Centre for Natural Gas
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THE UNIVERSITY OF QUEENSLAND
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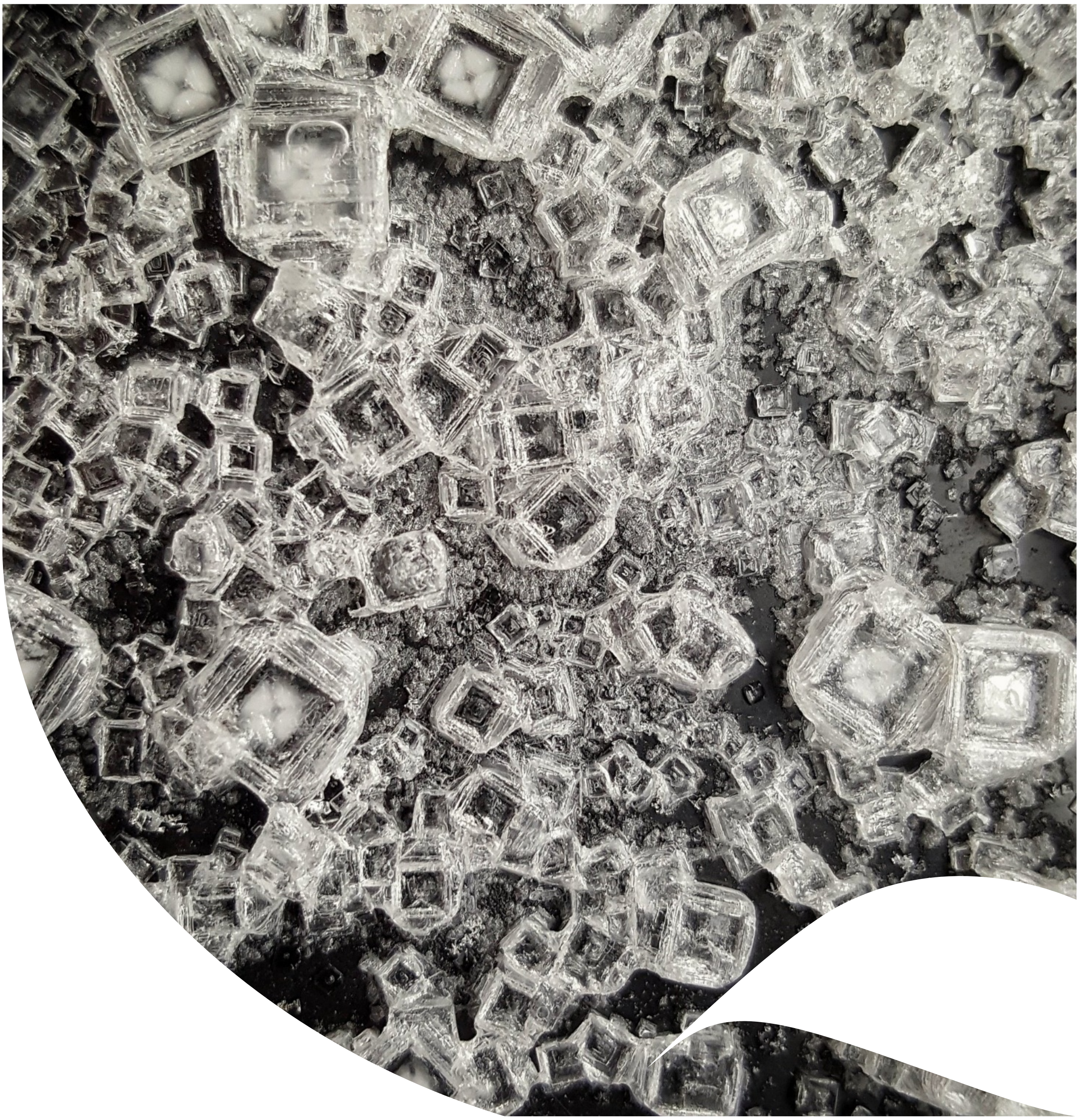
Independent Review: Brine and salt management (Section 6, Queensland Gas: end-to-end water use, supply and management)



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Disclosure

The UQ, Centre for Natural Gas (formerly Centre for Coal Seam Gas) is currently funded by the University of Queensland and the Industry members (Arrow Energy, APLNG and Santos). The Centre conducts research across Water, Geoscience, Petroleum Engineering and Social Performance themes. For more information about the Centre's activities and governance see https://natural-gas.centre.uq.edu.au/

This review was conducted independently from the Centre industry funding agreement and governance arrangements, under a separate contract with the Queensland Department of Environment and Science

1. Introduction

Australian Petroleum Production & Exploration Association Limited (APPEA) has submitted the *Queensland gas: end-to-end water use, supply and management* report to the Department of Environment and Science (DES) in response to a request from the former Minister for Environment and Heritage Protection and Minister for National Parks and the Great Barrier Reef. The APPEA report summarises the activities of the coal seam gas industry in relation to water use, supply and management.

DES has engaged The University of Queensland Centre for Natural Gas (UQ-CNG, formerly UQ Centre for Coal Seam Gas) to undertake an independent review of Section 6 of the report, *Brine and salt management*. Section 6 of the report outlines the work undertaken by industry to assess the feasibility of collaborative and alternative long-term solutions to salt management, and states that as a result of this work industry's preferred salt management solution is encapsulation in purpose-built facilities.

1.1 Scope of Work

The scope of work for UQ-CNG was (within tight time and budget bounds):

1. Undertake a peer review of the report prepared by APPEA "Queensland gas: end-to-end water use, supply and management" Section 6: Brine and salt management (approximately 17 pages) to:
    - Determine if all practicable salt management options have been considered (data gap analysis)
    - Comment on any feasibility (including economic, social, environmental and regulatory) assessment undertaken of the options
2. Participate in a workshop with representatives of the Queensland coal seam gas industry to obtain information on the brine and salt management investigations already undertaken and the documentation available.
3. Provide advice to the department on any other practicable options to address the long term management of CSG saline waste water. Evaluate the pre-feasibility of the options in terms of the potential for environmental harm, potential environmental benefit and economic cost /benefit.

2. Background

The extraction of coal seam gas (CSG) from Queensland's Surat and Bowen basins requires formation water to be produced from the coal seams to allow the gas to flow. A very large proportion of this coal seam water is treated via reverse osmosis (RO), producing treated water for beneficial use purposes and a waste stream of brine containing a range of dissolved salts. The Queensland coal seam gas industry commenced investigating salt and brine management options in the pre-development phase (~2008 – 2009), with detailed assessments provided in each company's environmental impact statements. The industry has continued to investigate options, both at the company level and through a range of collaborative studies, since commencing large-scale operations. APPEA estimates that the industry has spent more than $100M[1] on these investigations over a 10 year period. The APPEA report presents a very high level summary of the four leading waste management options considered:

1. Selective salt recovery (SSR)
2. Ocean outfall
3. Injection of brine into geological formations
4. Salt encapsulation.

[1] The estimate of investigation costs is based on the figures detailed in the APPEA report and workshop presentation. However, the APPEA report only provides specific information regarding costs for selective salt recovery and injection waste options. It is considered that the investigations for the ocean outfall and encapsulation options would have involved substantially more investment.

Following these detailed investigations, both at company and industry level, all companies have arrived at the same conclusion that the best management option, after considering long-term technological performance and all social, environmental, economic and regulatory factors, is to crystallise the salt and encapsulate it in a landfill.

Overall, long-term technological performance and reliability, and social licence issues have been the main factors that have determined the industry view that the remaining waste management options are technically unviable (injection), less technically reliable (selective salt recovery) or face the prospect of far more substantial social licence barriers (ocean outfall).

3. Review method

This review process has examined the APPEA summary of the salt and brine waste management options examined by the coal seam gas industry. Clearly, a 16 page document can only provide a very high level summary of a program of more than $100M of work conducted over an approximate 10 year period. UQ-CNG has, in conjunction with DES, sought additional, limited information from APPEA where this was considered useful to gain a more complete understanding of the summary provided in the report. This review has not had access to the many detailed technical reports that have formed the basis of the APPEA document. APPEA offered to make the independent market assessments for the SSR option available. After considering the other information made available to the review, UQ-CNG considered that detailed access to the market assessments was not necessary for the purposes of this review.

3.1 Process:

1. Receipt of document

DES provided UQ-CNG with a copy of the APPEA publication *Queensland gas: end-to-end water use, supply and management* on 4 July 2019. UQ-CNG was specifically engaged by DES to provide an independent review of Section 6 *Brine and Salt Management.* The review has also considered Section 7 *Conclusion*, as this was a logical extension of the review.

2. Initial review and written data request

UQ-CNG conducted an initial review of the document by categorising and summarising the Section 6 information against an overall assessment matrix (Electronic Resource 1). This categorisation and analysis process identified where additional information would assist the overall review of the document. A number of questions were developed, which were provided to DES and this data request was subsequently distributed to APPEA and the coal seam gas companies (see Appendix 1).

3. Workshop

A workshop was held at the Arrow Energy offices on 6 August 2019 and attended by representatives from DES, UQ-CNG, APPEA, Arrow Energy, Origin Energy, Shell and Santos. APPEA and company representatives delivered a presentation (see Appendix 2) that provided additional information regarding the four leading waste management options documented in the APPEA report. The workshop was highly interactive and the further information obtained is documented in the workshop minutes (see Appendix 3).

4. Reply to data requests from APPEA

APPEA provided a written response to the data request on 6 September 2019 and additional information was provided on 19 September 2019. The combined information is documented in Appendix 4.

5. Review of recent literature on saline waste disposal.

UQ-CNG prepared a technical update based on a review of recent publications related to the management of salt and brine waste (Section 5).

6. Finalisation of the review

This report provides the final review of the APPEA report based on the overall analysis of all information provided by APPEA, and gathered through the workshop presentation, workshop discussion and the technical update. All information gathered in this review is summarised in the Assessment Matrix (Electronic Resource 1).

3.2 Review outputs

The contract deliverables are:

- An assessment matrix providing categorisation of the APPEA paper information and identifying the relevant feasibility studies to the extent possible
- A summary of any information regarding feasibility assessment processes used and associated findings in the APPEA paper (incorporated into the assessment matrix)
- An assessment of additional information required to determine if existing assessments are reasonable
- A summary outline of:
    - existing brine and salt management technologies and strategies currently in use internationally
    - emerging brine and salt management technologies and strategies
- Documentation of the industry workshop discussion; identification of the range of reports available; and a prioritised list of reports/documents for DES review (if necessary).
- A pre-feasibility assessment of any additional practicable options that have been identified through this review process.

4. Review

The *Queensland Gas: end-to-end water use, supply and management* report summarises the investigations undertaken by the four large CSG companies, Australia Pacific LNG, Arrow Energy, QGC and Santos. These investigations were undertaken over a minimum ten year period. There is no information regarding any investigations undertaken by smaller companies, such as Senex Energy, Westside or Comet Ridge.

4.1 Data Collection

Section 6 of the APPEA report was reviewed and the information categorised against the assessment matrix, which had been developed to facilitate analysis of the information provided. UQ-CNG identified a range of overarching questions relating to both the age of the investigations and the assumptions that underpin the technical advice i.e.:

1. What were the assumptions regarding the volumes of water, salt and brine production that informed each of the investigations?

2. Had companies reviewed the studies based on contemporary knowledge of reduced water, salt and brine production volumes? Would these change in volumes materially change the design and cost of any/all of the management options?

3. While brine/salt production estimates are significantly lower than anticipated, is the current storage capacity and waste management design sufficient to allow a further period of investigation/review, or are the waste volumes accumulating at a pace that requires a decision to be made quickly given consideration of regulatory, construction and commissioning timeframes?

Other questions related to the specific information provided in respect of the individual waste management options or studies. These were mainly focused on detailed elements of the investigations. Two broader areas where more information was requested are:

1. Brine Injection studies – this had been dealt with briefly and generally in the report.
2. Specific studies – clarification of the nature of some of the company investigations was necessary to determine which waste management option assessment they related to.

A range of questions were developed and provided to DES. This formed the basis of a data request provided to APPEA. APPEA and the companies responded to the request via a workshop presentation, workshop discussion and written response. This information has been incorporated into the Assessment Matrix (Electronic Resource 1) and the discussion in Sections 4.2 and 4.3.

4.2 Assessment Matrix – content and process

The assessment matrix has been used to identify the type of assessments undertaken for each waste management option and to determine which industry or company reports are relevant to that particular topic.[2] Compiling the detailed assessment matrix also identified areas where additional information would be useful, and where the relevance of specific reports was unclear – this formed the basis of the subsequent data request to APPEA discussed in Section 4.1. A summary of the assessment matrix is provided in Table 1 and full details are provided in Electronic Resource 1.

Table 1 identifies which types of specific information were contained in Section 6 of the *Queensland Gas: end-to-end water use, supply and management* report, or were provided at the workshop or in response to the data request subsequently provided to APPEA. The detailed matrix (Electronic Resource 1) provides a summary of the overall material i.e. findings, provided against the same headings. Information has been provided regarding multiple variations of the ocean outfall and encapsulation management options. In these instances the subsequent assessments in the matrix relate only to the additional data provided regarding the extra option/s and must be considered in conjunction with the outcomes of the primary option assessment. The assessment for the Brine Injection option is based on details provided for one site (Pine Ridge), which industry had considered had the greatest potential. UQ-CNG are not aware of whether there was a more comprehensive, basin-wide review of injection options but note that injection options would (*all else being equal*) be limited to areas within existing tenements

Examination of the APPEA report showed that all four companies have undertaken independent studies relevant to the Selective Salt Recovery (SSR) and salt encapsulation management options. No reports from QGC or Arrow Energy were listed for the Brine Injection option, however at the workshop Arrow Energy advised that they had drilled a potential injection well, but not proceeded after the core analysis indicated the site was unsuitable. No information about QGC specific brine injection studies was obtained. The APPEA report did not list any QGC studies in respect of the ocean outfall option, and other information collected in the course of the review did not identify any such study. Discussion at the workshop held on 6 August 2019 indicated that the companies had some level of knowledge of the company specific investigations that had been conducted. The industry has undertaken collaborative studies of the SSR, ocean outfall, and salt encapsulation management options, although not all companies participated in all collaborative investigations.

This UQ-CNG review has not assessed the extent of information that is contained in the full technical documents upon which the summary report is based.

[2] Some of the detailed technical investigations may be related to multiple waste management options. UQ-CNG has allocated the reports to the option based on a judgement of which option is most likely to be the primary target of the information.

Table 1 Assessment Matrix Summary: Salt and brine waste management options considered by the Queensland coal seam gas industry. (Based on details recorded in the Assessment Summary – Electronic Resource 1).

Management option	Collaborative studies	Company studies	Estimated cost of studies	HSE impacts	Social impact	Economic impact	Regulatory impact	Other risk	Technical assessment	Delivery timeframe	Other
Selective salt recover	2 3 companies	7	$60M	✓	✓	✓	✓	✓	✓	✓	
Brine Injection		6	$50M	✓					✓		Multiple sites reportedly investigated
Ocean outfall (general & Tugan)	1 2 companies	2		✓	✓	✓	✓		✓	✓	Other potential outfall sites also reported to have been identified
Ocean Outfall (Agnes Water)		1		✓	✓		✓		✓		
Encapsulation (company sites)	3 3 companies	9		✓	✓	✓	✓		✓	✓	
Encapsulation (2 sites)				✓	✓	✓			✓		
Encapsulation (1 site)				✓	✓	✓			✓		

4.3 SSR, ocean outfall and salt encapsulation studies

The APPEA report provided a high level summary of the technical assessments of these three options. The report summarised technical processes, brine / salt transport requirements between gas-fields, water treatment facilities and the relevant end of waste disposal option. As shown in Table 1, the report summarised findings from assessments of health, safety and environment impacts, and social, economic and regulatory impacts. In the case of salt encapsulation and ocean outfall, secondary studies (encapsulation at either one or two sites; or outfall at a different location), the impact categories listed above were only discussed (in the Assessment Matrix or Table 1) where there was significant additional/different information provided in terms of the primary assessment. For example, the assessment of regulatory requirements is consistent across the three different models of salt encapsulation considered, however the potential location of an Agnes Waters ocean outfall required different/additional regulatory assessment to the Tugun option due to the proximity of Agnes Waters to the Great Barrier Reef Marine Park.

4.3.1 Selective Salt Recovery (SSR)

The opportunities for beneficial use of salt products recovered from CSG brine are constrained by the chemical composition of the brine stream. The APPEA report did not provide any information regarding the composition of the brine stream, however this information has been documented previously. A summary of typical coal seam water quality prepared by Sinclair Knight Mertz in 2011 is provided in Appendix 5 and indicates that Australian coal seam water does not contain economic quantities of more valuable minerals e.g. lithium, boron and zinc. Potential SSR production is therefore constrained to large volume production of lower value products (sodium chloride and sodium carbonate), which are commonly available from other sources.

The technical investigations of the SSR process were extensive, and included conceptual and basic engineering design studies of the treatment facility and pilot trials to test small-scale application. The collaborative study was undertaken by QGC, APLNG and Arrow. APLNG, Arrow and Santos have also conducted independent studies associated with this option. The level of detail provided regarding the impact assessments indicates that industry had undertaken sound, preliminary assessments across all categories. The main barriers to adoption of this option were determined to be:

- No proven examples of working commercial-scale plants, particularly those processing brine that varied in chemical composition over time
- The external consortium being unable to guarantee that the facility would consistently produce salts of sufficient quality to satisfy sales contract requirements
- Requirements for a separate waste disposal process to manage the waste generated from the SSR facility. It is noted that the waste production volumes from the trial plant (15 - 20% of solids, reported at the workshop), were higher than the optimal waste volumes that industry advised were reported in the technical documents prepared by the external consortia.

While UQ-CNG has not reviewed the detailed market assessments conducted in 2003 or 2012[3], the current APPEA estimate of total salt production over the life of the Queensland CSG of 6.1m tonnes roughly equates to the 2018 (annual) production by Dampier Salt (WA) of 6.153Mt[4]. This indicates that annual production from a CSG SSR process would represent only a small volume in the greater market and this, along with the quality reliability issue suggests that commercial contracts would be difficult to obtain.

It is expected, given the other options discussed in the APPEA report that the waste from a notional SSR facility would still need to be disposed of in a salt encapsulation facility (SEF). This conclusion is considered sound. Given consideration of the stated optimal waste levels and pilot trial waste levels, the SEF/s would

[3] Market assessment dates as per the APPEA response to the data request
[4] https://roskill.com/news/salt-rio-tinto-announces-dampier-salt-production-up-aided-by-autonomous-trucks/ (reported 4 February 2019)

need to have a capacity of perhaps as high as 25% of the full-scale SEF solution. Even if market and quality issues could be solved, SSR might effectively only provide a beneficial use for up to around 75% of the salt.

4.3.2 Ocean Outfall

Based on the APPEA report, APLNG, Arrow and Santos have all considered ocean outfall options individually, and APLNG and Arrow have also undertaken a collaborative study. Overall, APPEA and the companies have provided information regarding detailed desktop assessments of four sites and indicated that other options were also given preliminary consideration. Preliminary impact assessments have been undertaken, and the issues identified in the APPEA report and in other information provided to this review, have been very influential to the investigations into the design, construction and management of such a waste management option. From the information provided it appears that the preliminary studies have aimed to design the ocean outfall options to optimise use of existing outfall facilities, pipeline corridors and power supply facilities. This approach is consistent with minimising environmental, social and regulatory impacts. The main barriers to adoption of this option are:

- The perceived social acceptability of disposing of CSG generated waste products in ocean environments
- Proximity to i) environmentally sensitive areas (locations at the southern end of the Great Barrier Reef Marine Park), ii) high value tourism locations (Tugun option), iii) centres with a history or perceived risk of relatively high profile ‘activism’ (northern rivers of New South Wales – Tugun option)
- The possible need for a large number of property resumptions for the pipeline, particularly along the preferred Tugun route which includes large distances through Brisbane and Gold Coast urban areas.

The industry and companies have concluded that political support would be required to deal with the social barriers associated with this option, and consequently that there might be low likelihood of achieving “social licence” for this management option. While not a comment on the relative technical, financial or environmental merits of future ocean outfall options, UQ-CNG considers the industry conclusion to be sound.

4.3.3 Salt Encapsulation Facility (SEF)

APLNG, QGC and Santos have conducted the main collaborative study regarding this option, and all have completed independent investigations. Arrow Energy has undertaken more recent independent investigations. All companies funded collaborative research at the UQ Centre for Coal Seam Gas (now UQ-CNG). This developed an initial process for compacting and recrystallising the salt.

The SEF option is the industry’s currently preferred waste management option, with APLNG (Origin) and Shell currently undertaking more detailed planning in respect of facilities for each company. The industry as a whole, and the individual companies have reached this conclusion as the investigations into other options had identified greater technological, financial and/or social barriers preventing their implementation.

The various SEF studies have considered encapsulation at multiple sites (each company constructing their own facility/ies), two joint sites, or a sole joint site. Again, the studies have included preliminary assessments across the broad range of impact categories. Additional assessment information has been provided in relation to the environmental, social and financial implications of the two and single site options, as these have slightly different risk profiles due to the different pipeline configurations and transport distances. The main reasons that industry analyses result in this option are:

- The design, construction and operation requirements for waste disposal facilities are well understood and have proven to be effective at many sites
- The companies can better control risk factors by constructing and operating their own facilities

- The risks are well understood and can be dealt with using known approaches
- Construction of the facilities can be staged and more accurately matched to actual production. Other options may result in construction of under or over-sized facilities as they must be based on estimates of total production.

These are all sound operational and risk-management arguments.

One important barrier to this option is perceived to be that of social acceptance, with community concern regarding the safety of encapsulated landfill in terms of flood events, leakage to groundwater and management of long-term integrity far beyond the life of the industry. The APPEA report notes that “A moderate level of community concern is anticipated”, however this remains to be tested effectively. If SEF is to be implemented, the community will need to be well informed regarding the construction standards and management controls that will apply on site, and it is recommended that monitoring data be made publicly available to demonstrate effective management and compliance with regulatory requirements.

Limited information regarding the anticipated social impacts of the SEF option was provided in the APPEA report. However, this is likely to be a product of the investigations timeline, i.e., companies will invest in detailed assessment of social impacts when government indicates that the SEF option is likely suitable, and advises on the environmental assessment process and assessment requirements.

Ensuring that current regulatory controls are sufficient to manage flood and leakage issues is extremely important. Management of the long-term integrity issues must be addressed through some form of ‘Residual Risk Framework’, such as the framework currently being developed in DES (though this is not a judgement on the suitability of the precise form of that ultimate framework).

The regulator needs to ensure that the residual risk issues are well conceptualised and long-term management actions are appropriately funded and responsibilities and accountabilities regarding long-term monitoring activities are clear and actionable. Clarity on site closure and eventual relinquishment or surrender requirements need to be established. UQ-CNG consider this to be a non-trivial task, requiring technical and risk assessment (likelihood and consequence) expertise. Such expertise is likely to be found across government, industry and academia.

Discussion at the *Brine and salt management in the Queensland gas industry* workshop on 6th August 2019 also produced information regarding the current company planning timelines related to the construction and commissioning of the salt encapsulation facilities. This is summarised in Figure 1. Both QGC and APLNG have identified when detailed planning will need to commence for the SEFs, based on current estimates of brine production. The QGC SEF is expected to be the first commissioned facility (mid-2020s) and progress towards regulatory approval will need to commence in the near future. It is currently anticipated that the APLNG SEF will not be commissioned until the early-mid 2030s. For Santos and Arrow SEFs are likely to be required later than for APLNG.

Figure 1 Current indicative timelines for planning, constructing and commissions salt encapsulation facilities

Importantly, the modular nature of the SEF option provides the greatest flexibility for adoption of new technologies. SEFs can be progressively increased in size as disposal requirements increase. Alternatively, expansion of the SEF can be discontinued if a new disposal option with lower environmental risks or social impacts should become available. However construction costs associated with the SSR and ocean outfall options would be based on current total brine production estimates and therefore would require any new technologies to demonstrate substantial costs savings or performance improvements to justify transferring to any new management or waste disposal option. SEF is also the option that can be most readily rescaled to meet either increases or decreases from current estimates of brine production.

4.4 Brine Injection studies

All injection studies have been completed individually by the companies, aiming to identify suitable geological formations close to production facilities (presumed to be within their own PLs). Table 1 shows that information regarding the brine injection waste disposal option was focused on the technical and health, safety and environmental assessments. This is expected to be due to company determinations that brine injection was not technically feasible at the sites that they had high-graded for investigation, and assessment of the option did not progress to the stage where evaluation of social, economic and regulatory impacts was required. The APPEA report provided a brief summary of the injection investigations, noting that no suitable geological targets had been identified by individual companies. The area screened for potential options is not clear to UQ-CNG, but it is reasonable to assume that it included the tenement areas where brine injection *might* be permissible under the relevant legislation (and not elsewhere). A conclusion might be that areas technically suitable for deep brine injection *might* exist elsewhere (further afield) in the basin that would be ruled out by current regulations governing the permissible locations for the reinjection of produced fluids.

At the workshop there was discussion regarding the company finding that injection into "depleted reservoirs" was not viable. APPEA subsequently provided further information regarding the Pine Ridge injection target in response to the formal data request. This included technical details regarding zero mud loss when drilling, which while not conclusive is consistent with the conclusion provided in the APPEA report.

Given the technical barriers, and assuming that all sites theoretically permissible under relevant legalisation were screened, there is little value in determining if any social, economic and regulatory assessments have been conducted.

4.5 Suitability of current operational practice as a long-term management option

This review also briefly considered the long-term application of current operational practices, i.e., RO treatment and brine pond storage. At the simplest level, the options for managing co-produced water (which generates the salt waste disposal requirements) are to a) stop extracting the water, b) reinject the water or c) treat the water and dispose of the brine. Options a) and b) either halt the industry / suppress gas production, with extensive financial implications for both companies and government or are not permitted due to groundwater protection and water quality issues.

4.5.1 RO Treatment

RO treatment is still the leading technology for treating coal seam water to maximise beneficial use opportunities. Decreasing the water quality standards that apply to different beneficial uses, e.g., for irrigation purposes, would reduce the throughput of the water treatment facilities and the volume of brine created. However, this would also increase diffuse application of salt throughout the landscape and is not considered an appropriate option.

4.5.2 Brine pond storage

Companies are currently using brine storage ponds pending approval of final waste management options. While the current ponds provide substantial storage capacity, they are not long-term disposal option. Ponds require ongoing maintenance e.g., replacement of pond liners every 20 – 30 years, and salt in ponds remains in a mobile liquid form. Engineered ponds are appropriate for short to medium term storage, but do not represent a long term disposal option.

4.6 Clarification regarding selected investigations

The initial review by UQ-CNG aimed to identify which reports had been used in the assessment of the individual options. However, it was unclear how a number of trials and investigations listed in Table 3, Section 6 of the APPEA report that appeared to be pertinent to management of saline waste, may have relevance to the main disposal options discussed in the report. The data request made to APPEA requested clarification of these selected titles and this is summarised in Table 2. The details provided indicate that the Arrow investigations listed are relevant to the salt encapsulation assessment. This *is* now included in the Assessment Matrix.

Table 2 APPEA clarification regarding selected industry trials and investigations

Trial/investigation title	Company	Year	Description provided by APPEA	Notional disposal option
Acid regeneration trial	APLNG	2012	TBA	
Brine concept assessment	Arrow	2013	Arrow's Brine Concept Assessment brought together all of the relevant separate brine studies to determine the proposed brine management solution for Arrow's Surat Gas Project (SGP) development and documented the outcomes of Arrow's multi-criteria analysis (MCA).	Salt encapsulation facility
Salt plant concept study	Arrow	2015	Arrow's Salt Plant Concept Study documents a conceptual design for a waste salt plant (i.e. brine crystalliser to produce solid salt for encapsulation) for the SGP development.	Salt encapsulation facility
Integrated water balance	Collaboration	2015	TBA	
Brine and salt feasibility study	Arrow	2016	Arrow's Brine and salt feasibility study was an assessment of brine and salt management options for Arrow's existing operations. The preferred option was a waste salt plant and encapsulation.	Salt encapsulation facility
Longstraws trial	APLNG	2017	This was the opportunity to trial a 'super salt sucking sorgham' species. This species had shown good uptake of salt in laboratory trials without impacting yield. The species is overseas and only a small quantity of seed was available. This trial was not progressed due to the Australian quarantine requirements which deem that the seed be sent to another 'quarantine safe country' and grown before being sent to Australia.	N/A
Industry salt working group	collaboration	2017	Precursor to the End-to-end water management report provided to DES	

4.7 Consideration of updating assessments

As noted above, the detailed investigations have been conducted over approximately 10 years. The early investigations were based on estimates of water and salt production that have proven to have been significantly higher than actual water production (Underschultz, Vink and Garnett, 2018). APPEA have provided their latest estimates of water and salt production as part of this review:

- Total water production: 2,346 GL (DNRME, 2019)
- Total salt production: 6.1 Mt

Updating existing assessments of brine disposal options would only be of value if it is considered that this would materially affect the decision regarding the identification of the most viable disposal option. This issue was discussed at the workshop on 6th August 2019 and also considered by the UQ-CNG review team.

It is likely that the decreased volumes of salt, and therefore brine, would impact the overall size of some parts of the disposal process e.g. pipeline diameters may able to be reduced and the size of the encapsulation facility/ies would be smaller, and this would affect both construction and operating costs in some cases. However review of the assessments has shown that while construction and operating costs have been considered, they have not been identified as the *major* barriers or influencers to selection of any of the disposal options. Rather the key barriers for individual disposal options have been technical viability, environmental performance or social licence.

Consequently, no major update of the assessments to reflect the revised water and salt production figures is required at this time.

The need for updates should be reviewed if:-

- there were major changes (especially increases) to future predictions of brine or salt volumes or composition,
- there were new technology developments related to salt management,
- there were complimentary developments of ocean outfall by other parties which had been found to be socially acceptable; or if,
- regulatory changes permitted deep brine injection in areas other than those contained within CSG tenements.

For clarity, this is not to pre-judge that such eventualities would alter the current assessment of “preferred” case.

5. Summary Outline of existing and emerging brine / saline waste treatment technologies

Mehreen and Underschultz (2016) from UQ Centre for Coal Seam Gas investigated potential opportunities of using CSG associated water in other industries. At the time of their study, various options were considered including crop irrigation, surface water, managed aquifer recharge, livestock/feedlot, meat processing and leather industry, artificial wetland, municipal water supply, biofuels and cooling tower water. Based on the screening matrices applied, irrigation, livestock, meat and leather processing were considered as the most viable industries for beneficial use of CSG water (Mehreen and Underschultz, 2016).

On the brine management aspect, the main disposal options of reject water/brine from water treatment plants identified at that time were: 1) deep-well brine injection, 2) brine crystallisation and landfill disposal and 3) selective salt precipitation (Mehreen and Underschultz, 2016). Ocean outfall is a further, established option that is commonly used for the large volumes of brine waste generated by seawater desalination plants internationally (Darre and Toor, 2018).

In order to identify any new or advancement in current brine treatment and disposal technologies in recent years, relevant literatures published after Mehreen and Underschultz's work have been reviewed and summarised in the sections below. In addition, the review team also conducted a workshop with researchers across UQ who have expertise in areas such as water treatment technologies, algae production, bioenergy facilities, renewable energy and hydrogeology and have knowledge of the latest international developments in these fields. This workshop did not identify any emerging research areas or technologies beyond those discussed in the literature review below.

5.1 Investigated technologies

5.1.1 Brine Treatment

Brine treatment technologies have been widely studied by the desalination industry to more efficiently treat inlet water to desalination facilities, decrease energy and cost intensity and improve the recovery factor to minimise brine volume as a by-product. Darre and Toor (2018) report that reverse osmosis (RO) plants treating brackish water can achieve 75% - 85% water recovery. Technologies such as forward osmosis could offer water recovery up to 98% and are less energy intensive *but are still emerging* (Panagopoulos et al., 2019).

Even though the percentage water recovery of an RO plant has not been specified in APPEA report, the recovery depends on various factors such as inlet water composition, temperature and pressure and pre-treatment process in place (Millar et al., 2016). UQ-CNG has compared the produced water statistics published by DNRME[5] for the period 2015/16 – 2017/2018, with the CSG industry beneficial use of associated water statistics reported by the GasFields Commission Queensland (2019). On this basis beneficial use of associated water is ranging from 84.5% - 91.9% over the last three financial years, indicating that the CSG industry RO plants are achieving high recovery rates for this technology. Actual recovery rates reported are lower due to two factors:

- Office of Groundwater Impact Assessment reports that associated water production is actually higher than the figures reported in the publicly accessible Petroleum and Gas Production and Reserve Statistics spreadsheet.
- The beneficial use figures also include use of associated water that is not treated via RO.

[5] https://www.data.qld.gov.au/dataset/petroleum-gas-production-and-reserve-statistics

RO plants can be relatively energy intensive. The companies are currently supporting research to improve the efficiency of the current RO plants and this has the potential to increase future water recovery rates. While this could decrease brine volumes by reducing the water content, it would not change the mass of salt to be disposed of. Given the substantial financial investment in existing RO facilities and brine storage ponds, entirely new water treatment technologies (if developed) would have to compete on cost against an installed (sunk cost) base, and could create an additional environmental footprint.

5.1.2 Brine management and disposal

This review did not identify any major developments in brine management and disposal options – either in improvements to existing technologies or the development of new options. A brief summary of recent literature relevant to the management options considered by the CSG industry is included for reference purposes.

Current brine disposal options consist of surface water discharge (defined as including direct discharge to oceans), sewer discharge, deep-well brine injection, evaporation ponds and land application (Giwa et al., 2017 and Panagopoulos et al., 2019). The construction of evaporation ponds in Queensland has been banned since 2012 (CSG Water Management Policy 2012) and are not considered in this review.

Ocean outfall, a form of surface water discharge, is widely used in majority of seawater desalination plants while sewer discharge has been used to deal with smaller scale inland desalination plants (Millar et al., 2016 and Panagopoulos et al., 2019). Brine discharge via ocean outfall is the only form of 'surface discharge' discussed in the APPEA report, and this is the only form of brine discharge considered to have any potential in the Queensland context. Sewer discharge options in the CSG regions are totally unsuitable due to the very large disparity between brine volumes and sewer system capacity, and that conventional waste water treatment works will discharge the salt. The industry has concluded that ocean outfall options are not appropriate for both logistical and perceived social reasons, due to the large amount of brine produced, the scattered treatment sites and their distance to the ocean. In case of using the Tugun outfall, the brine transfer pipeline would cross through highly populated and sensitive urban areas and could also give rise to a perceived risk to the tourism industry in Gold Coast. More northern outfall sites such as Gladstone Harbour and Agnes Water are in close proximity to the Great Barrier Reef Marine Park.

Deep-well brine injection is a well-established approach to dispose of brine produced from oil and gas wells as well as desalination plants. In the USA, Class II wells have been extensively used to dispose brine. Class II wells are used to inject fluids for enhanced oil recovery, dispose fluid associated with oil and gas production and store liquid hydrocarbons (McCurdy 2011). About 29,000 class II wells (20% of total class II wells) are used for brine disposal of 1.27-1.9 GL/day in the USA where some wells could dispose an average of 4ML/day (API 2000, McCurdy 2011 and Marsac 2019).

The target formation needs to be a porous and permeable formation which is either a non-hydrocarbon bearing zone (not a potable water aquifer) or a depleted hydrocarbon bearing zone. The proposed receiving formation is required to be isolated from any overlaying aquifers with an impermeable formation and relatively clear from any faults (McCurdy 2011). A key concern, arising out of experiences in the USA (which are not necessarily analogous to Australian settings), related to deep-well brine injection, is the risk of induced seismicity. Management of seismic risks need to be addressed first by detailed site characterisation and then by developing of risk management strategies such as seismic monitoring programs and stakeholder engagement (Smith et al. 2017).

In addition to potential risks highlighted above, the injection option investigated by CSG companies showed that the proposed depleted gas reservoirs in the proximity of existing CSG water treatment plants do not have sufficient permeability relative to water/brine. In addition, the current estimated permeability could further reduce in the event of salt precipitation in these receiving depleted gas reservoirs.

Selective Salt Recovery: Commercially available techniques such as SAL-PROC and Selective Salt Recovery are applied to produce high purity solid salts from brine concentrates in desalination industry where relatively constant brine concentration exists (Giwa et al., 2017 and Panagopoulos et al., 2019).

However as noted in APPEA report, the significant salt variation in CSG produced water will impact SSR process resulting in mixed solid salt waste.

The Chlor-alkali technology, which converts sodium chloride to chlorine and sodium hydroxide, has been studied on brine from RO plants in desalination units (Casas et al. 2012). This technology can be considered to treat brine recovered from RO plant in CSG industry; however, no study related to CSG produced water has been reported (Millar et al., 2016). The industry workshop presentation used at the meeting on 6 August 2019 noted that production of chloralkali was a potential option, but would require development of an additional facility in conjunction with the primary SSR facility, with associated additional capital and operating costs (and footprint).

Salt Encapsulation comprises of 1) dewatering brine using commercially available brine concentrators or brine forced circulation Crystallisers (BCr) as proposed by CSG companies (Panagopoulos et al., 2019) with an advantage of fresh water collection during this process and 2) disposal of the mixed salt product in salt encapsulation cells (Brannock et al. 2011).

Companies consider that salt encapsulation with its proven technology and previous commercial scale applications is the most technically appropriate brine option currently available in the market. However, one challenge ahead for salt encapsulation is potential sensitivities in regional communities and new regulatory requirements (Millar et al., 2016, ABC NEWS 2010).

5.2 Emerging technologies

This review did not identify any emerging technologies with the potential to provide a viable alternative disposal method to those already considered in depth by the Queensland CSG industry. Relevant research is being conducted, but is expected to improve the efficiency of different components of existing processes rather than fundamentally altering the practical, ultimate disposal solution. There is a wide range of research focusing on improving RO membrane technology, with the aims of improving water recovery and reducing membrane costs. These initiatives are not addressed here.

Algae cultivation using brine

This is a nascent and probably small scale option. Algae cultivation using brine produced from desalination or CSG water treatment plants have been studied in recent years (Giwa et al. 2017 and draft UQ-CCSG report 2019). *Dunaliella salina* which is a chlorophyte microalga has received the most attention due to its remarkable environmental adaptation by producing large amount of carotenoids and glycerol (Raja et al. 2007 and Giwa et al. 2017). A pilot scale project has been conducted to cultivate *Dunaliella salina* using brine with salinity between 40000-80000 ppm in outdoor ponds under natural climate. It resulted in brine salinity reduction between 13% and 63% varied due to brine concentration, time in ponds and change in climate conditions (El Sergany et al. 2014).

Similar results have been derived from a recent pilot scale project completed at the UQ Algae Energy Farm using coal seam water with salinity between 25-170ppt. *Dunaliella salina* was able to reduce the salt concentration by about 40% when it grew in the optimum brine salinity of 90ppt (draft UQ-CCSG report 2019). Based on the techno-economic analysis of algae cultivation, ponds with capacity of 19ML (and total land area of 100,000 m^2) might create up to $6.4m profit per year (UQ-CCSG initial report 2019). Even though the ponds would need to be topped up during the cultivation process, the total brine quantities that can be used in these ponds is considered the main shortfall of this approach – they are very small in comparison to the overall brine volumes generated by the RO plants. It is also noteworthy to mention that the remaining brine in the algae ponds are required to retreated prior to being returned to the RO plants for final disposal in conjunction with the main brine volumes.

This research is exploratory and has yet to be peer reviewed – indeed, the report has not yet been released to the member companies. UQ-CNG considers that algae production may have some potential to become another form of beneficial use, which might deliver some regional benefit if logistical issues and commercial complexities can be dealt with. *Importantly however, it will not be sufficient in scale to make a material difference to large-scale brine disposal.*

Salt compression and recrystallization

This research was conducted by UQ-CCSG and reported to the member companies (APLNG, Arrow Energy, QGC and Santos) in 2017. This report was provided to DES and distributed to the workshop participants along with the minutes. This research developed a process for compressing and recrystallising the salt waste. The laboratory experiments demonstrated that the process had the potential to reduce the encapsulation volume by up to 30% (depending on loose salt composition and moisture content). The compacted samples also demonstrated reduced permeability, which would enhance long-term stability of the encapsulated salt. The study also identified the potential for further research into use of additives to further reduce permeability. Such additives would likely also reduce the potential for the encapsulated salt to be recovered for other use in the future.

Solar-evaporation system

Inspired by an oil lamp mechanism, a solar-steam generation system can be used to efficiently evaporate water from a bulk water surface. This bench scale system has been built of a carbonised cotton strand covered with polydopamine (PDA). The cotton strand acts as a wick allowing evaporation to occur above the bulk water surface. The system demonstrated high evaporation efficiency because of 1) the great photothermal effect of PDA, 2) the low thermal conductivity of cotton and 3) very thin water layer generated on the evaporation surface combined with the spatial separation between the evaporation surface and the bulk water surface (Wu et al., 2018).

In case of the system proving effective at the commercial scale, it might be used in CSG brine ponds to accelerate the evaporation process; however, the salt volume and its disposal challenge will stay unchanged. The main benefit of this technology would be in the reduction of the energy intensity and cost of the evaporation process used to crystallise the salt.

5.3 Review of Additional Technical Reports

Following consideration of the review of the APPEA report, the responses to the data request and information provided at the workshop, it is clear that the companies have invested considerable resources into the identification and assessment of leading brine waste management options. All information provided to this review in respect of the individual disposal options is consistent with the stated industry evaluation, and consistent with the technical information gathered in the review of recent scientific journal articles. The review has identified no areas where it is considered necessary to review the detailed technical documents or impact assessments at this time.

The need for the CSG industry to manage this waste is very well understood amongst the commercial sector and it is highly probable that the companies have and will continue to be approached to consider any new technologies with potential as an alternative disposal option.

5.4 Pre-feasibility assessment of any new technologies

This review has not identified any emerging technologies relevant to the disposal of large volumes of highly concentrated brine. As noted in Section 5.2, current research studies have the potential to produce process efficiencies and cost reductions across the water treatment and brine disposal process. This includes initiatives to increase water recovery, decrease energy costs and decrease the land area required for encapsulation. None of these improvements will change the volume of salt to be disposed of, or the relative suitability of the options already considered.

Using brine to grow algae for commercial purposes also shows some potential to reduce the overall volume of salt waste by a relatively small amount. If this option is found to be technically and financially feasible it is more consistent with a beneficial use option than a disposal solution.

In summary, the literature review and the UQ expert workshop have not positively identified any emerging technologies that provide a viable alternative to creating a solid salt waste to be disposed in multiple engineered repositories/landfills.

6. Conclusions

Section 6 of the *Queensland Gas: end-to-end water use, supply and management* report has been reviewed in conjunction with additional information obtained from APPEA, APLNG, Arrow Energy, QGC and Santos (response to the data request, workshop presentation and workshop discussion). The information provided has of necessity been a high level summary of investigations valued at more than $100M and conducted over approximately 10 years. The review has primarily considered collaborative, industry-wide studies, but has also considered investigations conducted by individual companies to some extent.

The review has produced an Assessment Matrix that categorises and summarises the information from all sources. This assessment shows that the leading brine disposal options have been subject to detailed technical assessment. The extent of environmental, social, economic and regulatory impact assessment has varied, but in respect of SSR, ocean outfall and brine injection options, appears to have progressed until major technical or social barriers to implementation have been identified.

A review of recent literature and consultation with UQ experts has identified that the industry have reviewed all reasonable brine disposal options, and even though some of this work is dated, no new options have emerged to make the original investigations irrelevant or provide new avenues for investigation. The review does indicate that current research may assist the industry to introduce processing efficiencies to reduce energy intensity, operating costs, land encapsulation areas and brine volumes. The only opportunity to reduce salt volumes identified in this review is growing algae on brine, and this can only provide a minimal reduction

The review concludes that the four large companies in the Queensland CSG industry have undertaken appropriately detailed assessments of the leading brine disposal options. The barriers identified to implementation of the SSR, ocean outfall and brine injection options have been considered realistically. The investigations have been conducted at substantial expense to the companies and have focused on highly technical options that require large capital investment, comprehensive design to minimise and manage risk factors, and high levels of operating costs. It is noted that the options investigated by the companies are the same as those proposed during project environmental impact assessment process between ~ 2009 – 2011. In the decade since then, no alternative viable technologies have been identified.

The information provided supports the industry conclusion that salt encapsulation facilities are the most technically viable brine disposal option currently available. This option is reliant on proven technology with well-established and effective regulatory processes to manage the key environmental risks. Limited information regarding the social impact or the SEF option was included in the report and it is assumed that the companies are intending to undertake this work as part of the detailed environmental assessment process for any proposal. There are likely social acceptance issues to be addressed. While not definitively tested, and not a testament to comparative environmental performance, it is reasonable to expect that social acceptance related to encapsulation would be more readily dealt with than those associated with ocean outfall. It is noted that the total costs of salt encapsulation (capex plus opex) were amongst the highest of the options evaluated by industry.

Discussion with the companies indicates that the first long-term disposal option (currently based on the SEF option) needs to be commissioned in 2025 with detailed planning to be commenced by 2021. As a result the regulatory pathway for assessment and approval needs to be defined rapidly.

7. Recommendations

The industry investigations have discounted SSR, ocean outfall and brine injection (within company tenements) as viable salt disposal methods. This review has not identified any existing or emerging technologies that provide alternate salt disposal methods for detailed investigation. It is therefore prudent for government and industry to plan on the basis that construction of SEFs will provide, at least in the medium term (10 – 15 years), the best option for the long-term secure storage of salt waste. It is noted that the SEF option provides the flexibility to adopt new salt disposal technologies if they emerge during the production lifetime of the industry. Accordingly, this review of the APPEA report makes the following recommendations:

1. The requirements of the environmental assessment process toward permitting SEFs should be determined rapidly in order to ensure that all technical information can be provided to meet regulatory requirements and the necessary public consultation and education processes can be managed effectively. As this review has identified no evidence of emerging technologies that will provide viable alternate disposal methods, the industry requires establishment of the regulatory pathway to allow sufficient time to meet disposal timeframes, i.e., first commissioning in 2025.
2. APPEA and the companies should place a high priority on stakeholder engagement and consultation to build the level of community acceptance required for SEFs. The level to which this achieved for the first SEF will affect future proposals and the ongoing social licence of the industry.
3. Department of Environment and Science determine the residual risk management requirements that will apply to the SEFs. This regulatory mechanism is critical ensuring the long-term physical integrity of the sites and addressing community concerns regarding the management of the facilities beyond the lifetime of the CSG industry.
4. A public reporting process be developed to provide access to all monitoring data and demonstrate that the SEF is complying with all regulatory requirements and that the physical integrity of the site is maintained.
5. Department of Environment and Science should conduct 5-yearly reviews of brine/salt production management to:
    a. confirm that industry planning for management and disposal options is at an appropriate scale, given the likelihood of production estimates continuing to change
    b. review the latest research and determine if there are any relevant emerging technologies
6. The CSG industry continue to invest in research that will:
    a. minimise the medium and long-term risks of SEFs
    b. reduce energy intensity and operational costs of brine management and salt disposal options
    c. investigate any emerging technologies that are identified through their own efforts or in future reviews

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A-1 Data Request

The UQ-CNG review team developed the questions included in Table 3 following an initial review of Section 6 of the APPEA *Queensland gas: end-to-end water use, supply and management.* This data request was distributed to APPEA and company representatives along with the invitation for the *Brine and salt management in the Queensland gas industry* workshop held on 6 August 2019.

Table 3 Questions associated with the peer review of APPEA salt and brine (Section 6)

<table>
<tr><td colspan="2">Overarching questions</td><td>For each option considered please provide details (where available) of:
Brine volumes considered in the feasibility assessment
Estimated energy consumption and carbon emissions
Construction timeframes
Any assessment of how field storage structures can be used to provide consistent feed of brine volume to treatment/disposal options
Any recent reviews of assessments to take account of changed brine estimates or changes in technology
Also please provide current estimates of water, salt and brine production for comparison purposes</td></tr>
<tr><td>Management Option</td><td>Key reports to discuss</td><td>Topics/questions</td></tr>
<tr><td>Selective Salt Recovery (SSR)</td><td>Selective salt recovery (QGC, APLNG, Arrow, 2011)</td><td>Brine specifications (SSR processing requirements and expected RO output range)
Expected composition and volume of other waste streams
Technology provider caveats regarding salt purity, production volumes and equipment reliability
Market assessment report</td></tr>
<tr><td>Injection</td><td>Company reports
Fairview Brine Injection (Santos), Large scale brine storage (Santos), permeate injection to Precipice Sandstone (APLNG), Depleted coal seam injection study (Santos), Brine injection (APLNG), Roma brine injection trial (Santos)</td><td>Please provide a table summarising the findings for the sites investigated by individual companies – location, data availability, reason/s for unsuitability</td></tr>
<tr><td>Ocean outfall</td><td>Ocean outfall assessment (Santos, 2011)
Ocean outfall (APLNG, 2013)</td><td>Did individual ocean outfall assessments by APLNG and Santos consider alternate sites to Tugun?
Did any of these reports include an assessment of the regulatory regime relating to ocean disposal?
Was there any assessment of pre-treatment requirements?</td></tr>
</table>

Salt encapsulation	Collaboration agreement (APLNG, QGC, Santos, 2015) (- this is an assumption) Brine transfers between proponents, 2015 Western & eastern encapsulation options, 2015	• Overview of operational modifications needed to cater for variations in brine feed composition/volume • Any specific assessment of brine only or multi-purpose waste facilities • What were the site selection criteria? • What are the physical sizes (land area, containment capacity) of facilities in the different options? • What is the proposed long-term management strategy?
Other reports	Acid regeneration trial (APLNG, 2012) Brine concept assessment (Arrow, 2013) Salt plant concept study (Arrow, 2015) Integrated water balance developed (collaboration, 2015) Brine and salt feasibility study (Arrow, 2016) Longstraws trial (APLNG, 2017) Industry salt working group (collaboration, 2017)	Please clarify scope of these reports and their relationship to the collaborative studies discussed in the APPEA paper.

A-2 APPEA workshop presentation

APPEA and company representatives delivered this joint presentation (Salt management option assessment) at the workshop held on 6 August 2019.

Salt management option assessment

Overview

- The oil and gas industry is a vital part of the Australian economy:
  - supplying energy to 5 million households
  - supplying the fuel for gas-fired generation in the electricity market
  - supplying essential inputs to the manufacturing sector, underpinning 225,000 jobs
  - investing more than $200 billion in developing new supply for domestic and export customers
  - paying more than $9 billion in taxes and resource charges to governments
  - employing tens of thousands of Australians in highly skilled, highly paid jobs
  - generating $25.5 billion in export earnings — adding almost 0.5 per cent to annual GDP growth.

Overview

- The industry's use of water is relatively modest — less than 0.2 per cent of the water consumed by Australians (by comparison, agriculture accounts for almost 59 per cent of water consumption).
- The oil and gas industry delivers an exceptionally high economic return from the water it uses. According to the Australian Bureau of Statistics, the gas industry's value-add is $933 million Gross Value Add per gigalitre of water used, compared to $4 million for agriculture, $37 million for aquaculture and $83 million for wood, pulp and paper.
- In the case of Queensland coal seam gas projects, the industry is more of a supplier than a user of water. Most water removed from coal seams as a by-product of gas production is treated and provided at low cost to other users such as farmers and local government or used to recharge aquifers.

Overview

- Industry in Queensland has invested more than $3 billion in water treatment infrastructure, and over 40 gigalitres of water was provided by the industry for beneficial use in 2016–17 with 83 per cent of this volume used for irrigation.
- This supply of water is particularly important where drought conditions exist. About one-quarter of the water removed from local coal seams is returned to aquifers.
- To date over $100 million has been expended by the industry in undertaking joint and company-based investigation and analysis into the feasibility of salt management options considering technical, environmental, social and economic implications of these options.
- New opportunities, technologies and partnerships with other industries and/or government will be examined as they arise.
- This presentation covers opportunities assessed and conclusions to date.
- Note - cost data presented in each section has not been baselined to a common reference year and is therefore indicative but not directly comparable.

Selective Salt Recovery (SSR)

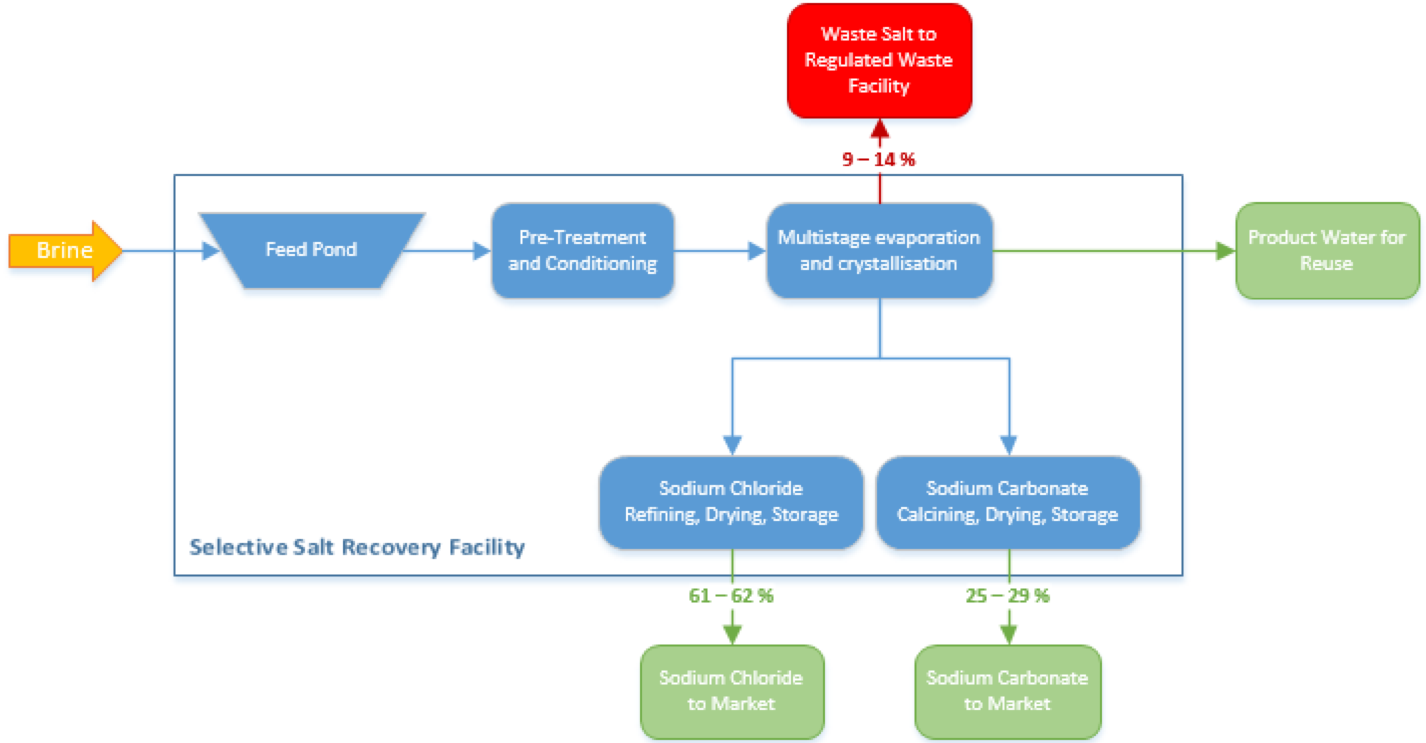
(Presenter - Mack Dreyer)

SSR summary

- Three industry proponents collaborated on a Pre-FEED and FEED investigation to inform a feasibility assessment
- Industry spent approx. $60 million on this evaluation
- Four pilot projects of which two progressed to a second piloting stage, including:
    - Identified a preferred site for the SRR facility (proximity to rail lines etc.)
    - Pre-FEED with two consortia
    - Assessment of brine pipeline network to transport brine to SSR facility (375km network)
    - Market assessment for salt products

SSR - Process and Feasibility

- Based on a ‘multistage evaporation and crystallisation’ facility with processing capacity of 3 ML/d brine:
    - Produces 25-40,000 Tonne of waste salt annually for disposal at a regulated waste facility
    - Highly energy intensive (gas fired power station required on-site 90,500 MWh pa) (a 30 MLPD water treatment facility with RO is approx. 37-47,000 MWh pa)
    - Greenhouse gas emissions 150,000 tpa CO_2-e
    - Uncertain if SSR facility would be a MHF (chemical storage)

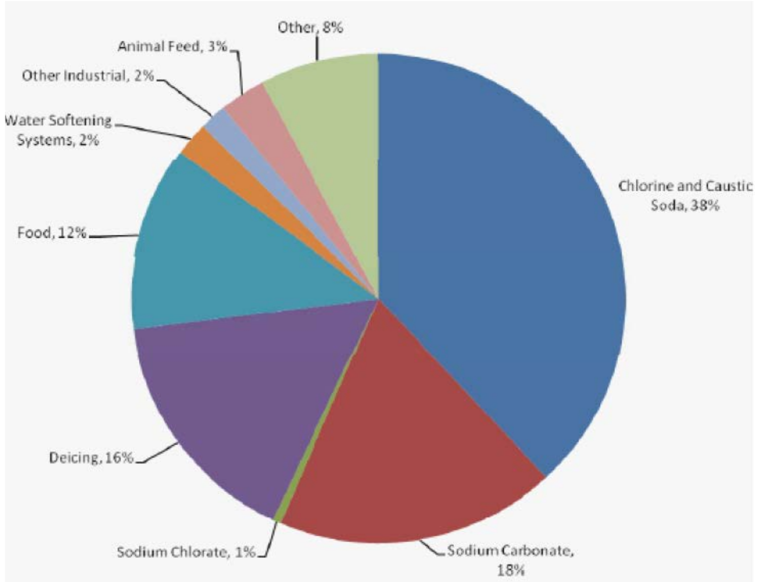


SSR - Pilot trial findings

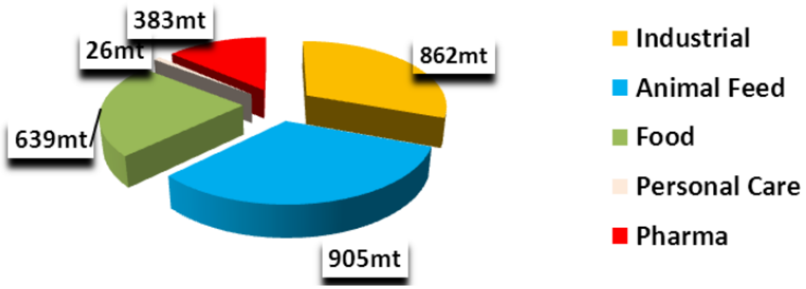
- At a conceptual pilot scale, the SSR process was successful, however this was not tested or proven to a commercial scale.
- The technology requires the chemical composition of the brine used in the process to be in a relatively narrow range.
- Natural variations in water quality across various fields means that maintenance of brine feed quality will be difficult to maintain – resulting in higher proportion of ‘waste’ salts.
- Disposal solutions for out of spec product still needs to be developed.
- Under ideal conditions the pilot trials produced large volumes of salt waste 15-20% that would require disposal at a Regulated waste facility.
- Technology providers would not provide assurance that end products would meet supply obligations.

SSR - Market assessment of salts

- Domestic market for NaCl limited and not readily accessible to new suppliers
- Bulk NaCl exported to Asia in competition with 11 mtpa NaCl already exported from Australia (solar evaporation and close to port)
- Transport cost to get NaCl from SSR facility to Brisbane port up to 3 times the value of salt (excluding salt production costs)
- Diverse domestic supply chain required to sell Na_2CO_3
- Domestic Na_2CO_3 market 370,000 tpa (2010) however long term market trends are uncertain - competing with
    - competitive pricing and market
    - Suppliers with 10 to 50 times production capacity and proven stable and long term supply



Global uses of sodium chloride (GE, 2012)



Global bicarbonate consumption (2010/11)
Source: CEH Marketing Research

SSR - Market assessment of salts

- Australian $NaHCO_3$ market approx. 35,000 tpa - stockfeed, food manufacturing, water treatment and industrial
- SSR facility would require additional capital investment to produce $NaHCO_3$
- $NaHCO_3$ market very competitive with excess capacity and dominated by large scale producers
- Possible chloralkali production via development of an adjacent facility. Facility would require significant capital investment and has high energy consumption

SSR – Economic Summary

- Total real cost estimate ($ 2012) for SSR ranged $5,350m to $6,235m
- Noting that:
  - The technology was unproven on a commercial scale
  - No guarantee that a saleable product would be produced requiring alternative management/disposal options to be developed
  - Any product from this process would have to be sold below cost, impacting the market and affecting more sustainable businesses

Ocean outfall

(Presenter – Derek Hannigan)

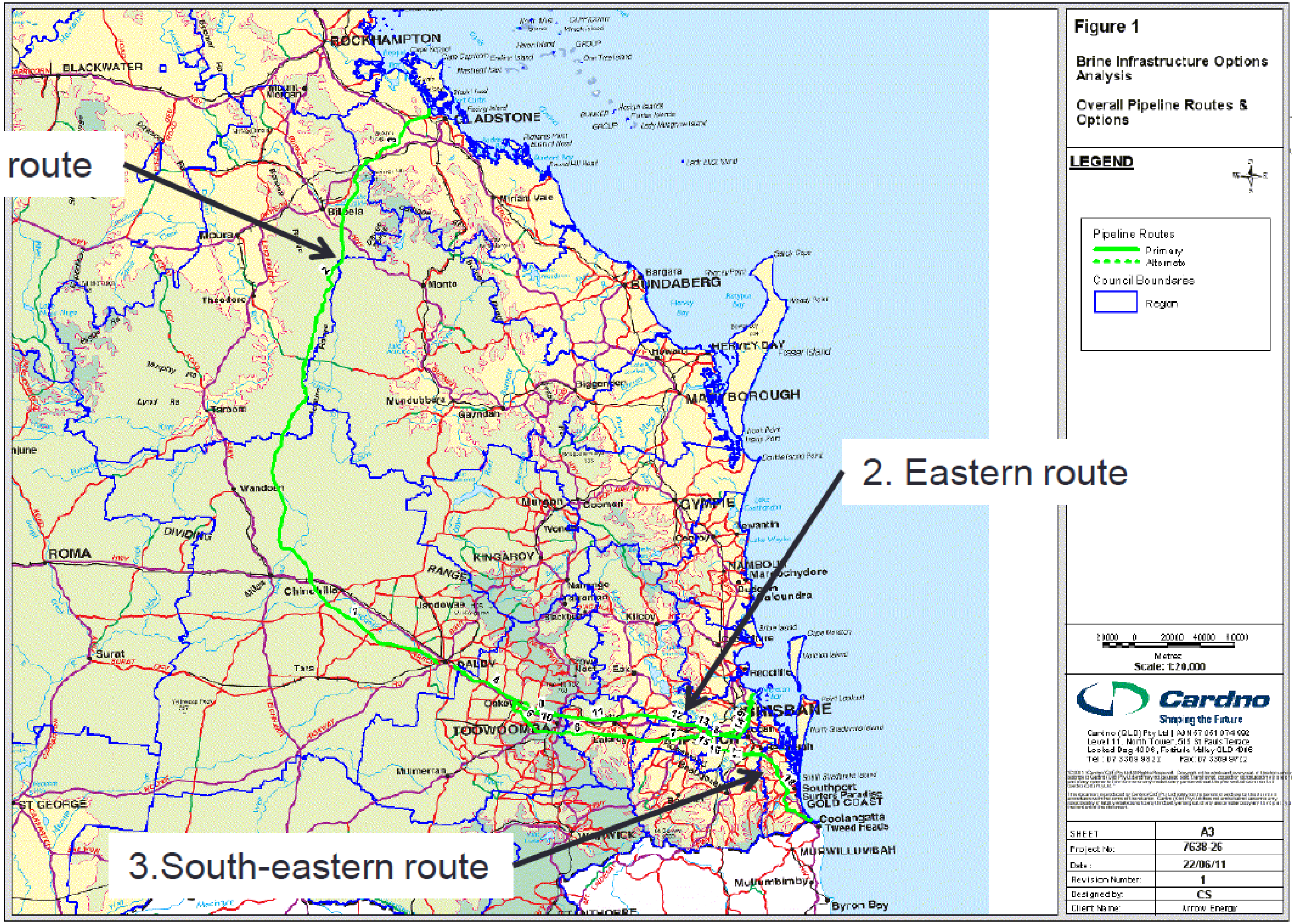
Ocean outfall

- Key considerations for ocean outfall:
  - Pipeline alignment
  - Pipe material and operating costs
  - Ocean discharge arrangement and water quality
  - Social licence
- Ocean outfall options involves the transfer of brine via pipeline to the Queensland coast.
- Depending on outfall location, this results in a pipeline between 230 and 500 km in length.

Ocean outfall

- After initial screening, 3 outfall locations were considered in detail (shown on next slide):
  - Option 1: Northern route (Curtis Island) that takes advantage of potential synergies with the gas export pipelines and potentially reduces geographic and environmental constraints that would occur with other routes to the coast between Brisbane and Gladstone.
  - Option 2: Eastern route (Luggage Point) that would utilise the potential of existing infrastructure corridors (i.e. shortest route). The existing corridors utilised include the Roma-Brisbane Gas pipeline and the Western Corridor Recycled Water Scheme (WCRWS) pipeline through the Brisbane metropolitan area.
  - Option 3: South-Eastern route (Tugun) that would utilise the potential of existing infrastructure corridors and the potential spare capacity (i.e. over the life of the project) at the existing ocean outfall for the Desalination Plant at Tugun. The existing infrastructure corridors utilised includes the existing Roma-Brisbane Gas pipeline and the Southern Regional Water pipeline (SRWP) and desalination mains at the Gold Coast area.

Ocean outfall



Ocean outfall

Option	1. Northern route	2. Eastern route	3. South-eastern route
Length (km)	486	279	227
Static Lift (m)	196	314	314
Friction Losses (m)	2,773	1,295	1,590
Total Lift (m)	2,969	1,609	1,904
No. Pump Stations	~30	~20	~20
Notes	New power supply for pump stations along route. New ocean diffuser.	Approval to use existing easements. New ocean diffuser.	Approval to use existing easements. Access to existing desalination plant ocean diffuser.

Ocean outfall

- The ocean disposal option has a challenging Environmental and Stakeholder Approvals environment:
  - Approvals at all levels of government required
  - Land and easement access approval from external stakeholders
  - Environmental approvals (ESAs – EP Act and MNES – EPBC Act)
  - Stakeholder impacts: congested and narrow alignment in metro areas – difficulty in construction and maintaining pipeline
  - Limited existing power along export pipeline easements
  - Approvals and stakeholder issues relating to installation of a new outfall in close proximity to marine parks - Northern and Eastern options
  - Management of pipeline scaling and corrosion whilst ensuring pipeline integrity – High pressure metallic pipes preferred from a pipeline design perspective (less pump stations and maintenance) are less favourable than plastics e.g. HDPE for management of these issues
- Obtaining and maintaining the required social licence for this salt disposal option was considered a key issue/barrier for this option.

Estimated costs[1] of shortlisted pipeline routes shown in table below based on predicted brine volumes to be transported at time of undertaking assessment and a 6% discount rate.

Option	1. Northern route	2. Eastern route	3. South-eastern route
Pipeline Capital Cost ($M)	$521	$280	$347
Pipeline Net Present Value ($M)	$620	$332	$411
Outfall Capital Cost ($M)	$75	$75	Use Existing
Additional Power Capital Cost ($M)	$150	Grid power available	Grid power available
Estimated Tariff NPV ($M)	N/A	N/A	37
Total ($M)	$845	$407	$448

[1] *Cost data compiled end 2011 /start 2012 and not revised for 2019*

Ocean outfall

- A multi-criteria analysis (MCA) was undertaken to determine the preferred route considering:
    - Design and Construction
    - Environmental Management
    - Operation & Maintenance
    - Social and Community
    - Capital Costs
- From this assessment, Option 3 – South-Eastern route was identified as the preferred option, with Option 2 – Eastern route close behind, primarily due to the following advantages:
    - Maximised use of existing electricity supplies
    - Use of an existing outfall minimising potential for construction and stakeholder difficulties
    - Low cost, though estimated to be higher than Option 2 – Eastern route

Ocean outfall

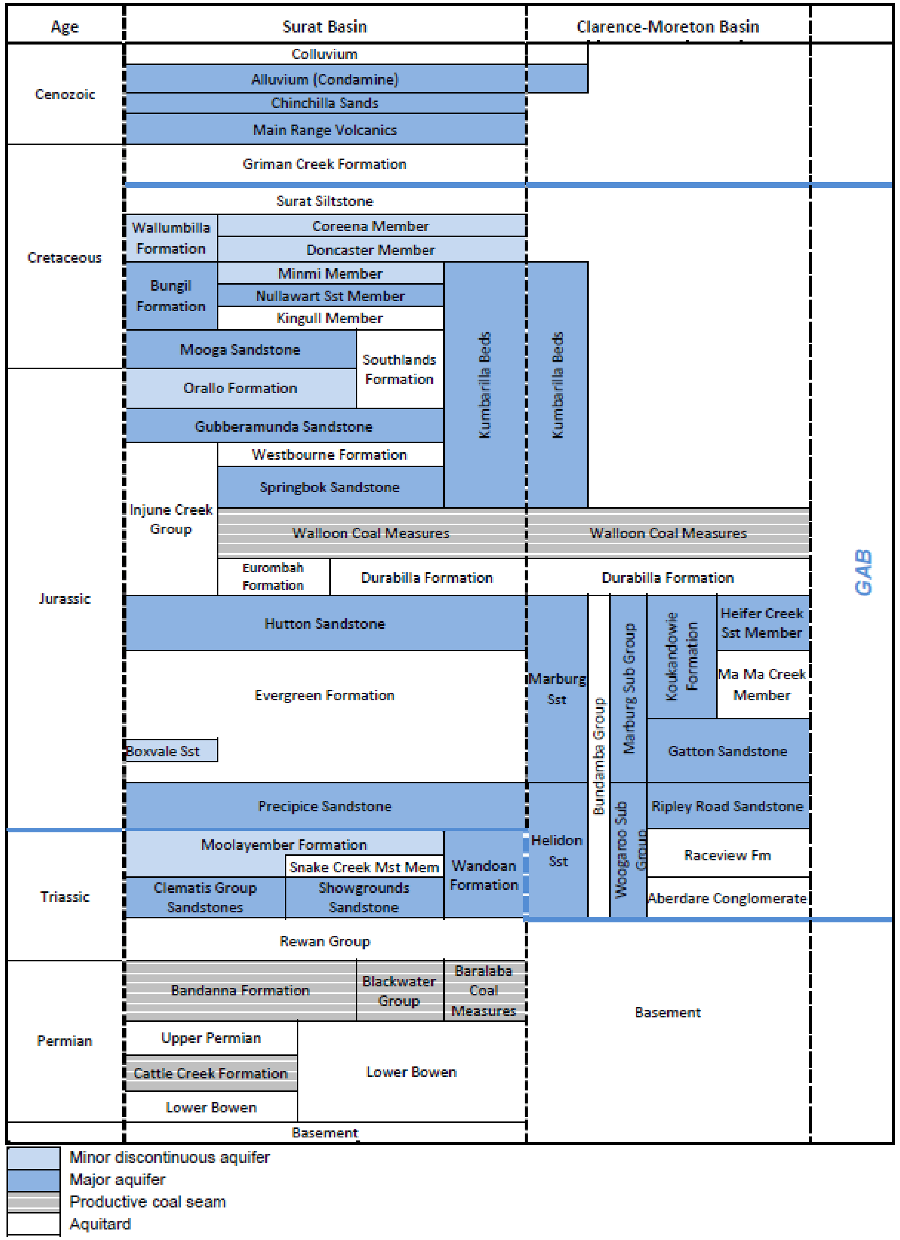
- SKM was engaged in 2012 to undertake diffusion modelling of brine through the Gold Coast desalination plant brine diffuser. The findings of the work are summarised as follows:
  - The minimum and maximum flow ratings of when the plant is operational are 66 MLD and 223 MLD, respectively. The corresponding TDS is 60,000 mg/kg and 57,600 mg/kg, respectively. There is also a commissioning operation which is rated at 366 MLD and 36,000 mg/kg TDS. The systems have been designed with additional capacity for a possible future plant expansion (from the current 125 MLD permeate rating to 170 MLD), with an ultimate rating of 389 MLD.
  - The modelled contribution of CSG brines range from 7 MLD to 16.75 MLD with 200,000 mg/kg and 59,489 mg/kg TDS, respectively. There is sufficient hydraulic capacity in the diffuser infrastructure to receive the maximum CSG brine flow during normal operation. During commissioning operation, the system is expected to become reach the hydraulic limit with the maximum CSG brine flow considered.
  - Diffusion modelling showed that dilution seawater up to 77 MLD would be required when the SWRO is offline but the diffuser is used to discharge CSG brine. When the SWRO is operating at full capacity, no additional dilution sea water will be required.
- SEQWater have not been approached for the use of and tariff for the existing outfall. The viability of using the outfall is dependent on the expected CSG brine flows and Desalination Plant operation.

Brine Injection

(Presenter – Paul Wybrew)

Brine Injection

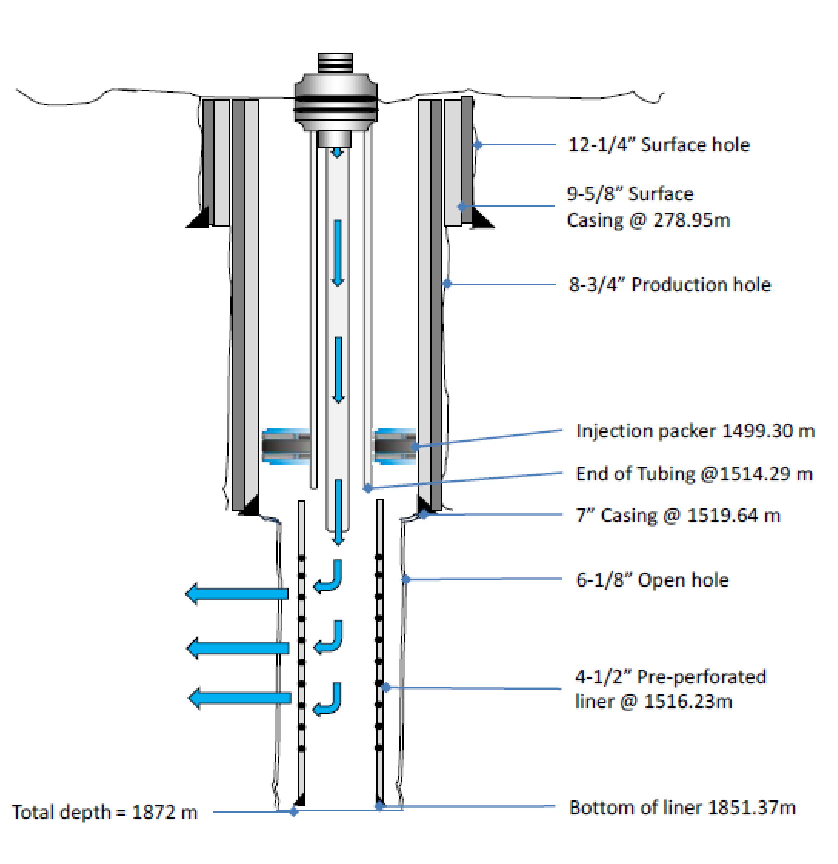
- Brine injection is not feasible because **a suitable injection target** could not be found that was:
  - geologically isolated formation; and
  - which contained sufficient capacity for the forecast brine volume produced that either:
    - did not contain groundwater; or
    - where groundwater is present, that the brine is of a similar or better quality than in-situ groundwater so as to minimise the potential for environmental harm to occur.



Regional hydrostratigraphy for the Surat and Bowen Basins in the Surat CMA (taken from UWIR for the Surat CMA, 2016)

Brine Injection

- In the Bowen Basin brine and produced water injection into basement rock (Timbury Hills Formation) was operated at two injection well locations over several years, however:
  - Pressures slowly rose, and injection became unsustainable as we were unable to inject without exceeding the host rock fracture pressure
  - Basement rock storage provided by secondary porosity (i.e. fracture dominated), which ultimately limits the potential storage volume and therefore the long term feasibility of operation.
  - Upwards of $35M was spent
- In the Surat Basin two potential targets were investigated:
  - Brine injection into basement rock was proven unfeasible since basement rock has no primary or secondary porosity – there were no voids to inject it into. Upwards of $10M constructing injection trials.
  - Brine injection into depleted conventional gas reservoirs was also deemed unfeasible in the Surat Basin because they are dry reservoirs, and dry reservoirs will not accept injected fluids. Feasibility studies did not progress beyond desktop assessment.



Emu Park 1 down hole arrangement – a well in which sufficient injection capacity was not deemed feasible

Encapsulation

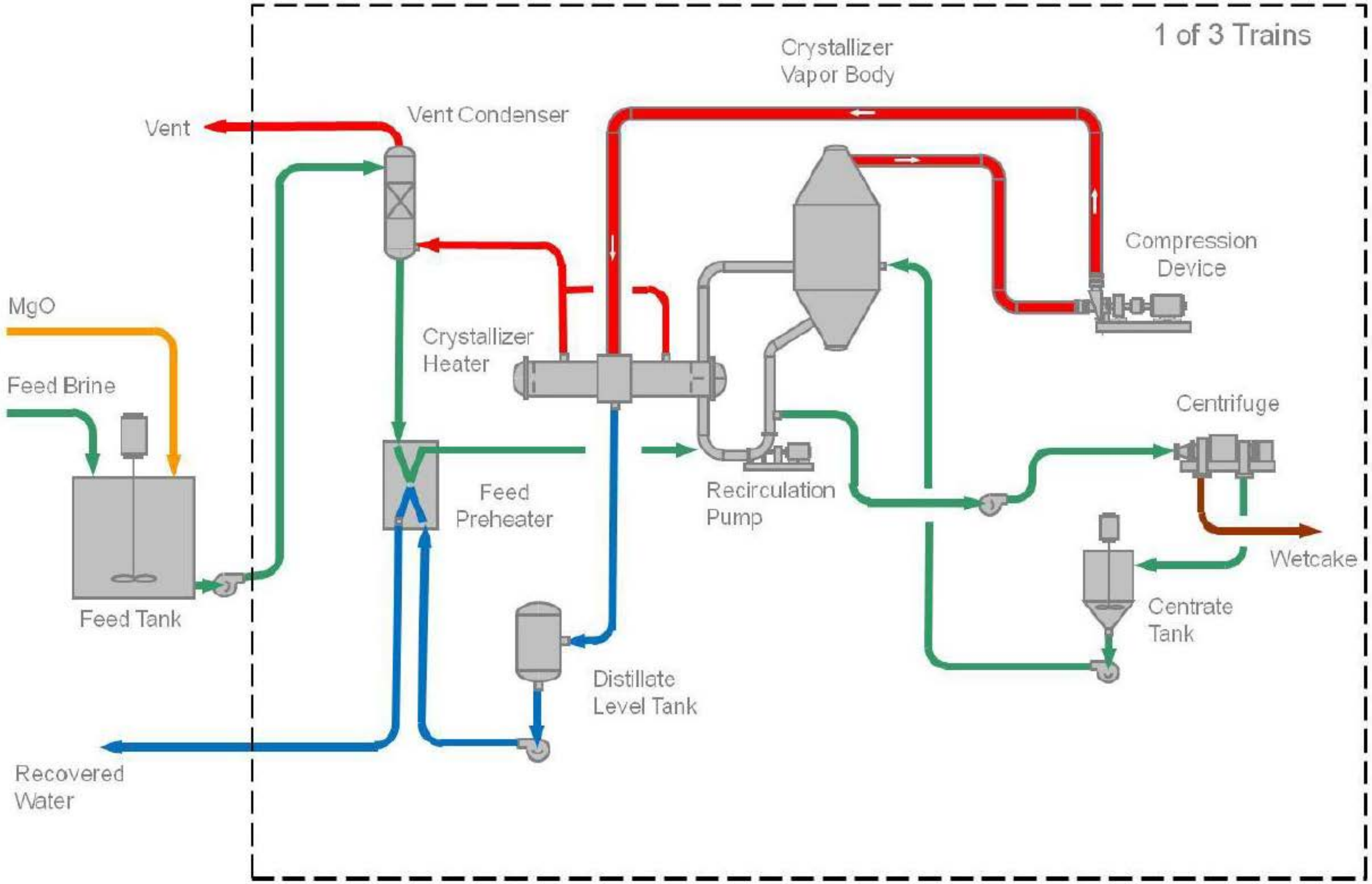
(Presenter – David Reinke)

Encapsulation Process Overview

- Brine from the water treatment plant process is safely stored in purpose built ponds
- These ponds are regulated structures – compliance and monitoring meet relevant regulations
- Brine would be processed through a mixed salt crystalliser to produce a solid salt product that will not break down over time
- This salt can be easily managed, mitigating environmental impacts during handling & transportation
- Salt would be stored in dedicated, purpose built Salt Encapsulation (SE) cells
- The SE cells are based on a multi-barrier system, providing redundancy, strength and durability
- Storage of salt in these cells enables the potential for the salt to be extracted at a future date to be further processed or removal to another facility

Crystallisation Process

- The crystallisation process dewaters the brine – making the resulting water available for beneficial use – and produces a wet cake like salt product
- This process provides a Zero Liquid Discharge (ZLD) solution – all water processed through the water treatment plants is beneficially reused
- The salt product is moist to prevent 'dusting' and 'salt drift' during handling, transportation & storage in SE cells

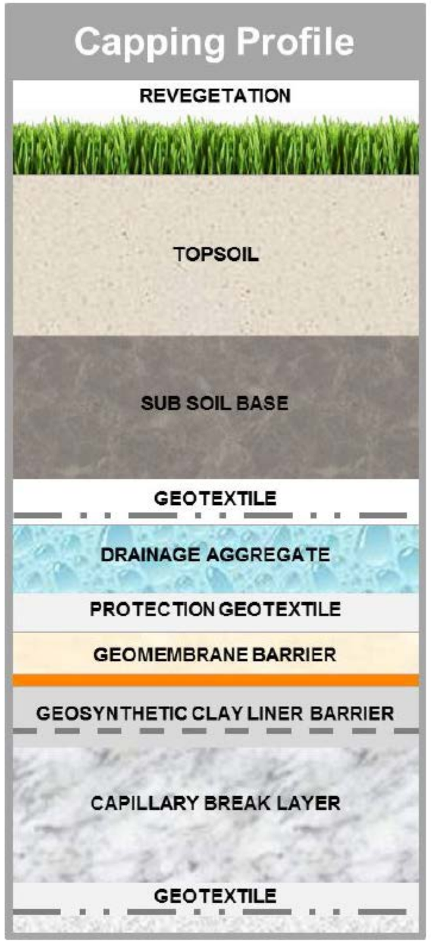


Crystallisation Process – continued…

- The crystallisation technology is used throughout the world in other existing crystallisation plants. Commonly used in power, oil & gas, mining and municipal wastewater industries
- General arrangement of a typical salt crystallisation facility outlined below:

Encapsulation Cell Design

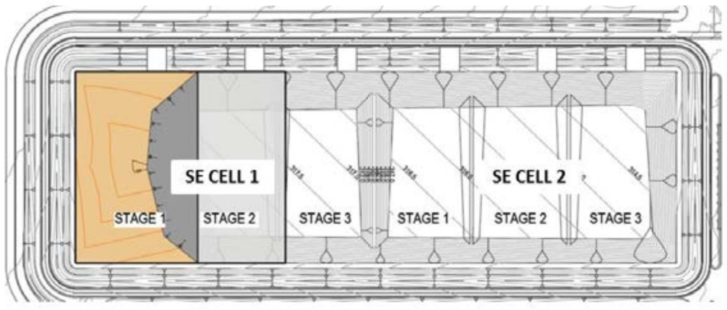
- The encapsulation of salt or other similar materials within purpose built cells is well understood and has been successfully accomplished in numerous industrial applications
- The design will comply with or exceed all applicable Australian and International Standards and Guidelines in relation to containment design
- Schematic below outlines the typical numerous barriers for both the base liner system and the capping system.



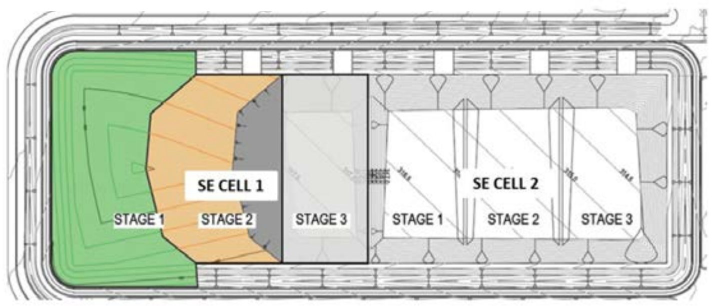
Encapsulation Cell Design – continued…

- The SE Cells will be developed in stages and will be hydraulically independent of each other and isolated
- This design approach allows for progressive construction, filling, capping and closure of each cell, minimising the impacts of rainfall and reducing to ALARP (As Low As Reasonably Practicable) the volume of internal salt leachate for extraction
- Refer below for schematic of progressive cell capping which aligns with well established national and state guidelines for landfill operations

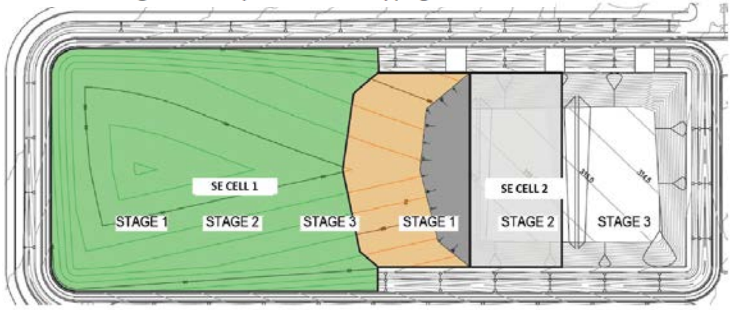
Phase 1 – Salt Placement within Cell1 – Stage 1



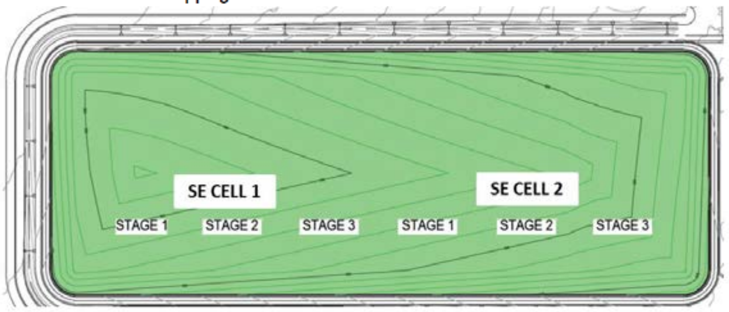
Phase 2 – Salt Placement in Cell 1 – Stage 2 – Capping of Stage 1



Phase 3 – Progressive Salt placement and capping

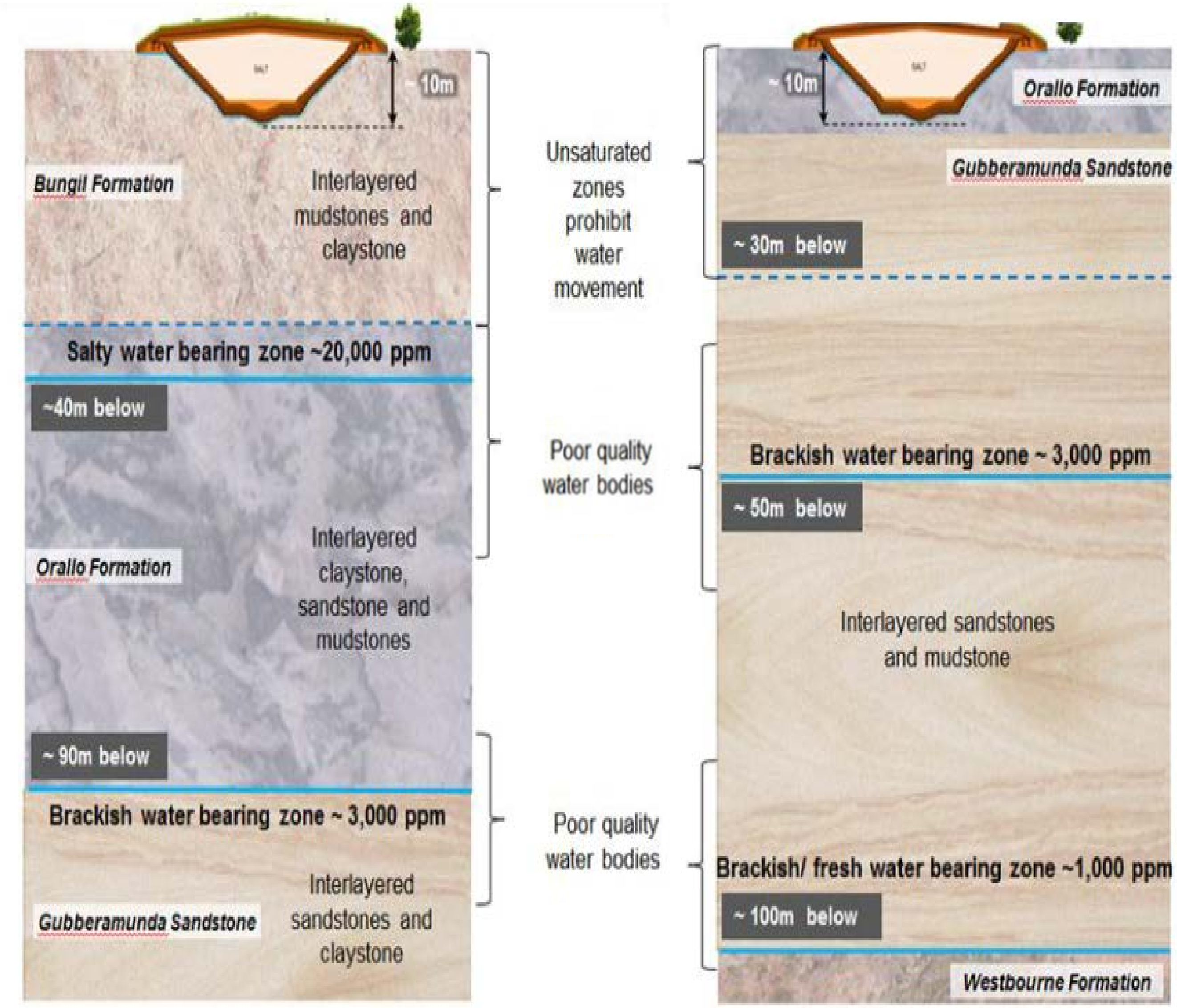


Phase 4 – Final Capping and Closure



Encapsulation Cell Design – continued...

- Site selection is a critical element to the success of the Salt Encapsulation Facility
- Crystallisation facilities should ideally be located in close proximity to the brine storage ponds, minimising transfer/transportation of liquid brine and utilities availability (power, gas etc.)
- Encapsulation Cells to be located outside of flood plains and consideration given to hydrogeological conditions (presence of ground water & ground conditions), environmental (flora & fauna) and cultural heritage constraints
- Below are examples of ideal site geology and hydrogeology conditions for siting of SE cells:



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Conclusion

- The approach of maximising desalinated water available for beneficial use, which has clear benefits and is supported by all stakeholders, also increases brine volumes as the water treatment process generates a brine waste stream that contains the salt removed from groundwater.
- Notwithstanding the need to manage brine and salt the desalinated water produced by the industry is in very high demand by landholders and communities.
- Over 40 gigalitres of water was provided by industry for beneficial use in 2016–17 and 83 per cent of this volume was used for irrigation.

Conclusion

- The brine by-product of the treatment process is currently stored in dedicated ponds that are designed, constructed and operated in accordance with strict standards with 14.7 gigalitres of brine storage capacity in place.
- Estimates of the total amount of salt in brine produced by the industry have declined significantly since original estimates were made in 2008.
- Total forecast salt volume was 15.4 million tonnes in 2008 and now stand at 6.1 million tonnes.
- The brine storage in place is therefore enough to hold brine produced until at least 2025, and several years more in most areas.

Conclusion

- The feasibility of each long-term management option as a whole of industry management solution has been assessed in accordance with feasibility criteria specified within government policies to determine a preferred option.
- Encapsulation in purpose-built facilities is the optimal option in the absence of regulatory change or a shift in community sentiment.
- Encapsulation facilities constructed off prime agricultural land, and either adjacent to brine ponds or within brine ponds that are no longer required for brine storage, or at a third-party regulated waste facility are the most viable/least impact whole-of-industry management solution.

A-3 Agenda and minutes of the Brine and salt management in the Queensland gas industry workshop (6 August 2019).

Meeting agenda:
Brine and salt management in the Queensland gas industry

Subject	Queensland Gas: End-to-end water use, supply and management Industry feasibility studies
Chair	Jackie McKeay, Department of Environment and Science (DES)
Meeting Type	Workshop
Date and location	6 August 2019 Arrow Energy Level 39, 111 Eagle Street Brisbane
Timing	2pm – 5pm (3 hours)

Invited

Name	Representation	Contact
Prof Andrew Garnett	UQ Centre for Coal Seam Gas (CSG)	a.garnett@uq.edu.au
Assoc Prof Phil Hayes	UQ Centre for CSG	phil.hayes@uq.edu.au
Dr Vahab Honari	UQ Centre for CSG	v.honari@uq.edu.au
Helen Schultz	UQ Centre for CSG	h.schultz@uq.edu.au
Matthew Paul	Australian Petroleum Production and Exploration Association (APPEA)	mpaull@appea.com.au
Derek Hannigan	Arrow Energy	Derek.Hannigan@arrowenergy.com.au
Tracey Lenz	Arrow Energy	tracey.lenz@arrowenergy.com.au
David Wigginton	Arrow Energy	
Mack Dreyer	Origin Energy	
Tony Hancox	Origin Energy	
Rachelle Willis	Origin Energy	
Trevor Robertson	Senex Energy	trevor.robertson@senexenergy.com.au
David Reinke	Shell	David.Reinke@shell.com
Joshua Millroy	Shell	Joshua.Millroy@shell.com
Jackie McKeay	DES – Regional and Regulation Support	Jackie.Mckeay@des.qld.gov.au
James Monkivitch	DES - Regional and Regulation Support	James.Monkivitch@des.qld.gov.au
April Hoyles	DES – Regional and Regulation Support	April.Hoyles@des.qld.gov.au
Clancy Mackaway	DES – Energy and Extractive Resources Assessment	Clancy.Mackaway@des.qld.gov.au
Tristan Roberts	DES – Energy and Extractive Resources Assessment	Tristan.Roberts@des.qld.gov.au

Roles and responsibilities

DES	• Workshop chair and industry regulator
APPEA	• Industry body and author of the report: Queensland Gas: End-to-end water use, supply and management
Industry representatives	• Undertook feasibility studies and contributed to APPEA report
UQ Centre for CSG	• Engaged by DES to undertake independent scientific peer review of APPEA report

Agenda

Item #	Description	Responsible	Timing
1.	Welcome, introductions and background	Chair	2:00 – 2:05pm (5 mins)
2.	Peer review: Intent, status, expectations for today	UQ	2:05 – 2:10pm (5 mins)
3.	Presentation on the options assessed	APPEA	2.10 – 2.30pm (20 mins)
4.	Updating feasibility assessments: • What are the strategies for quickly updating assessments to ensure they are based on current information regarding anticipated brine volumes and composition, technological developments, construction timeframes and costs?	Industry	2:30 – 2:55pm (25 mins)
5.	Critical decision dates (for each option): • Given expectations regarding option delivery timelines and brine storage capacity, what is the date when construction must commence for an option to remain viable? • Is there a combination of options that might extend the 'construction commencement deadline' in order to allow for technological improvements?	Industry	2:55 – 3:15pm (25 mins)
	- BREAK -		3:15 – 3:30pm (15 mins)
6.	Technical barriers • What are the major technical barriers for the options considered and are there any research opportunities that might address these?	Industry	3:30 – 3:55pm (25 mins)
7.	Current investigations • What current investigations/review are the companies (individually or collectively) undertaking?	Industry	3:55 – 4:20pm (25 mins)
8.	Further questions and discussion • Expectations of information request	UQ	4:20 – 4:45pm (25 mins)
9.	Confirm action items, responsibilities, delivery dates	Chair	4:45 – 4:55pm (10 mins)
10.	Conclusion and next steps	Chair	4:55 – 5:00pm (5 mins)

Brine and salt management in the Queensland gas industry

Workshop 6 August: Meeting notes

1. **Status of independent peer review process**

Ms Helen Schultz, Research Manager, Centre for Coal Seam Gas, The University of Queensland provided a short overview of the status of the peer review process, i.e.,

- A preliminary review of the Brine and salt management Section of the Appea report had been undertaken
- Questions identified through this review had been circulated by Department of Environment and Science prior to the meeting
- These questions mainly related to
    - understanding the assumptions that had informed the original studies, given that estimates of water and salt production had significantly reduced in recent years
    - factors influencing the economics of the various options
- the team had was in the initial phases of conducting a literature search to determine if there were any emerging technologies that should be assessed.

2. **APPEA presentation regarding major investigations**

Matt Paull provided an industry overview, which was followed by several industry experts providing summaries of each of the main salt and brine management/disposal options that had been considered by industry. Matt noted that the production of salt and brine was a result of the government policy that promoted beneficial use of the associated water from the CSG industry. A large volume of the treated water is now supporting irrigation and other agricultural uses. This form of use is highly valued by the agricultural sector, and a move away from this approach would be received negatively.
The following notes are additional information to that provided in the slide pack, and arose during the meeting discussions:

a) Selective Salt Recovery (SSR): Mack Dryer, Origin Energy

- The three CSG proponents involved in this assessment initially engaged four external companies to undertake an economic assessment of SSR products. Two were then selected to do detailed investigations (Veolia & a consortium).
- Industry spent approximately $60M on engagement with the companies as detailed above, and field trials.
- The preferred site for the SRR facility was identified as Bellevue (QGC)
- The market assessment included NaCl, $NaHCO_3$ and chlor alkali products
- The SSR process uses vacuum evaporation
- The pilot scale SSR process was successful based on the brine supplied at the time
- The chemical composition of the brine to be within a relatively narrow range in order to minimise waste generation
- Any liquid waste at the end of the process would be returned to the RO plant
- The solid waste is a combination of various other salts e.g. fluoride. This is also a potential contaminant for bicarb production.
- There are also issues with transport of the final product as the produced salts must be kept dry
- The market assessment was undertaken in 2012
- While SSR could produce Na_2CO_3 the market already had a large volume of stable suppliers. Production from the CSG SSR facility would be a relatively small volume with uncertain supply, therefore difficult to negotiate contracts in the overall market
- The economic costs detailed in the slides are for all costs i.e., capex and opex, but did not include pipeline costs which were estimated as an additional $230M
- The investigation was based on a feed of 3ML/day over 25 years.

b) Ocean outfall: Derek Hannigan, Arrow Energy

- Outfalls at three locations were considered. The northern outfall location was considered the most sensitive as it was located at the southern end of the Great Barrier Reef. There was no available dispersion modelling at this location
- The costs provided in the slides do not include costs of gathering pipelines from ponds to the start of the main brine pipeline
- The companies considered that community opposition to an ocean outfall proposal would be very high and that it would therefore be difficult to get the essential political support required to progress this option. In particular, legislative support would be required to secure the corridor. The pipline would also need to be designed to avoid areas where the matters of natural environmental significance (EPBC Act) applied
- The proposal did not involve any chemical treatment of the brine from the RO plant, however the brine be treated at Tugun desalination plant to meet the conditions imposed on the operator
- There was no detailed assessment of community attitudes towards outfall vs encapsulation. Companies consider that community issues associated with outfall are significant and are likely to have increased since the option was investigated.
- The Tugun outfall pipeline would involve acquisitions and there would likely be a tourism industry backlash against this proposal. Given the value of the Gold Coast tourism industry, and Tugun's proximity to the northern rivers region of NSW, the companies anticipate substantial community opposition in this area.

c) Brine injection: Paul Wybrew, Santos

- Brine injection was explored between 2008 and 2012
- Santos had approval for this and investigated disposal via deep injection wells (1.2 – 1.8m depth) at 2 locations
- Approximately $50M spent on investigations
- The studies concluded there was a need to create fractures or drill additional wells to dispose of the volumes due to the very low porosity. Have shared the results with other companies
- Arrow had also drilled an injection well, but didn't proceed after examining the core – the facilities are still in ground.
- Brine injection into depleted conventional gas reservoirs was also examined but considered unfeasible in dry reservoirs – this was based on a desktop assessment. Dr Vahab Honari (UQ) to meet with Santos Reservoir Engineers to discuss this further. UQ would also like a map of locations investigated and the reasons they were discounted.
- The group noted that in the event it was found technically feasible to inject into depleted conventional gas reservoirs, this would not be a sole management option as not all proponents have access.

d) Encapsulation: David Reinke, Shell

- A mixed salt crystalliser would be used to produce a solid salt for encapsulation. Sufficient water content would remain in the salt to prevent dust problems during handling.
- Depth to groundwater and groundwater quality are critical parameters considered in selecting sites for the Salt Encapsulation Facilities
- Companies are planning multiple facilities
- The WeKando facility is not associated with the industry
- Current brine storage is sufficient to hold brine until at least 2025 and possibly until the mid 2030s
- There's been lot of research into processes for making solid salt – all are very energy intensive. Less energy intensive processes would be of interest.
- Aspiration is to achieve geological stability of the encapsulated salt so that it won't breakdown and create problems. UQ CCSG to recirculate the report from the Compression and Recrystallisation of Salt project

- Encapsulation is proven technology and could be implemented without any trial
- Company preference is for the industry to encapsulate their own brine rather than work with an external facility where mixed wastes are encapsulated – considered easier to manage.

3. Additional discussion topics

a) Timelines to construction of disposal options

- Companies advise they need regulatory certainty to invest in people and facilities. They noted that they also get criticised for not having a plan. They have a plan, but their proposal to use encapsulation has not had final approval.
- Need to establish a timeline for revisiting the assessment to determine there are no better available options.
- For salt encapsulation, site closure, post closure monitoring and site relinquishment need consideration and a regulatory pathway.
- **Origin**
    - Aims to commence construction of encapsulation facilities around 2032 and to be operational in 2034
    - Site selection and final design to be complete 2030
    - Conducting an internal gap analysis in 2019
    - Origin Brine & Salt Strategy project is currently being defined
    - Brine ponds are relined every 20 years. There is capacity in the network to transfer brine between holding ponds to allow relining to occur
- **Shell**
    - Planning to commence the encapsulation facility in mid-2020s, likely operational by 2025.
    - Undertake an annual review of brine production to ensure that this timeline is appropriate
- **Arrow**
    - Brine ponds have a design life of 30 years. Brine disposal is in the longer term for Arrow, beyond timeframe of other operators.
    - Have notional location for the encapsulation site and understand the concentration options, but production is not at the point where there needs to be detailed investigations
    - Will look at combining with other companies
- **Santos**
    - Have undertaken a review of concentration technologies and a review of different providers
    - Working to optimise RO efficiency, including research at UQ re silica scaling
    - They are planning to maintain the brine storages to maximise their lifespan – a very expensive investment
    - Would like to see low-tech evaporation options that reduce the energy intensity of the process. The Futures Institute at University of South Australia is currently investigating a wicking system that may enhance evaporation without moving salt to the surface. However, has to demonstrate that it will work at the scale industry requires.

b) Some options for water use that do not produce brines already operation:

- Santos use some associated water directly for irrigation. This depends on concentrations of salts in associated water and on having sites with suitable soils. Water concept planning is customised to each field and companies use the full spectrum of the water quality guidelines.
- Origin is injecting water into the Precipice, but this is treated via RO first to match the water quality in the aquifer, and therefore is also creating salt.
- Santos has secured event based releases to water courses after flood events

c) Updating estimates and costs
- The studies undertaken by industry have been progressed over more than a decade and the impact of changing brine production estimated volumes and economic costs should be considered.
- Companies considered that while estimates of brine volume had decreased, this was unlikely to have a large impact on the size of plants or operational costs
- Costs associated with the SSR option cannot be easily updated as there were a lot of confidentiality provisions around the proposals and costings developed by the external companies. Suggestion to broadly pro-rata costs based on revised brine production and construction / energy inflation.

d) Combinations of management options
- Companies prefer one identification of one management/disposal option as each additional management option significantly increases cost and also management complexity
- Companies emphasised that the SSR option would still require encapsulation facility/ies to deal with the waste from the SSR process. This waste would also include chemical additives used in the SSR process, that would not be present where encapsulation is the only management option.

Actions:
1. APPEA to coordinate industry responses to the UQ questions circulated by DES.
2. Dr Vahab Honari to meet with Santos reservoir engineers to gain a better understanding of why injection into depleted gas reservoirs was considered unfeasible.
3. UQ CCSG to circulate the final report from the Compression and Recrystallisation of Salt

A-4 APPEA response to the DES data request

APPEA coordinated an industry response to the DES data request and this is shown in Table 4.

Table 4 APPEA response to the DES data request regarding Section 6 of Queensland gas: end-to-end water use, supply and management

Overarching questions	1. For each option considered please provide details (where available) of: a. Brine volumes considered in the feasibility assessment b. Estimated energy consumption and carbon emissions c. Construction timeframes d. Any assessment of how field storage structures can be used to provide consistent feed of brine volume to treatment/disposal options e. Any recent reviews of assessments to take account of changed brine estimates or changes in technology 2. Also please provide current estimates of water, salt and brine production for comparison purposes	**Ocean Outfall:** a. Various options between 14 and 45 ML/day b. Energy consumption was estimated to derive pumping costs, however only the costs appear to have been explicitly presented. c. 3.5 years from end of feasibility stage d. N/A e. N/A: pipeline was ruled out for reasons other than volume or technology limitations. **Salt encapsulation** a. Total salt quantity for QGC salt encapsulation facility (SEF) option is described below. b. Not assessed. c. Construction timeframe for the QGC SEF would be approximately 2 years. d. The brine ponds are very large structures – QGC brine ponds range from 1,100ML – 1,300ML. There will be relatively consistent feed by the very nature of this large volume. Over time it is expected that the brine composition will slowly change i.e. increase in concentration of various elements such as TDS etc. however plant design is expected to be sufficiently robust to accommodate these changes. e. At QGC a thorough subsurface and brine modelling exercise is completed on an annual basis and this forecast is regularly checked against actual produced brine volumes. This review has identified a current

		estimated salt volume for the life of the QGC project of approximately 1.4 million tonnes. f. This reduced salt quantity has been considered and a SEF remains the current base case technology. **SSR** a. Total volume of brine: 12,000 ML b. Energy consumption: 85,000 - 90,500 MWh pa of electricity (assumed supplied at the boundary of the SSRF) and 1.1 million GJ pa of natural gas Carbon emissions: 150,000 tonnes per annum of CO2 equivalents c. 3 years, Design, regulatory approval and procurement process: adds a further 2 years. Timeframe provided only for construction and commissioning period. Refer to SSR option schedule provided. d. SSR feed pond: 40ML to buffer incoming brine Approximately 13 days buffer storage capacity Based on 3ML per day SSR facility. APLNG is progressing with access to final Pre-FEED submissions which may have addressed this requirement. Vendors where requested to identify departures from design envelope and any alternatives to improve outcomes. It is uncertain whether buffer storage sizing was considered. e. Each year, APLNG updates the Development Plan and Restoration provision to take into account changes to forecasted water and brine. Brine estimates have reduced but not to the extent that the current strategy would change. To date, there have been no notable changes in technology that have warranted a review of the existing strategy. APLNG are often approached by vendors with brine concentration technologies. These are reviewed however, no technology has triggered a review for the strategy.

			2. The latest figure for salt production is 8.1 million tonnes which is unchanged since the APPEA report was produced. Total water production according to the 2019 OGIA UWIR is forecast at 2,346 GL. We do not have an industry forecast for brine production but one could be produced.
Management Option	**Key reports to discuss**	**Topics/questions**	
Selective Salt Recovery (SSR)	Selective salt recovery (QGC, APLNG, Arrow, 2011)	1. Brine specifications (SSR processing requirements and expected RO output range) 2. Expected composition and volume of other waste streams 3. Technology provider caveats regarding salt purity, production volumes and equipment reliability 4. Market assessment report	1. Refer to SSR Pre-FEED Brine Specification (August 2013) Base case SSRF treatment capacity of 3ML per day with option to expand to 4.8ML per day also considered. 2. 25,000-40,000 tonnes per year of solid regulated waste 2ML per day of product water. Technical documents suggest that potential vendors submissions indicated the optimal waste production of 10-16% of the overall solids input to the SSRF. Technical documents refer to other operational wastes such as sewage, domestic waste, parts and fluids from operation and maintenance activities. APLNG has requested access to Pre-FEED submissions which may provide additional detail with respect to quality of solid regulated waste, product water and other waste stream quality. 3. [Note – The information below is only a high level summary of the potential vendor Pre-FEED submissions. APLNG is still progressing release of commercially sensitive documentation that may add additional information and/or provide clarification to the information provided.] • Separate pre-treatment testing on CSG brine indicated that all impurities could be dramatically reduced including boron, organics, fluorides, silica, potassium, sulphates and barium. Only fluoride was not able to be reduced

			below that level at which the SSR could produce merchantable soda ash. • Potential vendors noted that whilst the technologies utilized within the proposed process flow scheme were proven in their own right, their use in this application and on this particular feed source would be considered a first-time application and therefore unproven at a commercial scale. • Proposals for a full scale SSRF was based on the production of high silica sodium carbonate and sodium chloride. It was noted that the SSRF may be able to be upgraded to produce low silica sodium carbonate or sodium bicarbonate but this would depend on the outcomes of further pilot and other testing confirming that impurities could be reduced to acceptable levels. • Potential vendors identified concerns on the potential impact of certain impurities such as bromine on sodium chloride product quality and merchantability, particularly in regards to the global chloralkali industry. It was also noted that sodium chloride had the lowest value of the potential products and would provide a significant negative return. • Potential vendors indicate that the most challenging aspect was the uncertainty and variability of the brine over the field life in terms of flow and chemistry. It was further noted that the variability was further accentuated by fundamentally different brine chemistry ranging from “high carbonate/low chloride” to “high chloride / low carbonate” across the CSG fields. • At the time of potential vendors' submission, an attempt to achieve saleable product with right product quality over a wide range of brine chemistry and reducing waste

			at the same time had resulted in a complex and expensive process design. 4. Market assessments were undertaken in 2003 (Stratum Resources) and 2012 (Evans&Peck). The 2012 SSR market assessment report has been located however, as with a lot of work that was done on this project, there are confidentiality issues. APLNG have organised the relevant information UQ would be able to come and view the reports on request.
Injection	Company reports Fairview Brine Injection (Santos), Large scale brine storage (Santos), permeate injection to Precipice Sandstone (APLNG), Depleted coal seam injection study (Santos), Brine injection (APLNG), Roma brine injection trial (Santos)	Please provide a table summarising the findings for the sites investigated by individual companies – location, data availability, reason/s for unsuitability	Range of contributing observations/concerns: Technical: • Pine Ridge is the largest conventional reservoir proximity of existing water treatment facilities / brine ponds. A field trial was proposed but rejected on technical grounds: “Water relative permeability endpoints of 0.15 won’t allow for injectivity at economic rates” • This is supported by field observations - conventional gas well workover / remedial works had observed effectively zero mud losses when open to the fully depleted reservoir. Even with many 100s of metres of effective head pressure, the loss observed in 5 wells in Pine Ridge reservoir recorded effectively zero m3/day of mud loss. By comparison, mud losses of many 100’s m3/day have been recorded in depleted CSG reservoirs in Fairview. • This is supported by field observations – in order to enhance gas injection rates for underground gas storage, well stimulation activities had to be undertaken using nitrogen gas, not water based stimulation fluids. This approach was designed to avoid reducing the permeability of the reservoirs.

			Commercial: • CAPEX Pine Ridge trial risk was high. In the order of $10-15M to set up a field trial – with no to limited potential for success (based on the above). • The conventional reservoirs are small and isolated from one another. This means depletion (and therefore injection) in one reservoir does not carry over between reservoirs. And only the largest reservoirs, not already in use for gas storage, could be considered as options. • The three largest, available reservoirs were approx. 25-30km from water treatment / brine storage facilities – further adding considerable cost. Environment / commercial: • Uncertainty about the cost and feasibility of monitoring to demonstrate subsurface containment – the target conventional reservoir would be the Precipice Sandstone, a regionally important aquifer.
Ocean outfall	Ocean outfall assessment (Santos, 2011) Ocean outfall (APLNG, 2013)	1. Did individual ocean outfall assessments by APLNG and Santos consider alternate sites to Tugun? 2. Did any of these reports include an assessment of the regulatory regime relating to ocean disposal? 3. Was there any assessment of pre-treatment requirements?	1. APLNG considered Agnes Water. Santos considered Port of Gladstone, Luggage Point as well as Tugun. 2. Yes – approval requirements were considered in the multi criteria analysis. 3. Pipeline corrosion and scaling issues were considered as part of the multi criteria analysis. An assessment of seawater diffuser feasibility was also undertaken. No specific brine pre-treatment requirements were identified at the feasibility stage. **ADDITIONAL INFORMATION** The following locations were considered for ocean outfall by CSG proponents:

			• Gladstone Harbour (Arrow) • Agnes Water (APLNG) • Luggage Point (Arrow) • Tugan (via the Gold Coast Desalination Plant) (Arrow) • Existing seaway discharge systems within the region such as the upper Brisbane River. (Arrow) **Agnes Waters** Due to the existing water quality issues and potential cumulative impacts with Gladstone Harbour ocean outfall location, APLNG engaged ParsonsBrinkerhoff to undertaken an assessment for the potential ocean outfall to be located at the proposed Agnes Water desalination plant. The Agnes Water location was considered as a potential ocean outfall location for the following reasons: • The location south of Gladstone allowed the majority of the total pipeline route to Gladstone to share the gas pipeline corridor. • Whilst the location was within the Great Barrier Reef Marine Park, it was one of the few open coastal locations close to Gladstone that falls within the General Use zone of the park. • There was good background information available for a potential discharge at Agnes Water based on previous works undertaken for the Agnes Water desalination plant. • Site provided an open coastal ocean outfall alternative to Gladstone Harbour. The key findings and conclusions from investigations of this location were as follows: • Initial assessment indicated that Chinamans Beach at Agnes Water may be a suitable location to discharge brine.

			• Extensive additional work would be required to confirm this, in particular: o Assessment of alternative coastal discharge locations would need to demonstrate that Agnes Water was the optimal discharge location. o Initial dispersion modelling showed that likely parameters of concern are likely to include ammonia, nitrate, aluminium and copper (even with dilution of brine of ratio of 1 in 10 prior to discharge). o The brine chemistry and concentration would need to be confirmed as this would impact on the dispersion modelling methodology as well as the results. o Full 3D near-field and far-field dispersion modelling would be required to confirm mixing zones. o An assessment of the viability and cost of removal of non-compliant brine constituents would be required.
Salt encapsulation	Collaboration agreement (APLNG, QGC, Santos, 2015) (- this is an assumption) Brine transfers between proponents, 2015 Western & eastern encapsulation options, 2015	1. Overview of operational modifications needed to cater for variations in brine feed composition/volume 2. Any specific assessment of brine only or multi-purpose waste facilities 3. What were the site selection criteria? 4. What are the physical sizes (land area, containment capacity) of facilities in the different options? 5. What is the proposed long-term management strategy?	1. Limited operational modifications are envisaged as the process is very robust as it is effectively a distillation process, stripping the water out of the brine. 2. No, the assessment has contemplated that the encapsulation cells would be dedicated for salt storage as opposed to mixed waste storage. 3. The key site selection criteria were: o Site elevation at least 1m above Q100 flood plain. o Groundwater levels at least 20m below ground surface.

			o Not located directly above an area where the uppermost aquifer is of drinking water quality and useable quantity. o Located outside environmentally sensitive areas (ESAs), cultural heritage constraints, and any existing or proposed infrastructure. o Proximity to brine storage ponds, minimising transfer / transportation of liquid brine, and utilities availability (power, gas, etc.). 4. The salt encapsulation facility required for QGC would have an estimated processing plant footprint of approximately 3-5 hectares with a cell storage footprint of approximately 10-15 ha. The required area relates to a containment capacity of approximately 1.4 million tonnes for QGC. Additional pro-rated area would be required for the other operators' facilities. 5. The encapsulation cells would be progressively filled and capped as the salt is produced over the life of the project. The cells would be designed to comply with or exceed all applicable Australian and international standards and guidelines in relation to containment design. The containment cells would require monitoring to confirm ongoing integrity. Site selection to avoid sensitive environmental areas and hydrogeological conditions would minimise the risk of any future intervention being required.
Other reports	1. Acid regeneration trial (APLNG, 2012)	Please clarify scope of these reports and their relationship to the collaborative studies discussed in the APPEA paper.	1. Acid regeneration - 2. Arrow's Brine Concept Assessment brought together all of the relevant separate brine studies to determine the proposed brine management solution for Arrow's SGP

	2. Brine concept assessment (Arrow, 2013) 3. Salt plant concept study (Arrow, 2015) 4. Integrated water balance developed (collaboration, 2015) 5. Brine and salt feasibility study (Arrow, 2016) 6. Longstraws trial (APLNG, 2017) 7. Industry salt working group (collaboration, 2017)		development and documented the outcomes of Arrow's MCA 3. Arrow's Salt Plant Concept Study documents a conceptual design for a waste salt plant (i.e. brine crystalliser to produce solid salt for encapsulation) for the SGP development 4. Integrated water balance - 5. Arrow's Brine and salt feasibility study was an assessment of brine and salt management options for Arrow's existing operations. The preferred option was waste salt plant and encapsulation. 6. Longstraws trial – This was the opportunity to trial a 'super salt sucking sorgham' species. This species had shown good uptake of salt in laboratory trials without impacting yield. The species is overseas and only a very small quantity of seed was available. This trial was not progressed due to the Australian quarantine requirements deem that the seed be sent to another 'quarantine safe country' and grown before being sent to Australia. 7. Industry salt working group – this was the precursor to the End to End Water Management report provided to DES and UQ.

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A-5 Coal Seam Water Composition

Table 5 Typical coal seam gas co-produced water quality for data collected from across Australia and typical guideline values (© Copyright, SKM 2011; ANZECC/ARMCANZ 2000). Reproduced from Co-produced water – risks to aquatic ecosystems, Background review, Commonwealth of Australia 2014.

Water quality variable	Unit	Min	Max	Guideline trigger value range	Guideline description from ANZECC 2000
TDS	mg/L	200	10000	1000	Recreation
SAR	mg/L	16	567	2-102	Primary industries (irrigation)
Temperature	C	22	32	20th-80th percentile	Aquatic ecosystems
pH	pH	7	9.1	6.5-9.0+	Aquatic ecosystems
EC	µS/cm	200	16000	30-5000+	Aquatic ecosystems
SS	mg/L	9	2669	<40	Primary industries (aquaculture)
Colour (Apparent)	PCU	125	340		No guideline recommended
Colour (True)	PCU	5	14.5		No guideline recommended
UV Transmission @ 254nm	%	99.7	99.98		No guideline recommended
Turbidity	NTU	230	935	0.5-200+	Aquatic ecosystems
Total Hardness as $CaCO_3$	mg/L	39	185	500	Recreation
Hydroxide Alkalinity as $CaCO_3$	mg/L	0	1		No guideline recommended
Carbonate Alkalinity as $CaCO_3$	mg/L	36.5	600		No guideline recommended
Bicarbonate Alkalinity as $CaCO_3$	mg/L	580	8200		No guideline recommended

Water quality variable	Unit	Min	Max	Guideline trigger value range	Guideline description from ANZECC 2000
Total Alkalinity as $CaCO_3$	mg/L	899.5	1460		No guideline recommended
Sodium	mg/L	35	4500	3000	Recreation
Calcium	mg/L	0.5	49	1000	Primary industries (stock watering)
Magnesium	mg/L	0.7	16	2000	Primary industries (stock watering)
Iron	mg/L	1	25	0.2-10	Primary industries (irrigation)
Barium	mg/L	1	10	1	Recreation
Chloride	mg/L	150	2500	400	Recreation
Sulphate	mg/L	1	10	400	Recreation
Silicon	mg/L	7	20		No guideline recommended
Potassium	mg/L	1	300		No guideline recommended
Boron	mg/L	0.05	3.1	0.37	Aquatic ecosystems
Aluminium	mg/L	0.01	0.3	0.055[#]	Aquatic ecosystems
Arsenic	mg/L	0.001	0.0065	0.013	Aquatic ecosystems
Beryllium	mg/L	0.001	0.001	0.1-0.5	Primary industries (irrigation)
Cadmium	mg/L	0.0001	0.0002	0.0002	Aquatic ecosystems
Chromium	mg/L	0.005	0.3	0.001	Aquatic ecosystems
Copper	mg/L	0.001	0.2	0.0014	Aquatic ecosystems
Lead	mg/L	0.001	0.2	0.0034	Aquatic ecosystems
Manganese	mg/L	0.004	0.3	1.9	Aquatic ecosystems
Nickel	mg/L	0.0001	0.003	0.011	Aquatic ecosystems

Water quality variable	Unit	Min	Max	Guideline trigger value range	Guideline description from ANZECC 2000
Selenium	mg/L	0.001	0.01	0.011	Aquatic ecosystems
Zinc	mg/L	0.005	0.15	0.008	Aquatic ecosystems
Bromine	mg/L	1	12		No guideline recommended
Mercury	mg/L	0.0001	0.001	0.0006	Aquatic ecosystems
Silica	mg/L	15.6	20		No guideline recommended
Fluoride	mg/L	0.4	5.9	1-2	Primary industries (irrigation)
Nitrite and Nitrate as N	mg/L	0.01	0.01	0.005-0.2	Aquatic ecosystems
Sulphide	mg/L	0.1	0.1	0.05	Recreation
TOC	µg/L	2000	3900		No guideline recommended
C6-C9 Fraction	µg/L	20	20		No guideline recommended
C10-C14 Fraction	µg/L	50	50		No guideline recommended
C15-C28 Fraction	µg/L	100	100		No guideline recommended
C29-C36 Fraction	µg/L	50	113		No guideline recommended
1,2-Dichloroethane-D4	µg/L	118	120	ID	Aquatic ecosystems
Toluene-D8	µg/L	94.6	98.22	ID	Aquatic ecosystems
4-Bromofluorobenzene	µg/L	99.2	102.9		No guideline recommended

+ - specific guideline depends on geography (southeast Australia, tropical Australia, southwest Australia, south central Australia), receiving environment (upland river, lowland river, freshwater lakes and reservoirs, wetlands) or beneficial use.

ID - insufficient data to determine guidelines.

- dependent on pH.

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