Coexistence Opportunities for Coal Seam Gas and Agribusiness

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:// Supporting information is linked to this article on the *JIE* website

Summary

Australia's prospects to become a key energy exporter in the Asia-Pacific region has driven rapid development and expansion of its coal seam gas (CSG) industry, particularly in regional Queensland, Australia. The vast majority of Australia's current CSG developments and reserves are situated in agriculture-rich, cattle-grazing regions; therefore, it is critical to identify symbiotic relationships between agri-based industries and the CSG industry to achieve beneficial coexistence. The CSG industry has generated infrastructure such as gas and water pipelines, water storage and treatment facilities, transportation and electricity networks, and other CSG-associated services (e.g., accommodation, education, and medical facilities), which have the potential to improve regional communities and facilitate economic growth. This article aims to investigate these coexistence opportunities, including the use of by-products (mainly water produced during CSG extraction), infrastructure, and services generated from the CSG industry, which can provide value to the local industries. Focusing on the cattle value chain, the authors suggest an agri-based industrial coexistence model that indicates material-water flows and optimized utilization of infrastructure that not only promote coexistence between the agribusiness and CSG industries, but expand the cattle value-chain productivity in rural Queensland. A water balance has been conducted around the suggested coexistence model with the aim of quantifying water flows, to indicate the supply versus demand scenario associated with CSG-sourced water production. The results of the water balance indicate that CSG water supply has the potential to meet the requirements of agribusiness promoting industries.

Introduction

The upsurge in international demand for low-cost gas has driven the development and expansion of the coal seam gas (CSG) industry in Queensland and has facilitated its international export through the three ~$USD50 billion CSG to liquefied natural gas (LNG) projects constructed at Gladstone (Smith et al. 2014; O'Kane 2013). However, CSG development in Australia has been shadowed by public concerns associated with environmental issues (management of CSG associated water and salt) and land-use conflict between new CSG developments and already existing farmland (Khan and Kordek 2014). The economic incentive associated with supplying international markets, and the environmental benefits of fuel switching from coal to gas (Towler et al. 2016), must be balanced against the industry and regulator's ability to manage risks associated with onshore gas development and its successful coexistence with other local industries and economies.

The location of Australia's CSG industry is constrained by the distribution of geological resource potential, which often occurs in the same areas as intensive farming (e.g., cattle and irrigation properties). Besides the installed infrastructure (e.g., roads, telecommunications, electrical power supply, gas and water gathering pipeline networks, etc.) (Fleming and Measham

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2014; GISERA 2013; Khan and Kordek 2014; Measham and Fleming 2014; Walton et al. 2014), the CSG industry by-products include water and its dissolved salt (Chen and Randall 2013; Dunlop et al. 2013; Jakubowski et al. 2014). Regulations in Queensland encourage the beneficial use of this water, which often requires desalination, which, in turn, generates a smaller volume of brine or salt. Careful management of produced water is required (Jakubowski et al. 2014; Tan et al. 2012, 2015) to gain maximum local benefit from these by-products.

Numerous options for the beneficial use of water and salt (DNRM 2004) include irrigation, contributions to surface water, managed aquifer recharge, livestock watering, abattoir/meat processing industry, tannery/leather industry, inland aquaculture, coal mine water, artificial wetland/ lake ecosystem, municipal water supply, water storage for rural fire use, growth medium for harvesting biofuels, and cooling tower water, which are investigated in this study.

The viability of industries that could utilize the CSG by-products could be tested with collocation pilot trials. If this proves successful, it will help lessen the concern in managing the volumes of water and salt, from both an economic and environmentally sustainable standpoint (Khan and Kordek 2014). Ideally, the new collocated industries would also integrate with existing agricultural industries and promote collective synergies and higher productivity. We describe this type of new industry as an agribusiness promoting industry (API).

This article explores symbiotic relationships of coexistence between the CSG industry, APIs, and existing agricultural industries, specifically investigating the potential for industrial use of CSG by-products and services. The coexistence model suggested in this study may be implemented for already functional industries or future CSG developments located in agriculture-rich regions, in order to optimize the production of both energy and food. We present an analytical framework to evaluate which APIs could optimally coexist with the CSG and existing agricultural industries and benefit the local economy. The preferred API is constrained by a realistic quantified water balance that provides insight into the supply-demand context of water resources distributions and requirement.

Coal Seam Gas Industry-Derived Services and Infrastructure

Gas Extraction Process

CSG is naturally occurring gas that typically consists of around 97% methane adsorbed into the coal matrix of subsurface coal seams (Hamawand et al. 2013; Khan and Kordek 2014; O'Kane 2013). Coal has a dual porosity system where blocks of coal have micropores filled with adsorbed methane separated by a water-filled cleat (or fracture) structure (Duus 2013; Fallgren et al. 2013). CSG-associated water (CSGAW) is defined as the subsurface water that is extracted to depressurize coal seams, which allows gas to desorb and flow through the production well to the surface (Davies and Gore 2013; Hamawand et al. 2013; Pineda and Sheng 2013).

The extracted gas and CSGAW are separated into individual pipelines (Hamawand et al. 2013; Khan and Kordek 2014). The gas is then pumped to a processing facility, where it is further dehydrated and compressed before transport through a network of high-pressure pipelines to power stations for the domestic energy market (Williams and Walton 2013). In Queensland, with the completion of the CSG to LNG conversional facilities, a portion of the CSG will be liquefied for transport and shipped to international gas markets (O'Kane 2013). The first shipments of CSG to LNG export began in January 2015 (APPEA 2016).

Australia is regarded as a dry continent, and in Queensland, many of the agricultural regions are heavily dependent on groundwater resources where water is a valuable commodity (DERM 2000; DNRM 2004). The CSGAW is collected from wells and transferred through a water gathering network into centrally located storage ponds. Depending on the water quality required for the intended use and the water quality in the storage pond before distribution, some water may be directed through water treatment facilities. Alternative to water treatment plant processes, chemical dosing agents may be added to the CSGAW to make it suitable for direct use by the requiring industry.

Establishment of the Australian CSG industry has also introduced an array of "CSG industry-derived services." These can include the use of CSGAW for beneficial purposes, but also CSG industry-generated infrastructure, and enhanced community services and facilities.

Coal Seam Gas–Associated Water Production Profile and Quality

CSGAW production is typically highest in the early part of a well's life (Hamawand et al. 2013; Khan and Kordek 2014). Over time (typically 10 to 15 years), these volumes decline, with increasing CSG flows (Dunlop et al. 2013; O'Kane 2013) and remain very low, if not zero (Davies and Gore 2013; Huth et al. 2014), but new wells are continually being drilled. On average, most production wells have been estimated to have a life of approximately 20 to 30 years (Khan and Kordek 2014; DNRM 2004).

The chemical profile of CSGAW is dictated by the geochemistry of the subsurface coal measures from which the CSG was extracted, as well as subsurface interactions with other sources of groundwater adjacent to the coal (Davies and Gore 2013; O'Kane 2013). CSGAW chemistry varies across different wells, but has been typically characterized with dissolved solids made up of various inorganic ions in solution and organic compounds associated with the coal itself (Flukes 2009; Abousnina et al. 2014; Dunlop et al. 2013). Other chemical constituents may include chemicals used on the CSG operator's sites during well construction, such as cement, drilling operations (drilling mud), reservoir stimulation (fracture fluid), and maintenance activities (workovers) (O'Kane 2013). Table 1 summarizes the typical CSGAW water quality from the Surat Basin.

CSGAW is categorized as "brackish water" because of its characteristic total dissolved solids (TDS) range of 3,000 to

Table 1 CSG-associated water quality in Surat Basin and acceptable livestock watering limits

Water quality parameter	*Unit*	*Range*	*Acceptable livestock watering limits*
pH	—	8–9	None prescribed
Total dissolved solids (TDS)	mg/L	1,200–7,000	Table 4; table S2 in the supporting information on the Web
Sodium adsorption ratio (SAR)	—	107–116	None prescribed
Fluoride	mg/L	0.77–4.5	2–4
Sodium	mg/L	300–3,461	None prescribed
Magnesium	mg/L	4–13	None prescribed
Silica	mg/L	19–51	None prescribed
Sulfate	mg/L	5–10	None prescribed
Chloride	mg/L	550–2,092	None prescribed
Potassium	mg/L	20–78	None prescribed
Calcium	mg/L	2.3–24	None prescribed
Manganese	mg/L	0.07–0.10	None prescribed
Iron	mg/L	0.07–4.50	None prescribed
Bicarbonate (as $CaCO_3$)	mg/L	580–2,060	None prescribed

Sources: AGL (2013) and DNRM (2004).
Note: CSG = coal seam gas; $CaCO_3$ = calcium carbonate; mg/L = milligrams per liter.

15,000 milligrams per liter (mg/L) (Stearman et al. 2014; Nghiem et al. 2011). Careful water management (including appropriate treatment before use) and water-quality monitoring is required to prevent detrimental effects on the environment or the end user (Jangbarwala 2007; Khan and Kordek 2014).

Water Treatment Technologies and Brine

Because of the CSGAW quality often being less than required for a desired use, its direct use by many industries is limited (Khan and Kordek 2014; Tan et al. 2012, 2015). Although there are few end users for raw CSGAW (e.g., livestock watering and some irrigation), almost all of the beneficial use options require some degree of water treatment (i.e., removal of dissolved salt) to meet the suitable requirements of water-quality standards for the respective end user (ANZECC 2000; Davies and Gore 2013; DNRM 2004; Khan and Kordek 2014). These generate a small volume of highly concentrated saline effluent (brine) and a larger volume of treated CSG water (permeate stream) (Hamawand et al. 2013; Nghiem et al. 2011). Increasing the water recovery rate to volume of liquefied brine ratio forms the basis of many CSGAW treatment strategies (Jangbarwala 2007; Nghiem et al. 2011).

Currently, the majority of CSGAW treatment technologies rely on reverse osmosis (RO) (Hamawand et al. 2013; Nghiem et al. 2011) for desalination. Therefore, the major stages of CSGAW treatment include feed collection ponds, ultrafiltration to remove particulate matter, ion exchange (IX) to reduce the hardness, and RO units for desalination (Nghiem et al. 2011). Finally, chemical amendments and conditioning may be implemented to add constituents, making the treated CSGAW suitable for the end user (Hamawand et al. 2013). As an example, figure 1 represents the overall CSGAW treatment process that is used at the Kenya Water Treatment Plant (100,000 cubic meters [m^3]/day capacity) operated by QGC Pty. Ltd and managed by SunWater (QGC 2010).

Brine Management

A waste product from water treatment is the reject water that has high salinity (approximately the salinity of seawater). Brine management options include underground brine injection into a "geologically isolated" structure, which is at an acceptable distance from groundwater resources (DNRM 2004). The second option is evaporation or thermal concentration of the saline effluent/brine to generate a smaller volume of highly concentrated brine or even a dry solidified salt. This solidified product can be transferred to a regulated waste disposal/landfill facility, either on the CSG operator's site or off-site. Careful brine management is integral to prevent any adverse environmental impacts that may occur from inappropriate disposal practices (Abousnina et al. 2014; Khan and Kordek 2014; Nghiem et al. 2011).

Alternative chemical solidification processing of CSG brine, through selective salt precipitation, has been generating interest in recent times as a potential commercial opportunity from the recovery and sale of its commodity salts (e.g., sodium bicarbonate, sodium carbonate, and sodium chloride) (Khan and Kordek 2014). However, because of the low value of the end product, technical complexities, and declining CSGAW volumes, it appears that this option is currently economically unfeasible.

Potential Agribusiness Promoting Industries

Historically, the agricultural sector has dominated the regional industrial profile across much of southern Queensland (Schandl and Darbas 2008). Many of Australia's CSG developments have been established in close proximity to agricultural irrigation and cattle-grazing corridors (Huth et al. 2014). The fertile soils of much of the Maranoa and Darling Downs regions of the Surat Basin have been the site of CSG development activities, such as construction of drilling infrastructure, water and gas gathering networks, access roads, and electricity and telecommunications infrastructure (Huth et al. 2014).

These CSG development benefits, coupled with a sustainable agricultural industry, are vital to Australia's economy and growth; therefore, it is pivotal to promote a balanced coexistence for both industries. A holistic approach that optimizes by-product usage between existing and new regional industries, particularly APIs and the CSG industry while maintaining world-class environmental management, would be ideal.

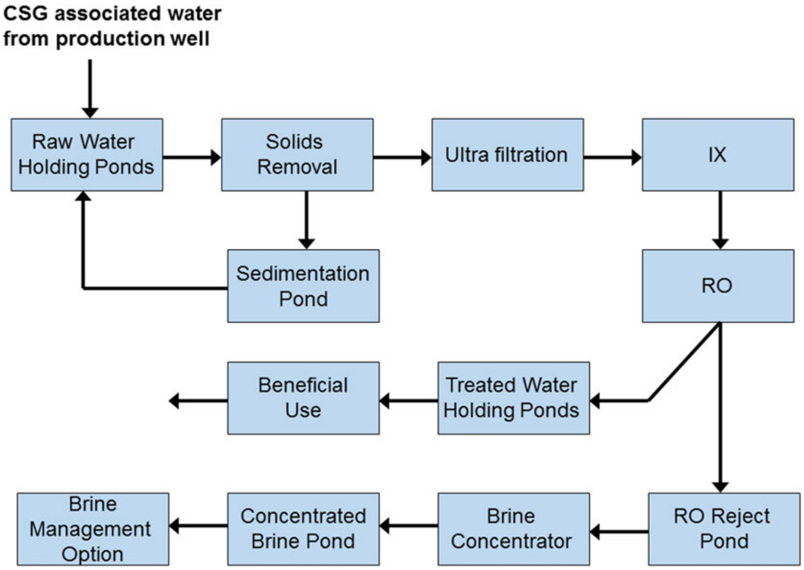

Figure 1 Example of coal seam gas (CSG) water treatment process. IX = ion exchange; RO = reverse osmosis.

The location of the end user/industry and its proximity from the CSGAW distribution site is one of the most important criteria that defines the underlying economic feasibility and coexistence potential. Therefore, an important economic consideration is the high transportation costs associated with delivering the resources (e.g., water) to the end user (TCT 2013). Alternatively, industries could be collocated near the source of the CSG-associated service, to avoid transportation costs. This would inject investment interest into the area and increase the region's economic potential. Increased industrial growth can increase employment opportunities and further infrastructure, which can facilitate the return of residents who had initially relocated to urban areas for better economic options to come back to the rejuvenated opportunities sourced from CSG industry-derived services. The advantages from promoting coexistence opportunities provide the basis for analyzing the beneficial effect of using CSG industry by-products by potential APIs.

We assessed numerous industries that could utilize the identified by-products. However, not all these candidate industries are equally appropriate for realistic implementation in the rural setting of CSG development. In order to evaluate the applicability of each potential new industry, screening matrices were applied as the analytical tool of choice. The screening matrix criteria are summarized in table 2. Upon careful consideration and extensive literature review (table S1 in the supporting information available on the Journal's website), each criterion was scored a rating (1 = low, 2 = medium, and 3 = high) and totaled for each potential beneficial use option (industry end user).

The screening matrix assessment results indicated that the highly ranked industries for CSGAW were major role players in the agriculture-based supply chain and were considered as feasible industries for collocation or coexistence with the local industries in the agri-based regional industrial context. These high-scoring APIs, which have high potential to complement the CSG industry, included (1) crop irrigation, (2) livestock /feedlot operations, (3) meat processing/abattoir industry, and (4) tanneries/leather processing. The aforementioned APIs can be considered potentially high-value industries involved in assisting the sustainability of existing local industries in the characteristically agriculture-rich region (predominantly cattle grazing), often in close proximity to CSG developments. For these reasons, the authors concentrated analysis on the native cattle industry-agricultural value chain as the foundation upon which coexistence opportunities are most likely to be initiated.

Agricultural Industry: Use of Coal Seam Gas–Associated Water for Irrigation

Because of the large water volumes generated from CSG production (expected to peak ~120 gigaliters per year) (KCB 2012) and the proximity of CSG operations to agricultural areas, irrigation provides a highly probable option for beneficial CSGAW use (All Consulting 2003; Biggs et al. 2012; Ginter 2012; Tan et al. 2015) and, in fact, is already in practice. Such successful implementation of irrigation scheme is the Australia Pacific LNG Project, which is enabling the use of treated CSGAW from Spring Gully CSG water treatment facility, for drip irrigation projects involving a 300-hectare (ha) Pongamia plantation (biofuel potential) in Queensland (Moser 2013). Besides food crops, plantations of leguminous trees with oil-rich seeds may be harvested and processed for biodiesel production.

Given that CSGAW is typically of poorer quality than the current irrigation water sources, direct use is often an unviable option. Depending on water quality, application of raw CSGAW for irrigation has indicated decreased plant growth (DNRM 2004; Khan and Kordek 2014). The viability of CSGAW for irrigation is dependent on the salinity and sodicity of water (Biggs et al. 2012), as well as soil chemistry, natural salinity levels, crop salt tolerance, geological landscape, and climate (Biggs et al. 2012; Khan and Kordek 2014). Saline

Table 2 Screening matrix criteria

Screening matrix criteria	*Description*	*Question guide*
Environmental sustainability	Environmental impact from establishment of prescribed industry was considered as a vital criterion to assess its viability.	• Is this option environmentally sustainable?/Does this option utilize a waste product of the CSG industry?
Location/proximity (importance of location)	The distance between the source of the CSG industry-derived service and the end user for beneficial use was regarded as critical because of increased costs that may be associated with transportation.	• Can the end user be in close proximity to the source location of the CSG industry-derived service?
Reliability	There must be a consistent uptake of the CSG industry-derived service by the proposed option for beneficial use for there to be an ongoing and "reliable" coexistence of all industries. A point to consider is that there should be an adequate production of the service to meet high-level demands from the end user, or, alternatively, there must be a sufficient demand from the end user industry for a reliable uptake of the CSG industry derived service.	• Will the end user regularly use the CSG industry-derived service?
Technical feasibility	The potential coexistent industry should possess a high level of technological maturity for a high score in this criterion. Alternatively, industries with underlying technologies that are considered to be under research and development (R&D) phase were scored as having low technical feasibility.	• Is the underlying technology mature and well known for the functioning/estaishment of the industry?
Community benefit	For a high score in this criterion, potential industries must directly inject benefit to the regional community near the CSG development. This benefit can be sourced from increased employment opportunities, increased social awareness of local businesses, and any facilitation of the regional community's well-being. Those industries that are regarded as having a justifiable negative impact from a social context have been considered as poor contributors to the advancement of the regional community.	• Will the community benefit from this industry?
Social acceptance	For there to be coexistence of other industries alongside the CSG industry in the nearby regional area, there must be acceptance of receiving the CSG industry-derived service from the regional community. Those options that are traditionally regarded as propagating community benefit from a social standpoint have been scored highly.	• Will there be social acceptance for this industry? Are there any social repercussions associated with this industry?
Supporting workforce	Industries that require a workforce with skills that are already present in the CSG development area were considered as a great advantage, given that it would promote the local employment sector without the need for upgrading skills or further training; consequently, these industries were scored highly.	• Is there a supportive workforce already present in the regional area of interest for colocation/coexistence of this industry?

Note: CSG = coal seam gas.

water used for irrigating low-salt-tolerance crops will result in soil crusting, increased runoff causing soil erosion, and reduced water retention capacity, resulting in improper crop growth (DNRM 2004). It is also important to maintain a soil pH range of 6.0 to 8.5, because highly alkaline soils may lead to plant deformations and scaling of irrigation equipment attributed to residue deposition (DNRM 2004). Therefore, some form of water treatment or amendment is required of CSGAW before its use for irrigation (Biggs et al. 2012). Aside from crop-salt-tolerance ranges (table 3), other water constituents and their effects on vegetation must be monitored to allow for necessary amendments during the water treatment process.

Although CSGAW may be adequately treated for irrigation purposes as per the regulatory guidelines (ANZECC 2000; DNRM 2004), there are some underlying potential environmental risks (DNRM 2004) of irrigation, regardless of the source and quality of water being used. Irrigation can cause risks to long-term soil structure from salt levels that may have concentrated over time (Biggs et al. 2012). Additionally, rainfall levels combined with irrigation practices may affect the discharge of

Table 3 Irrigation water salinity based on TDS content

TDS (mg/L)	*Water salinity rank*	*Crop suitability*	*Potential crop*
<390	Very low	High sensitivity	Flowers/fruits
390–780	Low	Reasonable sensitivity	
780–1,740	Medium	Reasonable tolerance	Clover
1,741–3,120	High	Tolerant crops	Corn, lucerne, sorghum, soy bean
3,121–4,860	Very high	Highly tolerant crops	Cotton, cereals (wheat), barley
>4,861	Extreme	Usually too saline	—

Source: DNRM (2004).
Note: TDS = total dissolved solids; mg/L = milligrams per liter.

flows in a lateral manner across the land and subsurface regions, as well as longitudinally downward (deep drainage) toward the water table (Biggs et al. 2012; Khan and Kordek 2014). The prominent land use, location of the landscape, soil profile, crops being grown in terms of their water use, and effect on soil structure are all possible factors that can affect the movement of water and subsequent environmental impact from the implementation of CSGAW for irrigation (Khan and Kordek 2014). It is important to consider that the relative impact and environmental sustainability of using CSGAW for irrigation is site specific (Biggs et al. 2012).

Increased water supply allows for increased crop production and grazing yield for livestock, which further increases overall productivity of the land and assists other agribusinesses to increase domestic and international economic opportunities, including food tourism/agri-tourism (APLNG 2010). An example of this type of agri-tourism can be sourced from promoting this Queensland region for its high-quality produce and food/wine trails. Such economic opportunities would facilitate regional employment, especially in the agriculture, retail trade, tourism, and hospitality sectors (Everingham et al. 2013; Fleming and Measham 2014).

Feedlots Industry: Coal Seam Gas–Associated Water Use for Livestock Watering

CSGAW may be used for livestock watering in the feedlot industry. In areas of high grazing activity and intensive animal farming, feedlots or animal feeding operations are constructed to house livestock, which consume specialized animal feed, to facilitate the growth of muscle mass on the animal before slaughter or live export trade. Livestock watering systems are systematically built at the feedlot facility for animal water consumption.

Untreated CSGAW can be considered for livestock watering purposes depending on the livestock's tolerance range (table 4; table S2 in the supporting information on the Web). In most cases, the quality of CSGAW is regarded as being within acceptable limits (table 1) with the occasional exception of fluoride content, which, if outside the acceptable limits, may cause dental problems (e.g., fluorosis) in livestock (DNRM 2004; Ginter 2012; Khan and Kordek 2014). In cases where water quality is unsuitable for livestock consumption directly, some form of low-level CSGAW treatment, to remove the high TDS or fluoride concentrations, before release for livestock watering would be required. This can often be accomplished by blending raw CSGAW with RO permeate or other aquifer-derived water (which is of higher quality than the raw CSGAW) to attain the desired chemistry deemed suitable for feedlot consumption (table 4) (DNRM 2004). If the stock to be watered are dispersed in low concentrations across large grazing properties, this may not be cost-effective for most CSG operators (DNRM 2004); however, the application to feedlots, where there is a greater density of livestock, is more economically feasible.

Providing CSGAW for livestock watering at feedlots would supplement water supply to drought-stricken regions (DNRM 2004) and accentuate overall employment security for the livestock industry, as well as the abattoir/meat processing supply chain from the availability of livestock for slaughter.

Meat Processing/Abattoir Industry: Coal Seam Gas–Associated Water for Meat Processing

The Australian meat industry injects more than $USD12.2 billion into the local economy, and because of the production of high-quality meats, it has great demand in the international export market (AIG 2013). According to a Department of Agriculture, Fisheries and Forestry (DAFF) report, there is a general shortage of meat processing facilities in Queensland (Gleeson et al. 2012). A report by Ullman (2013) suggests that to overcome this shortage, and rising demands for quality meats from Asian markets, new meat processing sites should be planned in regional Queensland (Ullman 2013). The establishment of new abattoirs in regional areas with high grazing potential would add economic value to the agri-based industries and facilitate enhanced trade to international markets. Surveys have revealed that Queensland produces the most cattle compared to the other Australian states, with approximately 12.2 million cattle livestock recorded of the 28.5 million total cattle in Australia (ABS 2012). Water is heavily used in abattoirs during slaughter, evisceration, and other meat processing stages (Johnson 1990; MLA 2014). Treated CSGAW can be used as the primary water source at abattoirs. New-build abattoirs and meat processing facilities that add capacity to the industry can be constructed close to CSG operations, thereby taking advantage of the water supply and reducing transportation costs (DNRM 2004). However, in cases where existent abattoirs are located midway between agricultural land and CSG operations, pipeline infrastructure would be required to transport treated CSGAW to the respective meat processing facilities. There onward, the meat processing facilities are responsible for water and waste management as part of their normal practice. A common issue for abattoirs is

Table 4 Tolerance range of livestock to TDS range for drinking consumption

Livestock	*Total dissolved solids (mg/L)* *No adverse effects on animals expected*	*Animals may have initial reluctance to drink or there may be some scouring, but stock should adapt without loss of production.*	*Loss of production and a decline in animal condition and health would be expected. Stock may tolerate these levels for short periods if introduced gradually.*
Beef cattle	0–4,000	4,000–5,000	5,000–10,000
Dairy cattle	0–2,400	2,400–4,000	4,000–7,000
Sheep	0–4,000	4,000–10,000	10,000–13,000[a]
Horses	0–4,000	4,000–6,000	6,000–7,000
Pigs	0–4,000	4,000–6,000	6,000–8,000
Poultry	0–2,000	2,000–3,000	3,000–4,000

Sources: Khan and Kordek (2014) and ANZECC (2000).

Note: TDS = total dissolved solids; mg/L = milligrams per liter.

[a] Sheep on lush green feed may tolerate up to 13,000 mg/L of TDS without loss of condition or production.

the high nutrient load of its effluent, which prevents its direct application as fertilizer to cropping land. CSG-amended water could be used to dilute abattoir wastewater if collocated. Community benefit as a result of this application of CSGAW includes added employment opportunities from the growth of the meat processing industry and increase in the number of carcasses that can be processed attributed to the extra source of water supply (DAFF 2012).

Tanneries Industry: Coal Seam Gas–Associated Water for Leather Processing

Salted water or brine solutions are typically used for antibacterial and dehydration purposes in hide curing during leather manufacturing. Treated CSGAW can be used in the leather industry for various water-consuming applications. Simultaneously, brine generated from desalination of CSGAW can be utilized during hide-curing and leather-degreasing processes (Rydin et al. 2013). Beneficially using CSGAW/brine for the purpose of hide-tanning and other leather-dying purposes does not add a new risk to the original business case scenario (Bosnic et al. 2000; Buljan and UNIDO 2005; Buljan and Kral 2011; Song et al. 2004). The tannery can be purposefully constructed close to the meat processing/abattoir facility and in optimal distance from the CSG water distributor's site to reduce water and hide transportation costs. The water usage of tanneries depends on the meat processing supply chain, whereby the availability of cattle hides or other leather processing feedstocks facilitates the processing operations and water/brine requirements at the tannery facility. This option has the potential to generate significant community benefits such as employment opportunities and increased economic activity from the manufacture of high-quality leather products to both international and domestic markets. Co-location of the tannery facility with CSG water treatment facilities has the added benefit that tannery waste water can be directed back through the water treatment facility to optimize its utility.

Complementary Industries and Coal Seam Gas: Proposed Industrial Synergistic Model

Activities within individual industries can contribute to the growth of other industries, indirectly or directly. For example, increased supply of a service (CSG water for meat processing, irrigation, livestock watering, and tanneries) facilitates increased supply value for agribusinesses, food productivity, agri-tourism, export trade opportunities, and industrial investments, thereby increasing the region's economic potential. We propose an industrial collocation model designed to minimize transport costs and optimize the utilization of CSG industry by-products and services. The proposed model also looks to utilize the services of the local labor force already trained in many of the required skill sets.

The agri-based industrial coexistence model (figure 2) summarizes potential relationships between the cattle industry-agriculture farms, feedlots, meat processing facilities, leather manufacturing operations, and CSG entities. Amended CSGAW can be provided by the CSG water treatment facility/distributor to agricultural farms for irrigation (at least the ones in the nearby vicinity) to boost their productivity/acre. The agricultural farms can be closely associated with feedlot operations, because they may provide land for grazing and the potential to grow the feedstock crops for livestock consumption. Amended or raw CSGAW can be piped to feedlot facilities for livestock watering. The feedlot industry can provide co-located meat processing facilities with the livestock for slaughter. Treated CSGAW can be provided as process water to the abattoir/meat processing facility. A local wastewater treatment facility that relies on biodegradation-based wastewater treatment processes, such as an anaerobic digestion system, can be constructed to treat the feedlot and meat processing wastewater (typically containing high organic biosolids, nutrients, and biologically hazardous content) to produce biogas (methane) (Luste and Luostarinen 2011) and

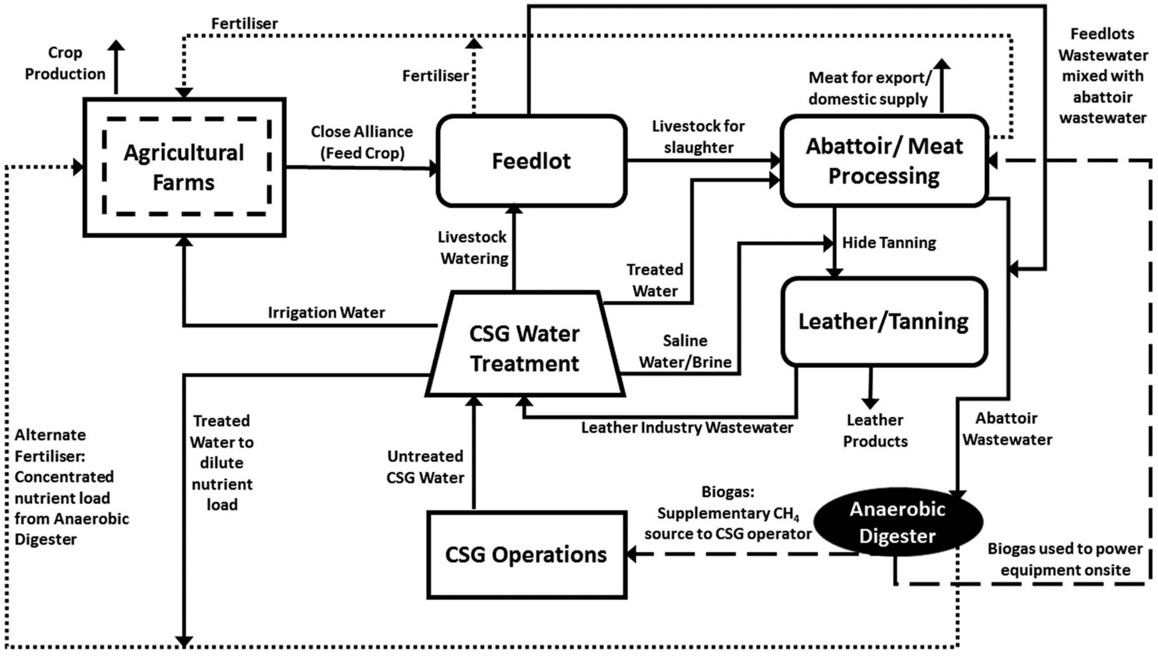

Figure 2 Suggested agri-based industrial coexistence model based on cattle value chain. CH_4 = methane; CSG = coal seam gas.

a typically high-concentration nutrient effluent load that must be diluted with freshwater from the CSGAW treatment facility before application as an alternate fertilizer for growing agricultural crops. The biogas generated from this methodical treatment process can be used to power abattoir equipment or provided to the CSG operator to supplement the source of methane for their local on-site use or pipelined to market. The naturally saline CSGAW can be used in the tanning process of animal hides produced as a by-product of the meat processing industry for use in the leather industry. Further, fertilizer produced by the abattoir/meat processing industry and feedlot operations can be used by agricultural or grazing properties for the cultivation of crops or sold to external customers. All these co-located industries can also benefit from the CSG-improved local infrastructure, such as roads, power, and telecommunication. It should be noted that the workforce skills required for this agri-based industrial coexistence model are largely matched to those already available in the local rural communities.

The water requirements for each of the agri-based industries were calculated and compared with the typical volumes of treated CSGAW that are expected to be produced at CSG water treatment facilities (figure 3). The assumptions that were considered in formulating the basis for calculating the water consumption rates include: The irrigation water requirements are prescribed for an approximate 40 ha (AGL 2010); an average daily slaughtering rate of 1,400 cattle per day (Johns 2011); 702 liters (L) of water required per whole cattle hide for tannery operations (Buljan et al. 2000); the characteristic feedlot water requirements of 130 L of water consumed per cattle head (Johns 2011; Bonner et al. 2011); and, although highly variable (ranging between 1,000 and 100,000 m^3/day depending on the CSG asset), a typical water treatment installed capacity of 20,000 m^3/day indicating an average of the treated CSGAW volumes that will be produced by the CSG water treatment facilities in the Surat Basin (GWI 2012). Calculating the water consumption rates for each of the agri-based industries revealed that the demand is lower than the average distributed supply capacity of the CSGAW from the CSG water treatment facility, thereby allowing the suggested model for consideration to promote coexistence of the agricultural supply chain with the CSG industry. It can be seen that the proposed agri-based coexistence model could easily be tuned to match a planned CSG water treatment facility's capacity.

Our observations and analysis identifying the potential for synergies between agricultural and CSG industries may have broader application. Shale gas and tight gas development is often thought to be similar to CGS development; however, the extraction process is considerably different, often consuming water rather than having it as a by-product in large volume (US EPA 2015). However, coal mining (open pit and underground) requires dewatering of aquifers adjacent to the mined area, and the volumes of water available for use can be similar to our case-study assumption of 20,000 m^3/day (Danoucaras et al. 2014). The wastewater from coal mining operations is of similar quality to CSG-associated water and coal mines are often located in agricultural areas, making them a good alternative application for the purposeful implementation of our agri-based industrial coexistence model.

This synergy between all the aforementioned entities would benefit agri-based industries and promote productivity of the existing agriculture-based regions typically surrounding CSG developments. Additional benefits include regional population growth, new infrastructure in regional towns, increased training and career opportunities, as well as enhanced electricity and

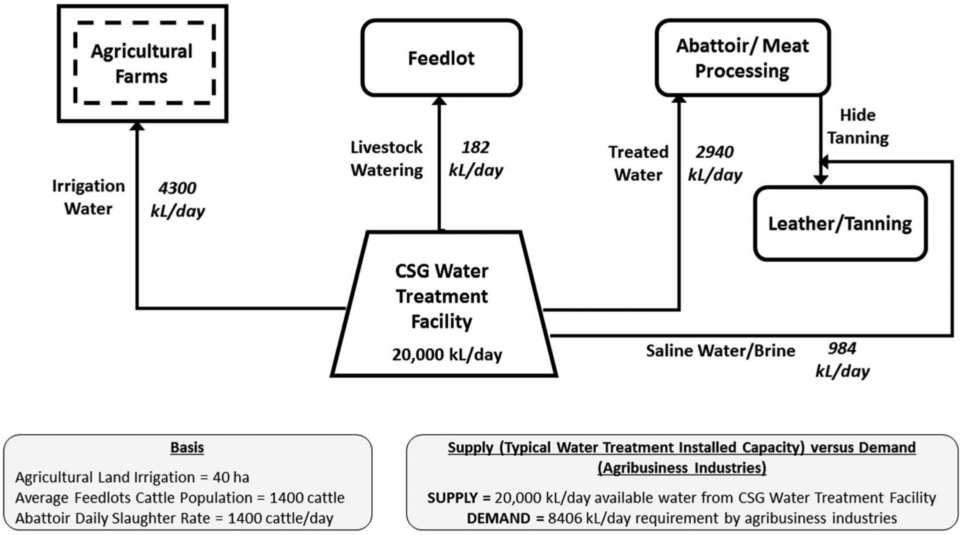

Figure 3 Typical water consumption by agri-business industries in comparison to coal seam gas (CSG) water supply. kL = kiloliters.

telecommunications infrastructure (Huth et al. 2014; Measham and Fleming 2014; Letts 2012). The skills base (farmers and farm managers), which dominates areas in close proximity to CSG developments, in particular, the CSG water distributor, has a strong connection to the agriculture industry. APIs would therefore promote the local employment sector without the need for significantly upgrading skills or further training. Despite the regional amelioration associated with synergizing rural business opportunities with the CSG industry, the main concern is the investment potential underpinning large infrastructure developments, coupled with future water supply during the end of life of the CSG industry, when water production ceases. A potential solution may be to utilize pipeline and well injection infrastructure that is presently being installed for managed aquifer recharge, which may form a significant beneficial use option for CSGAW. This infrastructure could ultimately be used in the future to reharvest the CSGAW and, in effect, extend the supply of water to a collocated agri-based industry even after the CSGAW production declines and eventually stops.

Conclusion/Future Directions

Coexistence can be characterized with sustainable operations of already established regional industries and also the advent of new industries that are ideally linked to the conventional agri-based supply chain. The agri-based industrial coexistence model discussed here indicated potential coexistence opportunities between APIs and the CSG industry with a specific focus on utilizing the waste by-product CSGAW for beneficial use. Amending or treating CSGAW was considered as a prerequisite for many industrial applications. Generally, investment and employment opportunities were more likely to be sourced from the application of treated CSGAW. Further, the distance between the CSG industry-derived service and end user was also considered as an important aspect. Upon analysis, it has been noted that the agricultural industry benefits the most from CSG industry by-products and services, attributed to the fact that agricultural lands span a significant portion of CSG developments and existing rural industries provide an appropriate workforce for APIs. Enhanced irrigation schemes as well as expansion of meat and leather processing facilities would contribute to improving land productivity and are therefore beneficial for the region's dominant industry. The purposeful collocation of these industries with CSGAW treatment facilities will reduce transportation costs, utilize power, transport and communications infrastructure, and optimize the beneficial use of CSGAW. The co-location also provides a repurposed use of the CSG water treatment facilities for the waste water from feedlots, abattoirs, and tanneries that would each otherwise require stand-alone facilities. The co-location allows for the lowest collective environmental impact and surface footprint. This integration of APIs with the CSG industry is ideal and presents innumerable opportunities, such as increased employment prospects (preventing the younger rural generation from moving to urbanized city centers), continued crop production (irrigation water supply), and creation of prospects for additional industries (biofuel production, leather industry, international meat exports, food tourism/other agri-based tourism opportunities). In effect, the agri-based coexistence model raises the overall financial productivity potential of the region by injecting export trade opportunities and industrial investments.

Continuous availability of the water resource should be considered beyond the ~40-year life span of the CSG development. CSGAW production typically declines over the life of a CSG production well, and the water treatment facilities may be operational for some 30 or so years; therefore, water supply to potential industries that will beneficially utilize the water should be strategically allocated in a way that ensures water supply at the post-CSG decommissioning stage. CSG infrastructure deployed for managed aquifer recharge use of CSGAW could be utilized to reharvest this water in the post-CSG production phase to extend the supply of CSG-derived water to collocated agri-based industries. Further, it is important to involve the agricultural industry as early as possible, given that many of the CSG developments overlap grazing and other agriculture-rich farmlands; in particular, to attain trust as a CSG operator and promote land access negotiation/consultation practices (Walton et al. 2013). The agri-based industries and natural resource development such as CSG establishments can exist and be developed concurrently provided there is a site-specific approach that is tailored toward the development and sustainability of regional assets.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information contains, in table S1, a list of references that aim at summarizing literature that formed the framework for the screening matrix analysis and subsequent scoring decision for each beneficial use option. It also includes, in table S2, a general overview of the effect of varying TDS tolerance ranges and its suitability for drinking water consumption for livestock.