RESEARCH IMPACT EVALUATION

Reservoir Rejuvenation Technology Case Study

February 2017

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1 Executive Summary

Coal seam gas (CSG) is becoming a widely used energy source, particularly in eastern Australia where a number of basins have been found to produce significant volumes of methane gas from coal seams.

However, the drilling and maintenance of CSG wells are gradually becoming less economically viable as a result of low gas prices and the comparably high price of maintaining and drilling CSG wells. Furthermore, the life span of a coal seam production well is only approximately 10-20 years. Due to this limited life time of CSG wells, establishing new CSG operations is not currently considered to be viable from an economic perspective.

The Microbial Enhancement of Coal Seam Methane (MECSM™) project (now called Reservoir Rejuvenation Technology, or R2T) initiated in 2008 aims to deliver to the CSG industry a solution for the rapid replenishment of methane in depleted or under-saturated coal seams to enable renewed production.

In collaboration with the industry, CSIRO has created a team of researchers who are conducting laboratory experiments to understand the processes involved in replenishment, and who are culturing the microbes to determine the viability of using them to optimise gas generation. A long term field trial is in the planning stage (to commence in 2017) where microbes and nutrients are injected into test reservoirs.

If successful, the benefit for industry of this research will include the development of a technology to increase the methane content of CSG reservoirs which could add considerable value to coal seam gas production and increase production of this energy source in Australia.

If a coal seam was used for geological storage of CO_2, ultimately the technology may enable some conversion of the CO_2 to methane, potentially delivering further environmental and economic benefits.

The overall benefits of the R2T project depend crucially on the adoption profile and actual achievement of CSG production. Most of this adoption takes place in the future, so impact analysis outcomes are associated with some uncertainty.

Looking at the midpoint of a range of impacts, our estimates suggest that the real project expenditure of $ 1.4 million by CSIRO could lead to:

- Total benefits (measured as cost savings in CSG production, in real, present value terms) between $0.7 million and $21.4 million, depending on the assumptions made;
- Net benefits between -$0.9 million to $20.1 million; and
- A benefit cost ratio between 0.4:1 and 16:1.

This case study uses the evaluation framework outlined in the CSIRO Impact Evaluation Guide. The results of applying that framework to the Reservoir Rejuvenation Technology case study are summarised in Figure 1.1.

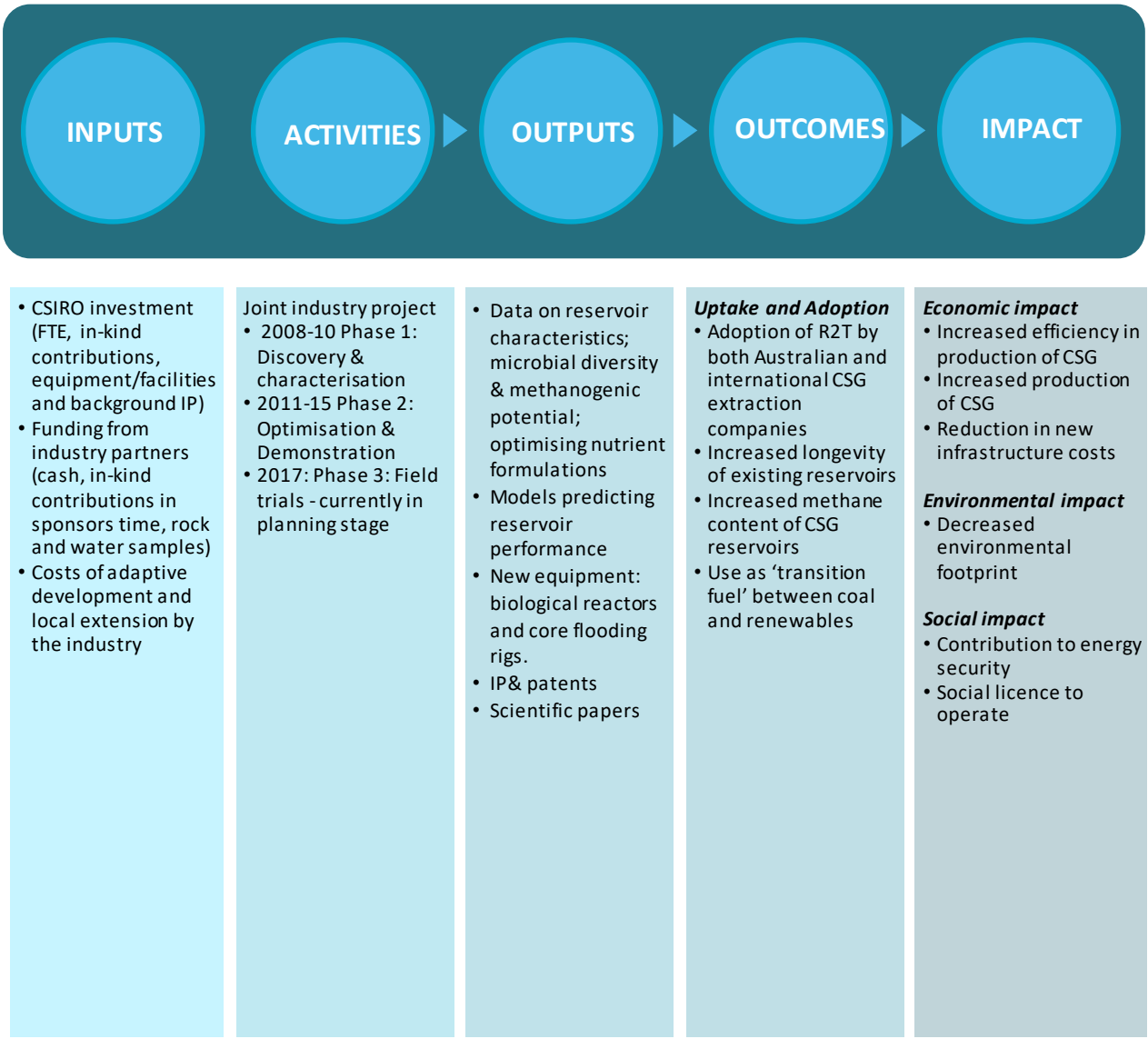

Figure 1.1: Impact pathway for R2T project

2 Purpose and Audience

This evaluation is being undertaken to demonstrate to a range of stakeholders the likely future impacts arising from CSIRO's work on the Reservoir Rejuvenation Technology (R2T). It focuses on the CSG production and therefore does not provide comparisons between CSG and other energy such as coals and renewables. It is intended to assist Members of Parliament, Government Departments, CSIRO, and the general public to understand the value of CSIRO and its contribution to Australia's innovation system.

This case study has been conducted for accountability, reporting, communication, and continual improvement purposes. Audiences for this report may include the Business Unit review panel, Members of Parliament, Commonwealth Departments, CSIRO, and the general public.

3 Background

Coal seam gas (CSG) is becoming a widely used energy source, particularly in eastern Australia where a number of basins have been found to produce significant volumes of methane from coal seams. CSG is cleaner than other fossil fuels; and already accounts for over 40 per cent of Queensland's natural gas consumption (Queensland Government, 2016).

CSG, also known as Coal Seam Methane (CSM), is an unconventional gas that is extracted from coal beds. Extractions of the gas requires depressurising of the coal seam through the removal of the water. This is achieved by drilling a vertical well into the coal seam and pumping out the water held in the seam (Figure 3.1). However, the drilling and maintenance of CSG wells is gradually becoming less economically viable as a result of low gas prices compared to the high price of maintaining and drilling CSG wells (Ramos 2016). Furthermore, the life span of a coal seam production well is approximately 10-20 years (Khan & Kordek 2014). Due to this limited life span, establishing new CSG operations is not currently considered to be viable from an economic perspective (Ramos 2016).

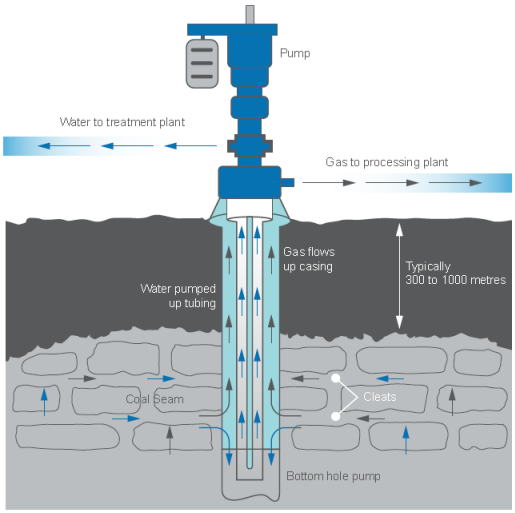

Figure 3.1: A schematic of a CSG well

Source: GISERA (2014).

Coal seam methane may be generated by thermogenic or biogenic reactions, or a combination of these two processes. Thermogenic methane is derived from the heating of organic matter over time. Biogenic methane, in contrast, is generated through microbial degradation of organic matter.

Numerous studies have shown that much of the methane occurring in eastern Australia Basins was formed biogenically. In some areas, the prospectivity and producibility of coal seam methane is enhanced where biogenic generation has occurred because both the gas contents and permeability may be higher than in areas where biogenic generation has not occurred. Scope

therefore exists for this 'bio-enhancement' to be artificially promoted through injecting appropriate microbial consortia or nutrients (or both) into coal seams to increase gas content.

Initiated in 2008, the Microbial Enhancement of Coal Seam Methane (MECSM™) project (now called Reservoir Rejuvenation Technology, or R2T) aims to deliver to the industry a solution for the rapid replenishment of methane in depleted or under-saturated coal seams to enable renewed production (Figure 3.2). As illustrated in Figure 3.2, hypothetical gas (red) shows the production curve for a typical coalbed methane well. The goal of microbially enhanced methane is to increase gas production during the decline phase, as illustrated in green.

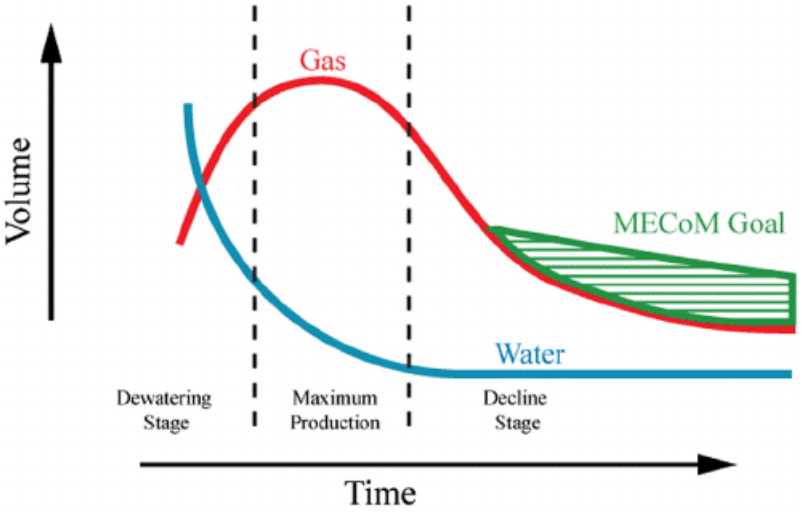

Figure 3.2: CSG production curve

Source: Ritter et al. (2015).

CSIRO has created a team of researchers who are conducting laboratory experiments to understand more fully the processes involved, and who are culturing the microbes to determine the viability of their use to optimise gas generation. The process of biogenic gas formation requires the collective actions of a variety of anaerobic microbes comprising a range of metabolic groups, and other conditions such as temperature, availability of nutrients, and appropriate substrates.

With the appropriate injection of microbial consortia or nutrients, an average of an additional 10 years could be added to the life of a well (Ramos 2016). Along with the prolonging the life of existing CSG wells, the need to drill new wells will be delayed. The addition of microbial consortia or nutrients to existing wells requires only operating costs for the process rather than capital costs to drill a new well.

4 Impact Pathway

Inputs

Table 4.1 shows the cash and in-kind support provided for the R2T project by the various contributors to the research. Industry was the major cash contributor to the project with a total of $3.6 million. In-kind contributions from the industry are mainly sponsors' time, and collecting

water and rock samples and are estimated to be approximately $1 million in total. In addition, CSIRO's contribution totalled just over $1 million.

All economic assessment of costs must also recognise the time value of money. Because the CSIRO and industry project dates back to 2008, it was important to first classify costs in real 2016/17 dollars to adjust for inflation. The real (in 2016/17 dollars) project costs were then readjusted in present value terms using a discount rate of 7%. This is necessary because any research costs incurred in the past had to be brought forward, as those funds could have been earning interest in the intervening time. Table 4.1 summarise the adjusted research costs for CSIRO and industry collaborators.

Table 4.1: Summary of CSIRO and industry adjusted project costs

Year	Industry CPI adjusted	CSIRO CPI adjusted	Present value of industry costs	Present value of CSIRO costs	Present value of total cost
2008-09	$395,942	$43,994	$680,301	$75,589	$755,890
2009-10	$387,964	$43,107	$622,985	$69,221	$692,206
2010-11	$528,121	$176,040	$792,567	$264,189	$1,056,757
2011-12	$621,392	$170,925	$871,535	$239,731	$1,111,266
2012-13	$607,990	$167,238	$796,950	$219,215	$1,016,166
2013-14	$488,310	$162,770	$598,201	$199,400	$797,602
2014-15	$468,208	$117,052	$536,051	$134,013	$670,064
2015-16	$716,987	$116,170	$767,176	$124,302	$891,478
2016-17	$710,433	$115,108	$710,433	$115,108	$825,542
Total	**$4,925,347**	**$1,112,405**	**$6,376,201**	**$1,440,769**	**$7,816,970**

Source: CSIRO

Activities

The R2T project aims to understand microbial generation of gas in coal, and develop and apply methods for stimulation of this generation in the laboratory which can be subsequently used in the field. In order to evaluate the potential for microbially enhanced coal seam methane production, a three-phased research and development program was established:

- Phase 1 – Discovery and Characterisation (2008-10)
- Phase 2 – Optimisation & Demonstration (2010-17)
- Phase 3 – Field Trials (2017-18)

Phase 1 was carried out in partnership with AGL Energy, Apollo Gas (previously Macquarie Energy), Eastern Star Gas, Origin Energy, and Santos. It was completed in September 2010. The key activities of Phase 1 included:

- the description of the microbial diversity in some of the coal and associated water of the major CSG producing regions of eastern Australia;
- the determination of the methanogenic potential of the samples; and

- the identification of a nutrient mix that stimulated methane production using coal as the sole substrate.

The samples analysed were from coal seams in the Sydney, Surat, Gunnedah, and Bowen basins. In addition, optimal environmental conditions for methanogenesis were determined; and various inocula and nutrient supplements were tested.

Phase 1 (2008-10) demonstrated that stimulation of biogenic methane in coal seams is feasible. Consequently, a second phase of study was deemed to be warranted to more fully understand and optimise the controlling factors for MECSM, and to increase confidence in planning a successful field trial.

Phase 2 (2010-17) was commissioned under the sponsorship of AGL, Australia Pacific LNG (APLNG), and Santos. The overarching objective of Phase 2 was to enable predictions of microbially stimulated methane production in coal seams, through understanding the relationships with the microbial consortiums present; the formulation and concentration of nutrients; and the nature of the coal susceptible to microbial activity and its physical parameters.

Phases 2A and 2B (2010-14) included the following key activities:

- optimisation of the nutrient mixture to maximise the rate of methane production for various scenarios;
- analyses of samples for gas composition, stable isotopes, water chemistry, BTEX (benzene, toluene, ethylbenzene, and xylene) and microbial metabolites to characterise methanogenic pathways;
- quantification of the rate of methane production for reservoir temperatures and pressures;
- evaluation of nutrient uptake, considering both microbial use and absorption; and
- modification of an existing coal seam gas reservoir simulator to represent MECSM™ and employ it to make predictions to aid in field trial design.

Phase 2C (2014-17)was largely focussed on ascertaining the optimal 'in seam' conditions to maximise the rates and duration of gas generation during in situ microbial enhancement, and on developing extension technologies that leveraged the knowledge gained from previous phases. This included special consideration of the fate of nutrients. The new information gathered will be applied to further develop the field trial design.

Phase 3 (2017-18) is the demonstration of the process in the field. Field trials are in the planning stage to commence in 2017.

Outputs

The key outputs of Phase 1 and Phase 2 activities include:

- Data generated on reservoir characteristics, microbial diversity and methanogenic potential, and optimising nutrient formulations;
- Models predicting reservoir performance;
- New equipment, such as biological reactors and core flooding rigs;

- Published scientific papers; and
- IP/patents, including novel methods for incubation, chemical analyses, replicating reservoir conditions, modelling, and nutrient formulation and delivery captured in four patents.

CSIRO Publications related to the R2T, including abstracts but not reports

Faiz, MM & Hendry, P 2006, 'Significance of microbial activity in Australian coal seam gas reservoirs – a review', *Bulletin of Canadian Petroleum Geology*, vol. 54, pp. 261-272.

Faiz, M & Hendry, P 2008, 'Prospects for microbial enhancement of Australian Coal seam Methane Reservoirs'*, The Australian Petroleum Exploration Association Journal*, vol. 48.

Li D, Hendry P & Faiz M 2008, 'A survey of the microbial populations in some Australian coalbed methane reservoirs', *International Journal of Coal Geology,* vol. 76, pp. 14–24.

Midgley, DJ, Pinetown, KL, Fuentes, D, Gong, S, Mitchell, DL, Sherwood, NR & Hendry, P 2010, 'Living on lignite: Molecular characterisation of microbial communities in coal seam formation water from the Gippsland Basin, Australia', *Proceedings of the 13th International Symposium on Microbial Ecology*, Seattle, USA, 22 – 27 August.

Midgley, DJ, Hendry, P, Pinetown, KL, Fuentes, D, Gong, S, Mitchell, DL & Faiz, M 2010, 'Characterisation of a microbial community associated with a deep, coal seam methane reservoir in the Gippsland Basin, Australia. *International Journal of Coal Geology*, vol. 82, no. 3-4, pp. 232–239.

Tran-Dinh, N, Midgley, DJ, Li, D, Pinetown, KL, Sherwood, N, Faiz, M & Hendry, P 2012, 'Microbially Enhanced Coal Seam Methane (MECSM): Biogenic gas production from coals from the Sydney, Surat, Gunnedah and Bowen Basins', *Proceedings of the 34th International Geological Congress*, Brisbane, Australia, 5 – 10 August.

Tran-Dinh, N, Midgley, DJ, Sestak, S, Rosewarne, CP, Vockler, CJ, Greenfield, P & Sherwood, N 2014, 'Looking Inside The Black Rocks,'Omic Exploration Of The Coal Microbiome', *Proceedings of 31st Annual Meeting of The Society for Organic Petrology (TSOP) —Organic Matter Down Under II.*

Tran-Dinh, N, Sestak, S, Rosewarne, CP, Vockler, CJ Greenfield, P & Sherwood, N. 2015, 'Metagenomic glimpses into coal-to-methane conversion by a microbial consortium sourced from the Talinga gas field, Queensland, Australia', International Society for Microbial Ecology.

Vick SHW, Tetu SG, Sherwood N, et al. 2016, 'Revealing colonisation and biofilm formation of an adherent coal seam associated microbial community on a coal surface', *International Journal of Coal Geology*, vol. 160–161, pp. 42–50.

Wang H, Lin H, Rosewarne CP, et al. 2016, 'Enhancing biogenic methane generation from a brown coal by combining different microbial communities', *International Journal of Coal Geology* vol. 154–155, pp. 107–110.

Wang H, Lin H, Rosewarne, CP, Li, DM, Gong, S, Hendry, P, Greenfield, P, Sherwood, N & Midgley, DJ 2016, 'Mixed mangrove and coal seam microbial communities for enhancement of methanogenesis from brown coal', *International Journal of Coal Geology,* vol. 154-155, pp. 107-110.

Outcomes

The primary potential user of the research outcomes is the Australian CSG exploration industry. However, potential impacts may also accrue for Commonwealth and State/Territory governments, and community stakeholders.

The channels of adoption include:

- commercialisation of CSIRO's technology;
- communication and capacity building, especially training and research activities; and
- Policy/Regulation.

As at the end of 2016, there were approximately 6,386 wells that were inactive or expected to become inactive over the next 15 years (Ramos 2016). In some instances, there is the potential for CSIRO to provide the coal analysis and the composing of nutrients as a service to companies to rejuvenate the gas production in these wells. In addition, this technology has the potential to enable the further production of methane in depleted CSG wells.

The introduction of new technologies such as R2T may reduce the need to drill more gas wells, and may also provide the opportunity to enhance local energy gas production[1]. Throughout the existing project, the technology has gained significant commercial interest from CSG companies. For example, Origin Energy has included the technology in its June 2016 investor's presentation, claiming an annual value of approximately $3.3 million per well in capital expenditure reduction or delays in expenditure (Origin Energy 2016).

Table 4.2: Adoption profile by wells

Year	Number of new adopted wells	Number of accumulative adopted wells	% of total inactive wells (accumulative)
2017	1	1	0.02%
2018	2	3	0.05%
2019	3	6	0.09%
2020	4	10	0.16%
2021	5	15	0.23%
2022	6	21	0.33%
2023	7	28	0.44%
2024	8	36	0.56%
2025	9	45	0.70%
2026	10	55	0.86%
2027	11	66	1.03%
2028	12	78	1.22%
2029	13	91	1.42%
2030	14	105	1.64%
2031	15	120	1.88%

Note: a) the total number of inactive wells are 6,386 as of the end of 2016

Source: Ramos (2016).

[1] If a company wants to increase its production it could drill more wells as well as apply the R2T to existing wells.

A -15 year adoption profile was developed to assess the potential uptake and adoption of the technology. The following assumptions were make for this analysis:

- The market size was the 6,386 wells that are inactive or expected to become inactive over the next 15 years.
- In the expanded field trial period (2017-19), the initial market uptake was estimated to be 5 inactive wells. It is estimated that from 2019 onward, production conditions will exist which will result in growth stage (Ramos 2016).

At the conclusion of the 15-year analysis, the technology were being applied to a total of 120 wells, which is equivalent to 1.88% of the total number CSG wells expected to be inactive over the next 15 years. This is a very conservative assumption which will give great confidence in our evaluation results.

Impacts

The R2T program has a variety of potential impacts, including increased efficiency in production of CSG, increased energy security for Australia, and reduced greenhouse gas emissions. Using CSIRO's triple bottom line impact classification approach, Table 4.3 summarises the nature of these potential impacts.

The estimated economic benefits are discussed below. The potential environmental and social benefits are noted, but not assessed, given the constraints of data availability.

Table 4.3: Impact of R2T project

TYPE	CATEGORY	INDICATOR	DESCRIPTION
Economic	Productivity and efficiency	Cost savings in CSG production	With the appropriate injection of microbial consortia or nutrients, an average of an additional 10 years is added to the life of a well. The addition of microbial consortia or nutrients to existing wells requires only operating costs for the process rather than capital costs to drill a new well.
Economic	Productivity and efficiency	Reduced agricultural production loss	A 2016 CSIRO study found that sample area averages an agricultural production loss of $2.17 million (gross output) over 20 years due to the existence of CSG infrastructure. If adopted, each rejuvenated well delays the construction of a new well by 10 years, therefore reduces the agricultural production loss.
Environmental	Environment	Water quality and biodiversity	New CSG development might cause environmental damage through release of production water at the surface; damage to, underground aquifers by hydraulic fracturing; damage to wildlife habitat in sensitive areas and contamination of surface water resources in drinking water catchments. The environmental damage can be decreased because fewer wells and associated infrastructure are required.
Social	Resilience	Income and employment	Much of the industry is located in rural areas where there are small populations, limited employment opportunities, and high unemployment rates. Increased production by the industry potentially increases the viability of industry-dependent communities – especially those with fewer alternative employment opportunities.
	Security	Energy security	The R2T increases the coal seam methane sources in Australia, thereby contributing to the nation's energy security.

5 Clarifying the Impacts

Counterfactual

In the United States, similar technologies to CSIRO's R2T have been developed (see, e.g., Luca Technology, Ciris Energy, Next Fuel, etc.). These technologies focus on stimulating microorganisms to produce additional coal seam methane from existing production wells. While other R2T programs exist elsewhere in the world, CSIRO has overcome some of the barriers that others have confronted when it comes to the microbial enhancement of CSG.

CSIRO's R2T process is expected to bring more potential benefits to the industry with the development of a novel protection of the nutrient delivering process. This technology is anticipated to be part of the R2T; and has demonstrated through several experiments that the encapsulation technology brings significant value to the R2T implementation.

It is assumed that without CSIRO's involvement and investment in the program, there would have been insignificant improvement of the microbial enhancement technology for CSG; and, consequently, that the barriers that other research organisations/bodies have confronted would probably have remained. Without prolonging the life of existing CSG wells, new wells will need to be drilled.

Attribution

CSIRO was the primary source of research, and the R2T expertise and resources, that underpinned the development of the process and products needed to microbially enhance CSG yield. Other contributors to the successful implementation of the CSIRO research include AGL Energy, Apollo Gas (previously Macquarie Energy), Eastern Star Gas, Origin Energy/APLNG, QGC, Earth Resources, Sydney Gas, and Santos, which provided important co-financing from 2008 to 2017. Industry partners have also played an important role in collecting water and rock samples; and providing critical background information, especially with regard to implementation in the field.

Since all of the CSIRO and industry stakeholders were considered necessary to achieve the ultimate objective of developing microbially-enhanced technology for CSG production, it was appropriate to attribute benefits among the project on a cost-sharing basis. CSIRO accounted for approximately 5% per cent of the total research and implementation costs. Consequently, in this analysis, we use a conservative estimate and assume that that roughly 5% per cent of the benefits arising from the research program can be attributed to CSIRO.

6 Valuing the Impacts

Cost-Benefit Analysis

Definition

This section provides a definition of key input costs, benefits, and our method of calculating the benefit-cost ratio (BCR) in this analysis. The process of calculating the BCR for CSIRO is a two-staged process.

Stage 1: Calculating the costs and benefits at the program level

Input costs are costs incurred by CSIRO and its collaborators to produce the research outputs. They include costs associated with such things as staff, in-kind contributions, equipment/facilities, and background IP. Where data is available, input costs should also include usage and adoption costs borne by the end users, such as costs of any trials, further development, and market tests.

Benefits represent cost savings in CSG production due to the fact that the need to drill a new well will be delayed. It is assumed that the average rejuvenated well produces the same annual output as a new well, and that the rejuvenated well has an average life of 10 years and a new well, an average life of 20 years.

Stage 2: Attributing the benefits to CSIRO and calculating a BCR for CSIRO

Input costs are costs incurred by CSIRO to produce the research outputs. They include costs associated with such things as staff, in-kind contributions, equipment/facilities, and background IP.

Benefits represent cost savings in CSG production that are attributable to CSIRO based on a cost sharing basis.

Therefore, the formula for calculating a BCR for CSIRO is defined as cost savings benefits attributable to CSIRO (Present Value) divided by all CSIRO's research costs (Present Value). This ratio can also be interpreted as a "Net Benefit/Research Investment Ratio".

$$Benefit\ Cost\ Ratio = PV(B_t)/\ PV(C_t)$$

Where

$PV(B_t)$ is the present value of the net benefits attributable to CSIRO at time t

$PV(C_t)$ is the present value of CSIRO's research costs at time t

Time period

While the R2T program is an ongoing activity, it is necessary to define a particular period for the cost-benefit analysis (CBA). Given the history of the project, the analysis is based on research activity since 2008/09.

In the program, there are lags between the development of the processes and products needed to microbially enhance CSG yield, and the realisation of benefits after adoption by the CSG industry. In recent years, the lag has averaged 10 years[2]. On that basis, the benefits are only measured from 2018/19 onwards. In the analysis, the costs from 2008/09 are included.

Given the costs are measured until 2016/17, the benefit must be estimated for the future, since the processes and products of the R2T developed and released before 2016/17 provide a foundation for CSG production impacts for many years. The life span of a coal seam production

[2] Author's analysis based on the CSIRO example.

well is typically between 10 to 20 years (Khan & Kordek 2014). CSIRO's R2T could expand the lifespan of existing wells by at least 10 years[3] (Ramos 2016). In this analysis, a conservative approach is adopted and it is assumed that benefits are measured to 2030/31.

Thus the analysis involves a small component of ex-post analysis (relating to the costs in the period 2008/09-2016/17), but also a large component of ex-ante analysis forecasting the benefits flowing from the research activities over the period to 2030/31. A thorough evaluation requires solid evidence to substantiate value. Particularly important is the maturity of research and evidence of uptake/adoption as the basis for projections. This valuation provides a ball-park estimate of the potential net benefits, therefore requires the need for a follow-up revision of the valuation once the results of the ongoing trials become available.

Costs

Research costs in the CBA had to include all relevant costs that went into developing the new MECSM™ technology. In addition to CSIRO's investment, industry investment and in-kind contributions were also critical in providing access to samples and sites for trials, without which the research could not have been undertaken. In our analysis, we assume that the implementation costs is $0.45m per well (2016/17 price) from 2017/18 to 2030/31 (Ramos 2016). Table 6.1 summarise the adjusted all costs for developing the new MECSMTM technology.

Table 6.1: Summary of CSIRO and industry adjusted project costs ($m)

	Present value of collaborators costs (2008/09- 2016/17)	Present value of CSIRO costs(2008/09- 2016/17)	Present value of implementation cost (2017/18 to 2030/31)
Total ($m)	6.4	1.4	27.3
% of total cost	17.0	5.3	77.7

Source: CSIRO

Benefits to 2030/31

The benefits calculated in the analysis are the difference between the 'with' and 'without program' scenarios. The analysis is equivalent to carrying out separate analyses for the 'with program' and 'without program' scenarios and calculating the difference between them.

The steps in quantifying the gains from the program are as follows:

1. Combine the cost savings per well in each year with the number of wells under adoption due to the program, to get an estimate of the cost savings in that year and all subsequent years.
2. Attribute the cost savings to CSIRO on a cost sharing basis for that year and all subsequent years.
3. All past benefit flows from 2008/09 to 2016/17 are compounded forward to 2016/17 and the benefits from 2016/17 to 2030/31 are discounted back to 2016/17 at a real discount rate of 7% to convert benefit flows to a present value in 2016/17.

[3] It will differ from well to well based on the microbial content and commercial viability (cost vs price). For the purpose of this evaluation, we believe this is a fair assumption.

Reduced costs in CSG production

With the appropriate injection of microbial consortia or nutrients, an average of an additional 10 years is added to the life of a well. The addition of microbial consortia or nutrients to existing wells requires only operating costs for the process rather than capital costs to drill a new well. The assumptions and sources for this benefit are outlined in Table 6.2.

As illustrated in Table 6.2, the key benefit is the difference in capital costs between rejuvenation versus new wells to produce the same CSG output. In the "with CSIRO research" scenario, the capital cost is assume to be a one-off set up costs for implementation R2T technology at a cost of $0.45m per well. These costs include regulatory approval, negotiation of agreement, and injection of technology into CSG well. In the "without CSIRO research" scenario, the capital costs is primarily exploration costs for finding and developing a new well such as cost of exploration, engineering and economic feasibility studies, procurement of finance, construction of pilot plants and all technical and administrative overheads directly associated with these functions.

Table 6.2: Costs benefits from the R2T project

Measures		Value	Source
With CSIRO research			
A_R	Additional economic life of a rejuvenated well (years)	10	Ramos (2016)
B_R	Initial R2T set up costs per well ($m) under adoption	0.45	Ramos (2016)
C_R	Annual operating costs per well ($m)	2.22	APPEA (2014)
D_R	Annuity Factor (year 10 at 7%)	7.024	
E_R	Annual cost per well under adoption ($m)	$=(B_{R+/} D_R) + C_R$	$2.28 m
Counterfactual			
A_c	Economic life of a new well	20	Ramos (2016)
B_c	Exploration cost of a new well ($m)	6.21	APPEA (2014)
C_c	Annual operating costs per well ($m)	2.22	APPEA (2014)
D_c	Annuity Factor (year 20 at 7%)	10.594	
E_c	Annual cost per well ($m)	$= (B_{c+/} D_c) + Cc$	$2.80 m
Impacts			
	World with CSIRO research – counterfactual		
	Cost savings per well per year ($m)	$=E_R - E_c$	$0.52 m

This shows that with the given assumptions each rejuvenated well generates a net benefit in terms of costs savings equivalent to $0.52m/annum over its life (10 years) in comparison with a new well.

Agriculture production loss delayed

A 2016 CSIRO study found that sample area averages a loss in gross output of $2.17 million (present value over 20 years due to the existence of CSG infrastructure (Marinoni and Garcia 2016). It found the biggest cause of losses to agricultural production was from gas industry access tracks and lease areas.

The R2T technology could delay the agriculture loss by 10 years. I examined the change in present values, which resulted in a gross savings of $1,100 (2016/17 dollars) per well per year under a 7% discount rate. This figure doesn't take into consideration of industry compensation paid back to landowners. Given the uncertainly around industry compensations, this benefit has not been included in our calculation.

The flows of costs and benefits from 2008/09 to 2030/31 (Table 6.4) were used to calculate the investment criteria. Investment criteria were estimated for both total investment and for the CSIRO investment alone (see Table 6.5). Results are attributed to CSIRO on the basis of cost shares.

Table 6.4: Analysis of benefits and costs of the R2T project

Year	Benefits from the program					Discounted @ 7%		
	Benefits ($m) A	Attribution rate B	CSIRO benefits ($m) C=A*B	Costs ($m) D	Net benefits E=C-D	Benefits ($m)	Costs ($m)	Net benefits ($m)
2008		5.28%		0.04	-0.04		0.08	-0.08
2009		5.28%		0.04	-0.04		0.07	-0.07
2010		5.28%		0.18	-0.18		0.26	-0.26
2011		5.28%	-	0.17	-0.17		0.24	-0.24
2012		5.28%	-	0.17	-0.17		0.22	-0.22
2013		5.28%	-	0.16	-0.16		0.20	-0.20
2014		5.28%	-	0.12	-0.12		0.13	-0.13
2015		5.28%	-	0.12	-0.12		0.12	-0.12
2016		5.28%	-	0.12	-0.12		0.12	-0.12
2017	0.38	5.28%	0.02	0.00	0.02	0.02		0.02
2018	1.13	5.28%	0.06		0.06	0.05		0.05
2019	2.25	5.28%	0.12		0.12	0.10		0.10
2020	3.75	5.28%	0.20		0.20	0.15		0.15
2021	5.63	5.28%	0.30		0.30	0.21		0.21
2022	7.88	5.28%	0.42		0.42	0.28		0.28
2023	10.51	5.28%	0.56		0.56	0.35		0.35
2024	13.51	5.28%	0.71		0.71	0.42		0.42
2025	16.89	5.28%	0.89		0.89	0.49		0.49
2026	20.64	5.28%	1.09		1.09	0.55		0.55
2027	24.39	5.28%	1.29		1.29	0.61		0.61
2028	28.15	5.28%	1.49		1.49	0.66		0.66
2029	31.90	5.28%	1.68		1.68	0.70		0.70
2030	35.65	5.28%	1.88		1.88	0.73		0.73
2031	39.41	5.28%	2.08		2.08	0.75		0.75

Source: CSIRO

Table 6.5: Results of cost benefit analysis

Criteria	CSIRO	Program
Present value of costs ($ m)	1.44	35.10
Present value of benefits ($ m)	6.06	114.82
Net Present Value (NPV)	4.62	79.72
Benefit-cost Ratio (BCR)	4.21	3.27

Table 6.5 summarises the present value of the increased benefits resulting from reduced CSG production costs. Benefits ranges from $114.82 million ('Program in context') to $6.06 million ('CSIRO in context'). Assuming total costs of $35.1 million and $1.44 million respectively, then BCRs from the research range from 3.27:1 ('Program in context') to 4.21:1 ('CSIRO in context'). Despite the conservative estimates of the potential benefits that might be delivered by the R2T program, the total estimated benefits comfortably exceed the costs of the research.

Distribution effects on users

The CSG has a net positive economic benefit to Australia and the affected regions. However, the distribution of these benefits and costs vary. Although distribution effects were not considered to be a significant issue, it is worth noting that the majority of the benefits identified accrue to the CSG industry. These benefits allow them to either increase production levels, or reduce costs for the same level of production.

Externalities or other flow-on effects on non-users

In terms of flow-on effects, some of the benefits assigned to CSG producers will be shared along the input supply and market supply chains, including both domestic and foreign consumers. There may be some potential environmental benefits in terms of new pathways to reduce emissions. For example, conversion of CO_2 that is artificially stored in a coal seam to methane could significantly benefit the environment. However, there are some uncertainties around the magnitude of these benefits due to the fact that further research is required to overcome some of the barriers related to the microbial enhancement of CSG.

In recent years, questions have been raised about the fugitive emissions (leakage from infrastructure) from the CSG production process. However, a pilot study undertaken by CSIRO indicates that of the 43 wells examined, only three showed no emissions and the remainder had some level of emission, but generally the emission rates were very low, especially when compared to the volume of gas produced from the wells (CSIRO 2014). Although this is a very low figure, it's important to note that this is only a pilot study, encompassing less than one per cent of the existing CSG wells in Australia. Another important consideration is that emissions were only measured from well pads, so cannot give a full representation of the whole-of-life emissions.

7 Sensitivity analysis

While the R2T looks promising, the establishment of a fully functioning and sustainable CSG extraction project using CSIRO technology is not certain. The take-up of new technology on a large scale relies on a number of legislative, environmental, and competition factors. For example, regulation in Australia could limit the viability of the technology. The nutrients being used and the methods of injection may require further development following field trails. In addition, the value of technology is partially dependent on the global gas price.

Given these uncertainties, it would be useful to look at results under different discount, adoption, and attribution rates. NPV and BCR calculations are particularly sensitive to changes in underlying parameters, so it is important to understand the results in perspective. In this section, we analyse the impact of variations in the discount, adoption, and attribution rates as well as the value of gas prices on benefit and cost streams coming out of our central case. The results of that analysis are shown in Table 7.1.

Table 7.1: Results of sensitivity analysis

Assumption	Central assumption	Low assumption	High assumption	BCR (low assumption)	BCR (central assumption)	BCR (high assumption)
Discount rate (%)	7	5	10	3.61	4.21	5.14
Additional life for CSG wells (years)	10	5	15	2.73	4.21	4.57
Exploration costs of a new well ($m)	4.5	3	6	2.57	4.21	5.85
Number of adopted wells (%)	No change	20% decrease	20% increase	3.37	4.21	5.05
Benefits of the program attributable to CSIRO (%)	5	2	10	1.59	4.21	7.97

Note: When we increase the discount rate the NPV also increases. The reason is that as the discount rate increases so too does the difference between the annualised cost of a new well vs. a rejuvenated well, thus increasing the annual benefit.

While the parameters used in the base-case scenario seemed reasonable in the light of current realities on the ground, it is nevertheless important to test the robustness of our conclusions to variations in these assumptions. The low and high alternative assumptions used in the above sensitivity analysis were brought together to estimate the benefit and cost streams under pessimistic and optimistic scenarios by combining changes across all variables jointly. The results under these different assumptions are summarised in Table 7.2. Based on this analysis, we estimate that the BCR of R2T is between 0.42 and 16.0.

Table 7.2: Alternative assumptions for sensitivity analysis.

Assumption	Pessimistic	Central (baseline)	Optimistic
Discount rate (%)	10	7	5
Additional life for CSG wells (years)	5	10	15
Exploration costs of a new well ($m)	3	4.5	6
Number of adopted wells (%)	20% decrease	No change	20% increase
Benefits of the program attributable to CSIRO (%)	2	5	10
Benefit cost ratio	0.42	4.21	16.0

8 Limitations and Future Directions

This evaluation uses a mixed methodology to evaluate the research impact arising from the R2T Program. It combines quantitative and qualitative methods to illustrate the nature of the

technology's economic, environmental, and social impacts. In cases where the impacts can be assessed in monetary terms, a cost-benefit analysis (CBA) is used as a primary tool for evaluation. As a methodology for impact assessment, CBA relies on the use of assumptions and judgments made by the authors. This relates primarily to the economic indicators for impact contribution, attribution, and the counterfactual. These limitations should be considered when interpreting the results presented in this case study.

Given the scope and budget for the analysis, we acknowledge that there are some limitations with regard to the evidence base of impacts. For example, the increase in CSG production volume was based on estimates only as limited information was available about the actual gains over time due to commercial confidentiality. In addition, reduced adverse environmental impacts, protection of employment, and increased sustainability of regional communities were not quantified, but were treated as potential impacts, owing to a lack of reliable data. This evaluation is mainly an ex-ante evaluation which makes the CBA a highly uncertain exercise, at best, providing a ball-park estimate of the potential net benefits.

In the future, we needs to address some key data constraints in terms of uptake and adoption of the R2T technology by engaging with customers and other stakeholders to collect data and information to ensure a robust and thorough investigation of all of the triple-bottom line outcomes and impacts. It is highly recommended that a follow-up revision of the CBA be undertaken once the results of the ongoing trials become available.

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CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

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Strategy, Market Vision and Innovation
Dr Anne-Maree Dowd
Executive Manager
t +61 7 3327 4468
e anne-maree.dowd@csiro.au
w http://my.csiro.au/impact