SOCIAL ASSESSMENT CRITERIA	SELECTIVE SALT RECOVERY	RECOVERY OF CRITICAL MINERALS AND OTHER IMPORTANT ELEMENTS	HARVESTING ENERGY	ACID MINE DRAINAGE NEUTRALISATION	ALGAE FARMING	SODIUM-ION BATTERIES
Community co-benefits	+	+	0	+	+	+
Economic viability	+	-	-	+	+	-
Circular economy considerations	0	0	+	-	+	+
Environmental and public health	0	0	0	+	0	0
Water use	0	0	0	+	-	0

Notes: + and − refer to local community advantages and disadvantages for each criterion, while 0 refers to no significant local advantages or disadvantages.

Five of the six options (see Table 20) can provide positive community co-benefits, mainly in the form of local employment, business, and training opportunities associated with establishing a small- to medium-scale plant for processing brine, with the exception of harvesting energy which only provides energy within the plant. However, energy harvesting can be considered part of a circular economy by using brine to generate energy.

The techno-economic analysis showed that the Sal-Proc selective salt recovery process was economically viable over 30 years, even though the Solvay selective salt recovery was not economically viable for the Narrabri Gas Project. Another economically viable reuse option was acid mine drainage neutralisation. The economic viability of critical minerals and energy harvesting was uncertain, whereas the production of sodium batteries was economically unviable.

All the options can be considered as contributing to the circular economy in terms of reusing rather than disposing of brine waste. However, three of the options can be considered more a part of the circular economy in terms of extending the life of generating new products and energy from what would otherwise be brine waste: harvesting energy, growing algae, and making sodium-ion batteries. Two other options can also be considered part of the circular economy in terms of extending the life of existing materials within brine for reuse in other products: selected salt recovery and extracting critical minerals. However, the extended life of these materials may only extend to the next product. Acid mine drainage neutralisation may be considered the least transformative in applying brine salts to remediate mine sites. While this is a reuse of brine, it would be the last or final use of brine salts in the circular economy.

Acid mine drainage neutralisation can be beneficial for environmental health as the process of drying and applying brine salts to mine tailings can neutralise the acids contained within them. The other five technologies have limited implications for public and environmental health. However, it is important to convey to local communities in ways meaningful for them how any health and environmental impacts are being monitored and addressed (e.g. NORM levels in brine). Acid mine drainage neutralisation may also improve the quality of waterways surrounding mine sites by reducing the level of acidity from mine site run-off or seepage.

6 Conclusion

This study was conducted to explore the beneficial reuse options for brine projected to be generated from the reverse osmosis of produced water from the Narrabri Gas Project. The options were evaluated for their techno-economic performance and social acceptance.

The techno-economic assessment of various reuse options for brine showed a positive net present value for the following options:

- Selective salt recovery (Sal-Proc process) with an NPV of A$17.0 million and a payback period of 4.2 years
- AMD neutralisation (salt crystalliser process) with an NPV of A$8.1 million and a payback period of 5.8 years
- Microalgae cultivation with an NPV of A$2.1 million and a payback period of 28.1 years.
  - Sensitivity analysis showed that the algae cultivation process could be a viable option with a lower OPEX, with a A$94.0 million NPV and a payback period of 6.4 years both possible if the OPEX is reduced by 50%.

Some of the brine reuse options present opportunities for community engagement and co-benefits, particularly through job creation, business opportunities, and training programs. This highlights the potential for brine reuse projects to contribute to local economic development and community wellbeing.

Economic viability is a necessary requirement for beneficial reuse options to provide community co-benefits. Economic viability varied across the options, with selective salt recovery, acid mine drainage neutralisation, and microalgae cultivation showing the most promise for long-term economic viability, while other options faced financial challenges. Long-term economic viability is important from a community perspective for maintaining local livelihoods in the face of long-term declining employment in agricultural industries.

Some brine reuse options contributed more to the circular economy by repurposing brine waste, rather than creating energy or new products. This aligns with global sustainability goals and the push towards more regenerative economies. Acid mine drainage neutralisation was least associated with the circular economy, but it also had a greater number of other community, economic, and environmental advantages. The demand for the domestic market for the recovered products is dependent on the sites requiring the neutralisation of acid mine drainage in the proximity of the CSG mining locations.

There was little difference between the options in public and environmental health considerations, though acid mine drainage neutralisation can help improve water quality around mine sites. However, there would be a need for ongoing monitoring and transparent communication with local communities relating to public and environmental health concerns. Further investigations are warranted to demonstrate the effectiveness of brine in neutralising acid mine drainage.

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Appendices

Appendix 1. Questions used in expert interviews with prompts

Background context questions (prompting and priming interviewees, and for interviewer's understanding and context):

Infrastructure operations and footprint for each of 5 technology types (approximate – big, medium or small; concentrated footprint v. dispersed?)

a. What is the size of operations (i.e. employment, investment, infrastructure footprint, small/big facilities)?
b. How do operations change in different phases (duration of phases – construction, operations, longevity of operations, decommissioning)?

Perceived impacts / concerns

How do you see these technologies and operations potentially impacting these community concerns?

a. Environmental
    i. quality of underground water for the future
    ii. depletion of underground water
    iii. contaminate underground water
    iv. contaminate above groundwater
    v. air contamination (pollutants)
    vi. ghg emissions/ contribution to climate change
    vii. affect the natural environment of the Pilliga State Forest
    viii. affect biodiversity (e.g. the variety of plant and animal life)
    ix. dust, noise, and light pollution (including in different phases)
    x. risk of fire
    xi. risk of spills
    xii. contaminate local land or soil
    xiii. introduce or spread weeds and other pests
    xiv. potentially create any future long-term negative issues (e.g. salinity issues)
    xv. Other?
    xvi. Overall negative environmental impacts (water, air, soil, noise, light etc.)?
b. Social
    i. traffic on the roads (safety and road conditions; on major or minor roads or through towns and populated areas)
    ii. housing affordability and rental prices (especially during the construction phase)
    iii. visual amenity (industrialisation of rural landscape)
    iv. rural/town identity
    v. Aboriginal and other heritage sites
    vi. Perceived health impacts (including social stress and anxiety more generally)

vii. Any actual or potential exposure pathways from contaminants, which could then result in a health impact?
viii. influx of external DIDO or FIFO workers vs local jobs (perceptions of decreased personal safety, cohesion, identity)
ix. additional pressure on local services and facilities
x. community division over technology project development
xi. Other?
xii. Overall negative social impacts?

c. Economic
    i. Reduced viability of local farming land for the future
    ii. Reduced property values (including nearby farms and towns)
    iii. other on-farm impacts (e.g. additional pipes, co-existence with agriculture)
    iv. create local skills shortages for existing industries (e.g. farm workers; electricians etc.)
    v. impacts on non-farming livelihoods (e.g. local business costs)
    vi. housing affordability and rental prices
    vii. increase local cost of living
    viii. Other?
d. Overall negative economic impacts?

Perceived benefits

How do see these technologies and operations relating to these potential benefits?

a. Environmental (local and regional)
    i. disposal of salt and brine (now a benefit of reuse)
    ii. Other?
b. Economic (local and regional)
    iii. good local businesses opportunities (ongoing opportunities vs construction period)
    iv. long-term job and business opportunities (extensive jobs or just a few; local job opportunities vs non-local contractors)
    v. diversity of industries and businesses in the local economy
    vi. improved town and regional identity (progressive/innovative/circular economy)
    vii. flow-on opportunities for other businesses (existing and new businesses)
    viii. building capacity and value in the region for the future
    ix. Other?
c. Social and community benefits (local and regional skills, opportunities for indigenous, women, and young people, local identity)
    i. good job opportunities (skilled vs. unskilled jobs; opportunities for indigenous and female employment)
    ii. opportunities for young people to stay in the region
    iii. corporate support for local community activities (e.g. the company sponsoring local clubs)

    iv. additional local services, facilities, and infrastructure
    v. diversifying local skills and education in the region
    vi. leaving a future social legacy in region
    vii. long-lasting benefits for the region
    viii. Other?
d. Overall, how much do you see these technologies and operations bringing significant benefits to the local community?
e. Potential benefits to the wider state and Australia?
    i. Exports
    ii. Reduced imports
    iii. Other
f. Overall, how much do you see these technologies and operations bringing significant state and Australia wide benefits?

Governance AND Trust in industry and government

Governance

a. Compliance and regulation
    i. Do regulatory or industry standards exist for managing any impacts?
    ii. … (what are they)
    iii. How recognised and effective are they (e.g. best practice)?
    iv. Who is responsible (industry, local government, state or regulators, other)
b. Monitoring
    i. Are monitoring standards or protocols in place?
    ii. How recognised and effective are they (e.g. best practice)?
    iii. Who is responsible (industry, local government, state or regulators, other)
c. Other governance considerations?
d. Overall, how well would these technologies and operations be governed?

Trust

a. Big or small companies?
b. Established or new companies?
c. Past and present reputations?

Risk perceptions

a. Technology maturity/well understood by science?
b. Proof of concept v. established tech
    i. have been identified
    ii. are understood by science
    iii. are understood by the community
c. Potentially catastrophic risks vs. managed impacts
    i. are manageable
    ii. can be alleviated as problems arise

    iii. have potentially uncontrollable impacts
    iv. are potentially catastrophic
    v. can adversely affect future generations
d. Perceived effectiveness for addressing the brine issue
e. Duration of operations (short-term/long-term)
f. Technology narrative? (why here, why now, why is this a good option)
    a. Positive narratives?
    b. Negative narratives?

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