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Treatment of coal seam gas produced water for beneficial use in Australia: A review of best practices

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ABSTRACT

There has been an exponential increase in both the production and exploration of coal seam gas (CSG) in Australia and many other regions in the world. A major issue associated with the production of CSG is the management of produced water. CSG is usually mixed with water in the coal seam, to recover the gas, the water must be first extracted from the coal seam to reduce pressure. This water — known as co-produced water or CSG water — is typically quite saline, large in volume and may contain heavy metals and other trace elements of concern. The management of this produced water is of paramount importance to the oil and gas industry. This paper reviews the key characteristics of CSG water and its possible beneficial uses. A specific focus is on the role of reverse osmosis (RO) membranes in the treatment of produced water for beneficial uses or safe discharge into the environment. Recent examples involving the use of RO membranes for the treatment of produced water are systematically summarised and discussed. Opportunities and challenges associated with sustainable management of produced water currently presented to the water industry are also highlighted and discussed in detail.

Keywords: Reverse osmosis; Produced water; Coal seam gas (CSG); Coal bed methane (CBM); Saline water

1. Introduction

Coal seam gas (CSG) — also known as coal seam methane or coal bed methane — is mainly constituted of methane adsorbed onto underground coal seams, originating from biogenic (attributed to biological activity), thermogenic (generated when coal is subjected to high temperature and pressure), and metamorphic (generated during coal formation) sources [1]. As a result, CSG can be readily liquidified into liquefied natural gas with very little processing for the removal of minor inert gases such as carbon dioxide and water vapour [2,3]. Since coal has a large internal surface area, a typical coal seam can store a significant volume of methane gas, often six to seven times of that by a conventional natural gas reservoir of equal volume in a rock formation [4]. Unlike most natural gas reservoirs, much of the coal and therefore, much of the CSG lies at shallow depths, making CSG an attractive energy resource [4]. In addition, CSG exploration results in virtually no negative impact on future mining of the coal seams [2].

Early attempts to extract CSG dated back almost three decades, initially stimulated by energy shortages and substantial tax concession by the US government [2]. By 1994, CSG production in the US had become a major industry with production growing exponentially [2]. CSG

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reserves have been identified in many other parts of the world (including Canada, Russia, China, South Africa and Australia) [2,5,6]. Although active CSG exploration in these countries remains limited, Australia is a notable exception [2,3,7]. The first commercial production of CSG in Australia was achieved by BHP in early 1996 at Moura (eastern part of the Bowen Basin) with a production volume of 4 terajoules (TJ) [2]. Since then, there has been an exponential increase in both the proved and probable (2P) reserves and production of CSG in Australia (Fig. 1) [2,8]. The Surat and Bowen basin account for more than 90% of the total 2P CSG reserves in Australia [7,8]. CSG has also been found in several other basins including the Gloucester, Sydney, Gunnedah, and Clarence-Moreton basin [2,7]. By the end of 2008, the 2P reserves of CSG of the Surat and Bowen basin alone amount to 15,714 petajoules (PJ) while production has increased to 133 PJ, representing more than 80% of the Queensland gas market [2].

2. CSG water management

2.1. Characteristics of CSG water

The production of CSG entails numerous technological and environmental challenges [2,6,9–11]. Most coal seams also act as underground water reservoirs with water permeating the coal bed, the water is well mixed with the methane and its pressure traps the methane within the coal. The extraction of CSG involves the reduction of pore pressure by pumping the water from the deep confined aquifer above and within the coal seams to the surface, allowing the methane gas to desorb from the coal. This water is essentially groundwater and is often referred to as CSG water. The rate of water production during the dewatering phase of CSG production at the beginning of the operation is usually high then decreases over time. On the other hand, CSG production increases and reaches a stable production stage followed by a decline stage. In general, water production can last for approximately 15 years, depending on the actual geological formation [2,4].

The volume of water generated from CSG production presents a unique challenge to the water industry. In 2007, according to the Department of Infrastructure and Planning, 12.5 gigalitres (GL) of CSG water were produced in Queensland [12]. If the CSG industry continues to supply gas to the Australian domestic market, it is estimated that the Surat Basin alone will produce an annual average of 25 GL of CSG water for the next 25 years. CSG is usually saline, sodic, dominated by bicarbonate content, with a high sodium adsorption ratio (SAR) and as a result CSG water needs to be managed carefully. The quality of CSG water varies greatly, depending on the depth of the coal bed and the origin of the water entering the coal. Typical ionic composition and characteristics of CSG water from several well known basins are presented in Table 1. The total dissolved solids (TDS), generally defined as dissolved salts and other materials that can pass through a 2 μm filter, can be as high as 170,000 mg/L as recorded in western USA [13]. The TDS of the CSG water is dependent upon several geological factors such as the depth of the coal bed, the composition of the rocks surrounding the coal beds, the amount of time the rock and water react, and the origin of the water entering the coal beds. Typical TDS values of CSG water in Australia are in the range from 1,000–6,000 mg/L which is comparable to brackish water (Table 1). Trace element concentrations in CSG water are commonly low. In a comprehensive survey conducted over the 2003-2005 period, Jackson and Reddy examined the concentration of 13 trace elements in the Powder River Basin CSG water [14]. These trace elements include iron (Fe), aluminum (Al), chromium (Cr), manganese (Mn), lead (Pb), copper (Cu), zinc (Zn), arsenic (As), boron (B), selenium (Se), molybdenum (Mo), cadmium (Cd), and barium (Ba). These authors found that most

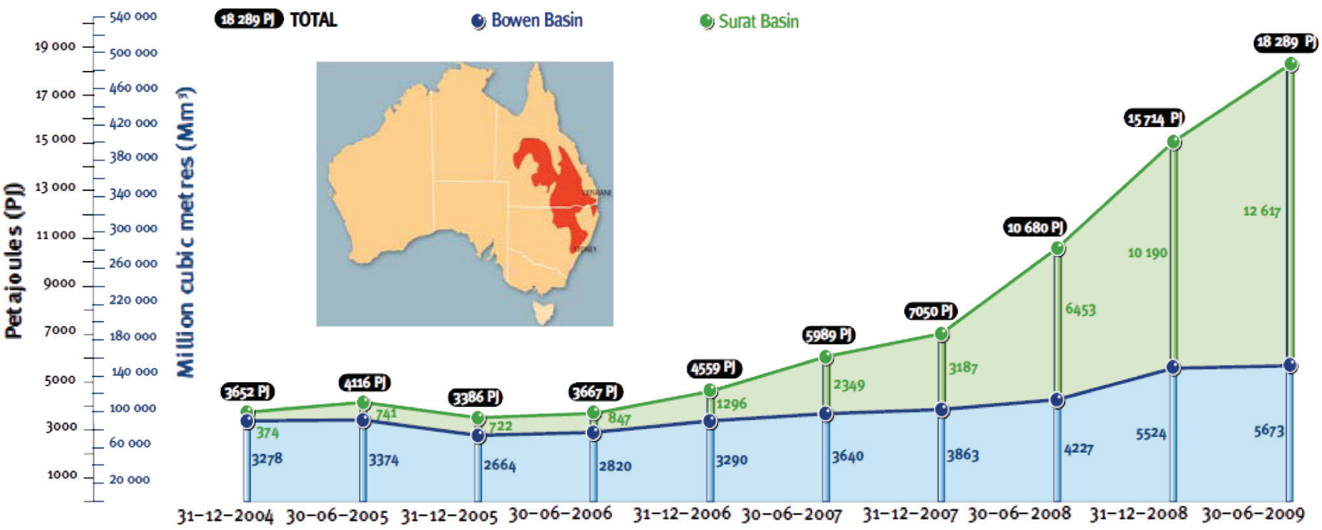

Fig. 1. Eastern Australia CSG exploration and development potential (From [8]).

Table 1
Ionic composition and other characteristics of CSG water [16–18]

Parameter	Surat Basin, Australia (Basin wide)	Surat Basin, Australia (Tipton)	PRB, USA (47 samples)	PRB, USA (Mitchell Draw)	Walsenburg, USA	Waterberg, South Africa
pH	8–9	7.6–8.9		8.2	8.41–8.52	7.8
TDS, mg/L	1200–4300	4500–6000	370–1940	3460	588–722	5125
SAR, $meq^{-0.5}$	107–116			25		85.4
Sodium, mg/L	300–1700	1840–3461	130–800	880	250–314	2023
Potassium, mg/L				35.2	1.2–1.3	16.5
Magnesium, mg/L				14.6	0.01	10.4
Calcium, mg/L			5.9–57	28.0	1.7–2.4	25.1
Chloride, mg/L	590–1900	2060	6.3–64	28.4		287.1
Sulphate, mg/L	5–10	2	0–12	1.0		418
Bicarbonate (as $CaCO_3$), mg/L	580–950	1030	290–2320	2416		4712
Iron, mg/L		0.07–4.50				0.99
Manganese, mg/L		0.07–0.10				0.3
Silica, mg/L				12		
Fluoride, mg/L		0.77–1.00		1.0		4
Boron, mg/L				0.2	0.21–0.26	

CSG water samples exceeded the aquatic life criteria for Al and Cu [14]. In addition, based on secondary water quality standards of the US, many CSG water samples contain higher levels of Al and Fe than the drinking water standards [14]. Nevertheless, concentrations of all other trace elements were sufficiently low and would not possess any significant risk to aquatic life [14,15]. Unlike co-produced water obtained from oil and conventional gas fields, the organic content of CSG water is usually low. An earlier study reported by Rice et al., [16] also confirmed the absence or negligible occurrences of most trace elements in CSG water from the Powder River Basin. Concentration of all volatile organic compounds in CSG was is typically less than 1 mg/L [16]. It is, however, prudent to note that data about the occurrences of trace elements and organics in CSG water remains very scarce. Comprehensive monitoring exercises would be necessary to ascertain the occurrences of trace element and trace organics in CSG water from each geological formation.

In general, without any treatment or amendment, CSG water is often not suitable for direct surface discharge or irrigation [5,19]. Most ions enhance the aggregation of soil particles, in contrast however, sodium causes soil particles to disperse, particularly if the soils contain montmorillonite clays. Consequently, water with high sodium content can result in surface crushing and soil structure breakdown, ultimately leading to a lower soil hydraulic conductivity or a reduction in the rate of water filtration [5]. The effect of dissolved sodium on soils is commonly assessed using SAR, which can also be referred to as the sodicity of the soil water. The relationship amongst SAR, salinity (measured by conductivity) and the risk of soil structure damage is presented in Fig. 2. The elevated SAR levels often at moderate TDS values of CSG water can potentially be detrimental to soil structure and plant growth (Fig. 2). In addition, high bicarbonate content can also affect plant growth through a decrease in the solubility of nutrients, which is caused by the increase of pH associated with increasing concentrations of carbonates [5].

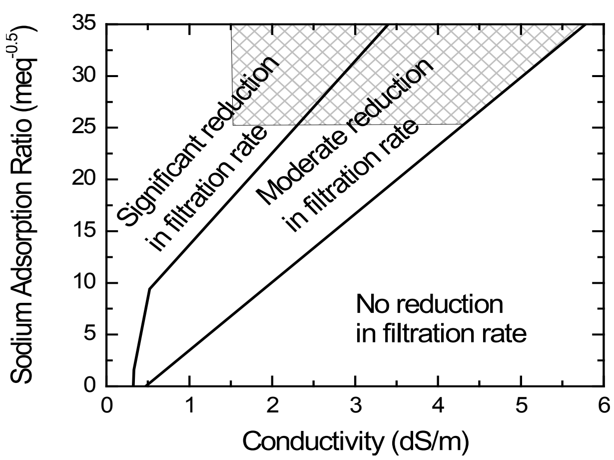

Fig. 2. Influence of SAR and salinity of irrigation water on long term soil degradation. Shaded area shows the region of typical SAR and salinity values of untreated CSG water [17,18,20].

2.2. Beneficial uses of CSG water

CSG water cannot be reinjected to the producing formation to enhance recovery as happens in many oil fields, thus effective management of the water is essential for the sustainable production of methane. Given the moderate salinity and highly sodic nature of CSG water, treatment is often required prior to its surface discharge or beneficial use. Indeed, there is a significant scope for the treatment and beneficial uses of CSG water, which in water scarce regions can be considered as a value resource. The key options available for the management of CSG water include surface discharge, underground injection, impoundment with no reuse (evaporation or recharge) and beneficial uses. In the Western United States, direct surface discharge and underground injection have been the dominant approach towards CSG water management [9]. Nevertheless, this approach is increasingly considered as an inappropriate use of a water resource. In fact, the regulations for surface discharge of CSG water in the US are becoming more stringent, with the ongoing study of US EPA effluent guidelines and adoption of watershed or general discharge permits in different states [21]. In Australia, impoundment in the form of evaporation ponds has accounted for most of the current CSG water being produced. In early 2009, the Queensland Government released a discussion paper outlining its position with regard to the management of CSG water [22]. It considered that the current use of evaporation ponds as a primary CSG water management option presents significant ecological risks to landscapes, shallow aquifers, and nearby water bodies, particularly when considering the likely expansion of the CSG industry. Furthermore, this approach would not maximise beneficial use of CSG water. The preferred option is to tighten the current requirements with respect to the management of CSG water to achieve more environmentally sustainable outcomes and better utilisation of the water resource [22]. As a result, the Queensland Government has decided that evaporation ponds would be discontinued as a primary means for disposing of CSG water. However, it would allow limited use of evaporation ponds necessary for water aggregation and the storage of brine from treatment facilities provided that these ponds are fully lined to a standard determined by the authority [22]. Overall, with rapid expansion and increasingly stringent regulations, the management of CSG water presents a major challenge to the CSG and the water industries in Australia, particularly in Queensland and some parts of New South Wales.

CSG production often occurs in water stress areas and there exists a range of beneficial uses of this water in Australia [18]. These include aquaculture, coal washing, industrial operations, irrigation, feedlots watering and as potable water for human consumption [12,18]. The challenge is however to identify treatment processes capable of meeting the water quality requirements of these beneficial uses. Many large scale inland aquaculture operations exist in Australia cultivating a variety of marine finfish, crustacean and shellfish [23]. Recent studies suggest that, with adequate amelioration techniques, CSG water can be suitable for use in many of these inland fisheries [12]. For example, it has been shown that both barramundi and mulloway can achieve commercial growth and survival rates with simple and inexpensive amendment of potassium and calcium levels [23]. Further treatment may be required if the CSG water contains high levels of specific constituents such as fluoride that are unfavourable for fish production [12]. The applicability of this option depends on the location of existing aquaculture operations or the potential for new operations.

Since open cut mines or coal washeries may locate in the vicinity of CSG operations, the coal industry has been identified as a potential user of CSG water. However, this option is limited by the high cost of transporting the water from CSG production areas to active coal operations. Furthermore, the rate of consumption of CSG water is limited as it must not exceed the requirements of the mine for coal washing and preparation. In addition, drainage from coal washing and preparation operation must be captured within the mine site for containment or treatment prior to environmental discharge.

Industrial uses of CSG water may vary widely and can include activities such as salt recovery and cooling water. In general, high quality water with low scaling potential is required for cooling towers and extensive water treatment would be required even for sources of relatively high quality such as surface water.

Irrigation has the potential to be a major use of CSG water. However, it also presents one of the most complex challenges related to the management of solids, waters and landscapes. Direct irrigation of CSG water without adequate treatment or amendment to lower salinity and the sodium adsorption ratio can lead to long term and sometimes permanent degradation of land. According to the Queensland Department of Environment and Resource Management, parties proposing to use CSG water for irrigation should engage professional advice and assistance in order to understand and manage site specific soil-water interaction, agronomic, monitoring, and irrigation management issues [12]. Amongst a range of criteria applying to the general approval for beneficial use of CSG water for irrigation purposes, the maximum salinity, SAR, and bicarbonate ion concentration (as $CaCO_3$) must not exceed 3,000 μS/cm (TDS of approximately 1,500 ppm), 8 $meq^{-0.5}$, and 100 mg/L respectively [12]. In most cases, desalination technologies must be employed to achieve these minimum standards for beneficial use of CSG water for irrigation.

Livestock can tolerate high levels of dissolved salts of up to 5,000 mg/L without any side effects. It appears that in general the quality of CSG water may be appropriate for livestock watering. Major issues associated with the use of CSG water for livestock watering are the availability of intensive feedlot operations in the vicinity of CSG production areas and the regulatory requirements on use and discharge of resulting wastes. In addition, at its best, livestock watering can account only for a small portion of the total CSG water produced.

Potable water supply is another potential beneficial use of CSG water, however, in most (if not all) cases, desalination technologies must be employed to satisfy the Australian Drinking Water Guideline recommended value for TDS of less than 500 mg/L in potable water. In addition, since the water can be used for human consumption, detailed characterisation of CSG water will be required. Such characterisation is likely to include comprehensive screening for the occurrence of trace organics and trace elements.

In addition to the beneficial uses of the treated water, the recovery of salt can further offset the cost of CSG water treatment. CSG water appears to be rich in sodium chloride and relatively lean in most other minerals, hence, it represents a significant potential for the production of sodium hydroxide and other sodium related chemical products. In fact, the potential of salt production from the brine stream of desalination plants has been demonstrated in the literature [24,25].

3. CSG water treatment

3.1. Selection of treatment technologies

Given the high SAR and salinity nature of CSG water, beneficial use of this water resource is unlikely without some form of treatment or amendment. The former refers to an active treatment process for the removal of salinity, particularly sodium chloride. The latter refers to the addition of chemicals such as calcium and magnesium to lower the SAR level, thus rendering the water suitable for irrigation. However, amendment is only applicable when salinity of the CSG water is less than 3000 μS/cm (or TDS of less than approximately 1,500 ppm) [12]. CSG water treatment has been a subject of intense investigation for over a decade [10,11,13,17,27–34]. In 2003, several US agencies commissioned All Consulting to conduct a comprehensive study on the management and beneficial uses of CSG water [35]. Nine different treatment technologies were considered for CSG water treatment. These include reverse osmosis (RO), ion exchange (IX), capacitive desalination, electrodialysis, freeze-thaw/evaporation, distillation, ultraviolet light, chemical amendment and artificial wetlands. In 2004, a similar effort was undertaken by the Queensland Department of Natural Resources and Mining to evaluate the economic feasibility of several different desalination technologies [26] (Table 2). It has been concluded that RO is the most competitive technology both in terms of capital investment and operating costs. The use of RO is particularly favourable for CSG water which is essentially moderately saline (Table 2).

3.2. CSG water treatment facilities

Although numerous processes have been promoted, RO and ion exchange are the only technologies deployed so far for the treatment of CSG water (Table 3). Nevertheless, RO technology dominates in both the number and treatment capacity of all CSG water treatment facilities documented to date in the US and Australia. Table 3 also highlights the limited practical experiences involving the treatment of CSG water. The treatment of CSG water is unique. Since CSG water varies widely in its water quality characteristics, pre-treatment is essential to prevent membrane fouling and scaling. In practice, CSG water treatment can be categorised into three distinctive stages — namely pretreatment, reverse osmosis and concentrate management.

Pretreatment and concentrate management are probably the two most challenging aspects of CSG water treatment [13,30,31]. Because CSG water is usually alkaline and rich in bicarbonate, it has a high scaling potential. In addition, soluble iron (typically in the form of Fe^{2+}) can be oxidised upon exposure to air when CSG water is brought to the surface, and can subsequently foul the RO membrane. Simple pretreatment techniques such as percolation can be employed in the field to remove iron. In the Wild Turkey facility (Fig. 3), chlorine addition and multimedia filters are used in the pretreatment stage for the removal of iron [17]. Given the high bicarbonate

Table 2
Capital and operating costs (in Australian dollars) of several desalination technologies (From [26])

Technology	Capital costs ($/KL.d)	Operating costs ($/KL.d)
Multistage flash distillation	2,000–3,800	Dependent on energy cost
Multi effect distillation	2,500–3,900	1.8–2.8
Vapour compression distillation	1,600–1,700	Dependent on energy cost
Reverse osmosis	700–1,000 (brackish water) 1,700–2,400 (seawater)	0.65–1.5 (brackish water) 1.89–2.2 (seawater)
Electrodialysis reversal	570–3,250	1.00–2.80

Table 3
CSG water treatment facilities recently commissioned in the US and Australia [17,28,36]

Facility	Capacity (ML/d)	Year	Location	Treatment processes
Wild Turkey	20	2006	Wyoming	Multimedia filter–RO
Spring Gully	9	2007	Queensland	Sand filtration–MF–RO
Mitchell Draw	12	2008	Wyoming	Multimedia filter–IX–RO
Gillette	5	2008	Wyoming	Zeolite prefiltration–IX

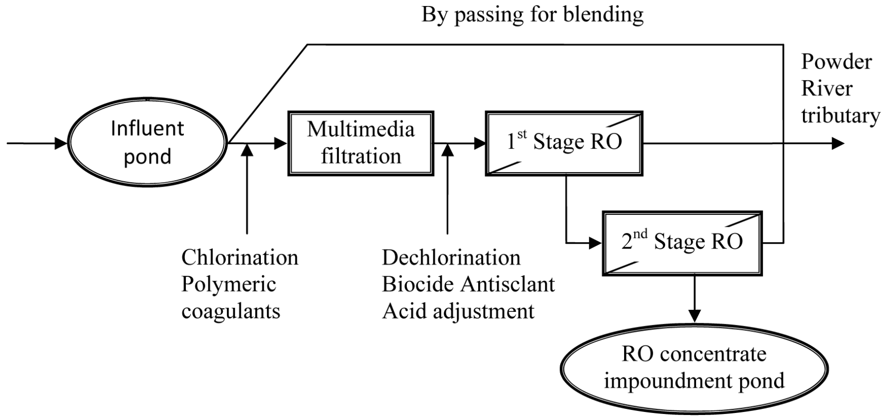

Fig. 3. Key treatment processes of the Wild Turkey CSG treatment plant (Adapted from [17]).

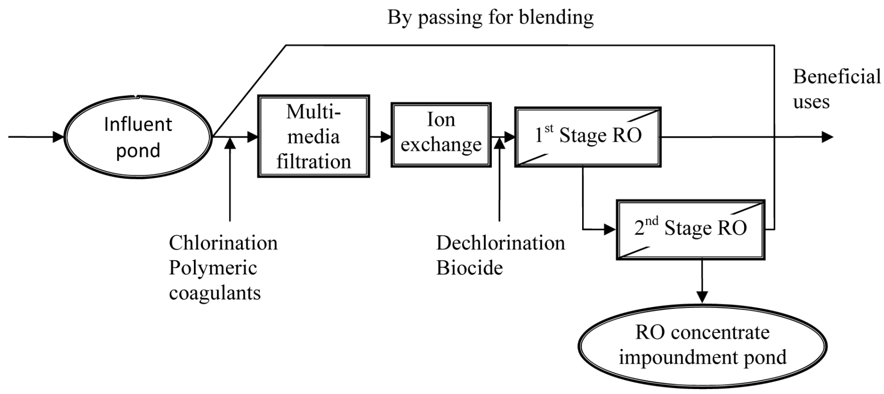

Fig. 4. Key treatment processes of the Mitchell Draw CSG treatment plant (Adapted from [17]).

concentration in CSG water, significant acid addition is required to reduce the feed water pH and therefore the scaling potential with respect to carbonate precipitation. However, because the reduction in pH also lowers the solubility of silica, this approach is counterproductive for the management of silica scaling. In fact, it has been revealed that the recovery of the RO system at the Wild Turkey plant is directly influenced by the variability of silica in the CSG water. Realising the limitation of pH adjustment, an innovative design using ion exchange for the removal of sparingly soluble cations (including calcium, magnesium, barium, and strontium) was adapted at the Mitchell Draw facility (Fig. 4) [17]. The ion exchange process can effectively control the Langelier saturation index of the feed water at negative 1.3 while the feed water pH remains the same [17]. As a result, both carbonate and silica scaling can be effectively mitigated [17]. During the design phase of the Spring Gully facility, which can be considered as a demonstration of best practices in CSG water management in Australia, several pretreatment options were investigated [28]. A combination of dissolved air floatation, sand filtration and coagulation addition could not achieve the required silt density index (SDI) of less than 5 as specified by the RO membrane manufacturer. As a result, microfiltration has been included in the final design to achieve an SDI value of less than 5 [28]. Similar to the Wild Turkey facility, the cost of pH adjustment at the Spring Gully facility is significant [28]. The rate of water production during the dewatering phase usually decreases over time and water production from each CSG well can only last for approximately 15 years. Consequently, as a notable innovative design feature, all major treatment units of the Spring Gully facility are skid mounted, to enable future relocation [28].

As discussed above, given the unique nature of CSG water treatment, several innovative designs have been implemented. However, it is noteworthy that none of the facilities reviewed in this paper has comprehensively addressed the issue of RO concentrate treatment. In all three cases, the RO concentrate is impounded in a tailing pond. While the impoundment of RO concentrate can be a temporary solution for a small scale plant, salt recovery from the RO brine is likely to be required in the future as the demand for CSG water treatment increases further. Several salt recovery technologies from RO concentrate have been successfully tested through laboratory and pilot-scale experiments as well as in small scale installations [25]. Examples of these technologies include the proprietary SAL-PROC systems and a range of evaporative techniques (falling film evaporator, circulation evaporator, fluidised bed evaporator, multi effect evaporator, mechanical vapour compression evaporator, scraped surface evaporator, spray dryer evaporator, and solar pond evaporator) [25,37]. While it is technologically feasible for the development of a zero liquid discharge treatment system for CSG water based on the integration of RO filtration and one of these evaporative techniques, further research is needed to improve efficiency and achieve economic feasibility.

4. Conclusions

Extraction of CSG depends significantly on successful management of the saline and sodic water that is co-produced with the methane gas. If appropriately treated CSG water can present a vital resource to alleviate water shortage that often occurs where CSG exists. In most cases CSG water treatment involves the use of RO membrane technology. Successful implementation of RO technology for the treatment of CSG water has recently been demonstrated in the USA and in Australia. Pretreatment and RO concentrate management are probably the two most challenging aspects of CSG water treatment. Further research is needed to address the issue of membrane fouling and particularly the treatment of RO concentrate to achieve the ultimate goal of zero liquid discharge.

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