RESEARCH IMPACT EVALUATION

Direct Injection Carbon Engine (DICE)

Case Study

June 2017

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1 Executive Summary

Global warming, largely caused by increases in greenhouse gases in the atmosphere, is a modern challenge. While various actions can be taken to reduce greenhouse gas emissions, the size of the problem is so large that a mix of approaches is necessary. Coal-based electricity provides about 80 per cent of Australia's National Electricity Market (NEM) supply. The major challenge for coal-fired power generation is to reduce its CO_2 emissions.

CSIRO has been developing an alternative pathway to low emissions electricity from coal and other sources of carbon through the Direct Injection Carbon Engine (DICE) project. DICE is suitable for large scale electricity generation and decentralised applications at industrial or remote locations. Benefits of this technology include increased efficiencies in electricity generation; significant reduction in greenhouse gas emissions, delivery of power in a shorter timeframe and at a smaller scale than conventional coal technologies, and diverse fuel potential including black and brown coal, as well as biomass, tar and plastics.

DICE technology is probably best described as in the demonstration to deployment phase of development which brings uncertainty into the cost analysis. Therefore, more data is needed to substantiate this analysis. As this was not available at the time of preparing this report, consideration of this issue is based on data published by the Australian Energy Technology Assessment 2012 report.

In addition, the overall benefits of the DICE project depend crucially on the adoption profile and actual achievement of cost savings. Most of this adoption takes place in the future, so impact analysis outcomes are associated with some uncertainty. A revisit to the analysis is highly recommended when more recent data is available.

Looking at the midpoint of a range of impacts, our estimates suggest that the real program expenditure of $61.8 million will lead to:

- Total benefits (measured as cost savings in capital/operating costs, carbon emissions, in real, present value terms) between -$477 million and $532 million, depending on the assumptions made ("program in context"); and
- A benefit cost ratio between -7.7:1 and 8.6:1 ("program in context").

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

INPUTS	ACTIVITIES	OUTPUTS	OUTCOMES	IMPACT
• CSIRO investment (FTE, in-kind contributions, equipment/facilities and background IP) • Investment from DICEnet and Brown Coal Innovation Australia Limited • Costs of adaptive development and extension by the industry.	• Develop an adapted diesel engine technology for carbonaceous aqueous slurry fuel. • Develop fuel cycle logistics. • Adapt diesel engine technology for biomass fuel.	• Suitable MRC slurries for use in DICE. • Solutions for adapting fuel systems and managing engine wear. • Novel coal cleaning techniques. • IP& patents • Publications.	***Uptake and adoption*** • Adoption of DICE technology by both Australian and international electricity generators. • Produce ultra-low ash MRC economically from a range of coal sources. • High efficiency and low emissions coal electricity generation for communities	***Economic impact*** • Lower capital and operating costs for power generation • New commodity (MRC fuel) for national and international market ***Environmental impact*** • Reduction in CO2 emissions • Reduction in water use for cooling ***Social impact*** • Contribution to energy security and stability

Figure 1: Impact pathway for DICE project

2 Purpose and audience

This evaluation is being undertaken to demonstrate to a range of stakeholders the potential positive impacts arising from CSIRO's Direct Injection Carbon Engine (DICE) research. Given that the research program is yet to complete large scale engine tests, and an estimated 3-5 years are required before the first commercial DICE power plant is expected to be operational, this evaluation is a forward-looking assessment of the likely future outcomes and impacts, rather than a description of outcomes and impacts that have been realised.

This case study can be read as a standalone report or aggregated with other case studies to substantiate the impact and value of CSIRO's activities relative to the funds invested in these activities.

This case study is proposed 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-based electricity provides about 80 per cent of Australia's NEM electricity supply. Australia has the second largest brown coal resource in the world but current utilisation technologies are carbon intensive so we need to implement cleaner and more efficient ways to generate energy from coal. While CO_2 capture and storage (CCS) has the potential to reduce these high emissions, both the costs and amount of CO_2 that would need to be captured and stored is high. There are strong needs to develop new clean coal technologies to reduce CO_2 intensity (Wibberly 2011).

In collaboration with industry partners including Exergen, Ignite Energy Resources, AGL, MAN Diesel & Turbo and Energy Australia, CSIRO has been developing an alternative pathway to low emissions electricity from coal and other sources of carbon through the Direct Injection Carbon Engine (DICE). DICE is a modified diesel engine running on a mix of coal and water. This advanced coal technology involves converting coal or biomass into a water-based slurry- a fuel called micronized refined carbon (MRC) that is directly injected into a large, specially adapted diesel engine. The fuel burns to produce intense temperature and pressure in the engine, which provides highly efficient power to turn electrical generators. CSIRO's research will help determine whether DICE can enable brown coal to produce Australia's lowest cost, reduced CO_2 electricity for the staged replacement of existing coal power plants. An existing laboratory scale prototype engine will trial fuel based on Victorian brown coal and this work will be followed by trials using the same fuel in a large scale test engine in Japan.

Although DICE has been shown to be technically feasible for a range of coals, there is no equivalent data for the use of biomass in DICE, i.e. *bio*DICE. *bio*DICE is a renewable technology which offers the potential to provide near zero net greenhouse gas emissions (GHGs), be cost competitive with wind power generation and offer dispatchable power production. In 2016, CSIRO submitted a funding proposal to Australian Renewable Energy Agency (ARENA) on the feasibility study into dispatchable, cost effective power from forest and mill waste using the *bio*DICE.

An international umbrella organisation, DICEnet has been established to help coordinate efforts, and a staged, integrated DICE development program has been devised for both black and brown coals with a goal of a large-scale demonstration after 2020.

4 Impact Pathway

Project Inputs

DICE has been the recipient of investment to the value of more than $15 million from a range of research and development organisations. These investments have contributed to the establishment of the DICE project and to the improvement in the accuracy and technical fidelity of the simulations and outputs generated. Estimates of the funding by institution for the project are show in Table 4.1.

Table 4.1: Total investment in DICE Project ($m nominal)

Year	CSIRO (in-kind)	Industry (cash)	Total
2009-10	$1.4	$2.3	$3.7
2010-11	$1.8	$2.0	$3.8
2011-12	$1.3	$1.2	$2.5
2012-13	$1.1	$0.9	$2.0
2013-14	$0.2	$0	$0.2
2014-15	$0.5	$1.0	$1.5
2015-16	$1.1	$0.5	$1.6
Total	**$7.4**	**$7.9**	**$15.3**

Source: CSIRO.

Activities

The energy division at CSIRO has a long history with coal research. In 2007, CSIRO reassessed the use of coal in diesel engines and began work on the DICE engine. CSIRO’s DICE research program has been underway for 10 years with the goals of developing the DICE concept, obtaining fundamental data for key process steps and producing fuel for engine tests. The key activities have been divided as DICE and *Bio*DICE.

<u>DICE</u>

The key activities involved laboratory experiments to improve MRC production techniques and to modify diesel engines to use coal water slurries. The presence of ash in MRC used in DICE engines increases wear and reduces the operational lifespan of DICE engines. Research at CSIRO has focused on removing ash from coal sources in an economically and environmentally friendly manner. Large scale MRC production and fuel cycle logistics were developed. CSIRO successfully trailed a small scale demonstration of DICE in a 1MW single cylinder engine in Japan in 2016.

CSIRO has tested small scale DICE engines to improve the efficiency of DICE engines. Issues related to engine wear, jamming, fouling and ignition delay were investigated. Adapting diesel engine technology for biomass fuel, to halve the cost and double the benefit of biomass, were also investigated. Novel solutions to resolve DICE issues were found.

In the long term, CSIRO aims to facilitate commercial scale adoption of DICE technology. CSIRO will conduct a full scale demonstration of MRC production with a 12-30 megawatt (MW) prototype engine for 8000 h in 2019-2020. If successful, commercial deployment of DICE technology will be able to commence. It is expected the first commercial DICE power plant at a cost of $1.4 million - $2 million/ MW will begin operation in 2020. Adoption of DICE technology has the potential to significantly improve the efficiency and reduce the emissions from coal sourced electricity generation.

*Bio*DICE

A CSIRO report in 2012 indicates that a substantial proportion of Australia's power supply could be generated from biomass. The report indicates that 10 to 20 percent of power production could be available from currently forestry, rising to over 20 percent in coming decades. As a consequence of the high efficiency of the DICE technology, the actual potential power production from *bio*DICE is believed to be significantly higher than indicated in 2012 report. In 2016, CSIRO initiated a project proposal that covers the first stage of a 3 stage program to commercialise *bio*DICE. It is proposed that to commercialise *bio*DICE requires the following stages:

- Stage 1 –testwork and pilot scale trials to obtain data to complete a business plan and the design for a demonstration scale project (ie the present feasibility study).
- Stage 2 – demonstration scale project (5-10 MWe for 8,000 hours at Heyfield, Victoria), culminating in the design of package plant modules.
- Stage 3 – first commercial plant (package plant modules).

ARENA support is requested for Stage 1 – benchtop studies, testwork, a pilot scale engine test, business planning and demonstration plant design. Stage 1 is expected to commerce in April 2017.

Outputs

CSIRO's advanced coal research has developed techniques to produce ultra-low ash MRC economically from a wide range of sources including black/brown coals and biomass. CSIRO has developed fuel cycle logistics, allowing MRC to be safely transported. Improved diesel engines modified to use MRC fuels have been developed. A standard diesel engine cannot use MRC – the fuel pump and atomiser needle/cut off valve will jam within seconds (among other problems).

Publications

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Tulloch, J, Allen, J, Wibberley, L and Donne, S., (2014), 'Influence of selected coal contaminants on graphitic carbon electro-oxidation for application to the direct carbon fuel cell'. *Journal of Power Sources*, vol. 260, pp.140-149.

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Giddey, S, Badwal, S, Wibberley, L., (2010), Coal utilisation in a fuel cell for ultra clean power generation. 9th International Symposium on Advances in Electrochemical Science and Technology (iSAEST-9), Chennai, India, December 2-4, 2010. Society for Advancement of Electrochemical Science and Technology (SAEST).

Wibberley, L, (2009), 'Alternative pathway to lower emissions'. *Energy Generation*, vol. 2009, no. October-December, pp.5-9.

IPs/Patents

The table below provides details of the title, registration number and status of the active Australian filed patents arising from the project.

Table 4.2: Title, registration number and status of the active Australian filed patents

Title	Registration number	Status
Treatment of low rank coals for diesel engines	AU2010205896	Granted
Injection of heavy and particulate laden fuels	AU2013211482	Granted
Method of treatment of low rank coals	AU2012308099	Under examination
Improved carbonaceous slurry fuel	AU2014240271	Granted
Improved fuel system for diesel engines using carbonaceous aqueous slurry fuels	PCT/AU/2017/050016	International phase
Improved injector for diesel engines using slurry and emulsion fuels	AU2016903419	Provisional application

Source: CSIRO.

Outcomes

The primary potential user of the research outcomes is the Australian energy industry. However, potential impacts may also accrue for mineral extraction companies by providing a possible export market for Australian brown and black coal, biomass producers and users of electricity in remote locations.

The channels of adoption include commercialisation, communication and capacity building. Once commercial deployment of DICE technology begins, training electricity generators to install DICE engines and continuing research activities to improve DICE technology and MRC production will increase the rate of DICE adoption.

DICE technology is under development and is probably best described as in the demonstration to deployment phase of development which brings uncertainty into the uptake and adoption analysis. Therefore, data is needed to substantiate the uptake and adoption. As this was not available at the time of preparing this report, consideration of this issue is based on the use of scenario analysis. Scenario analysis is aimed to estimate the potential adoption and associated impacts in Australia.

We suggests two possible scenarios for DICE deployment, assuming that with the introduction of social costs of carbon, DICE is likely to be competitive with other existing energy source.

1. Potential deployment in base-load operations in Australia to displace Brown Coal Supercritical (SC) with carbon prices.
2. Potential deployment in base-load/shoulder-load operations in Australia to displace Combined Cycle Gas Turbine (CCGT) with carbon prices.

Impacts

DICE has a range of potential impacts, including a reduction in the operating costs associated with coal electricity generation, reduced greenhouse gas emissions, reduced water consumption and improved energy security. Using CSIRO's triple bottom line impact classification approach, Table 4.3 summarises the nature of the existing and potential impacts.

Table 4.3: Summary of DICE project impacts

TYPE	CATEGORY	INDICATOR	DESCRIPTION
Economic	Productivity and efficiency	Reduced operating costs	DICE systems have high efficiency at small unit size resulting lower capital cost.
Environmental	Climate	Reduced greenhouse gas emissions	The superior thermal efficiency of DICE systems results in a reduction in kg of CO_2 emitted / MWh of electricity generated.
Environmental	Aquatic environments	Reduced water consumption	The use of DICE systems reduces water consumption as DICE systems do not need cooling water.
Social	Security	Energy security	DICE technology can facilitate intermittent renewable energy penetration by providing rapid response power when renewable energy generators are unable to meet demand, decreasing the cost and improving the effectiveness of renewable energy generation.

Of the benefits identified, economic benefits are estimated in monetary terms, as discussed in the section below. Given the constraints to data availability for social benefits, these benefits are noted, but not assessed.

5 Clarifying the Impacts

Counterfactual

The counterfactual scenario describes what happens if CSIRO's DICE technology is not implemented and the status quo or extension of current trends prevails. As identified in the outcome section, the DICE deployment scenario has been simplified into two broad elements:

- Scenario 1: Potential deployment in base-load operations in Australia to displace Brown Coal SC with carbon prices.
- Scenario 2: Potential deployment in base-load/shoulder-load operations in Australia to displace CCGT with carbon prices.

Conversely, the Counterfactual scenario includes the following two broad key elements:

- Scenario 1: No adoption of DICE as base load to displace Brown Coal SC, as coal substitute for MRC is not expected. Today's approach to pricing and incentive environment prevails resulting in no adoption of incentives for CSIRO's DICE technology. This reflects ongoing carbon policy uncertainty and lack of confidence in and coordination of resources for delivering lower emissions and high variable renewable.
- Scenario 2: No adoption of DICE as base-load/shoulder-load operations to displace CCGT, consistent with current national electricity system planning assumptions. MRC-DICE is not competitive compared to gas when natural gas prices are expected to contained by government policies.

CSIRO's Contribution

As has been noted above, CSIRO was (and remains) an essential member of the consortium which developed and owns DICE technology, and CSIRO remains central to the ongoing development of the DICE technology. It is because of CSIRO's national reach that it was able to undertake extension work in a number of Australian states, and it was through CSIRO's advanced coal power program that this extension took place. It was because of the outreach and research performed by the energy division at CSIRO that CSIRO began working with industry collaborators, DICE itself would not have occurred without CSIRO. Outcomes from the work of DICE can to a significant extent be attributed to CSIRO. Industry collaborators provided important co-financing from 2008 to 2017. The industry has also played an important role by providing access to trail sites and facilities, without which the research could not have been undertaken.

Since all of the CSIRO and industry collaborators were considered necessary to achieve the ultimate objective of developing an alternative technology pathway to reduce CO_2 intensity, it was appropriate to attribute benefits among the project on a cost-sharing basis. CSIRO accounted for approximately 12.3% of the total research, development and extension costs. Consequently, in this analysis, it is assumed that roughly 12 per cent of research impacts arising from CSIRO's DICE technology can be attributed to CSIRO. Based on the above, this case study will attribute total impacts as follows:

6 Evaluating the Impacts

Cost Benefit Analysis

This section provides definition of key input costs, benefits and our method of calculating the benefit cost ratio (BCR) in this analysis.

Input costs are the costs incurred by CSIRO and its research partners to produce the research outputs and include cost 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 adoptions costs borne by the end users such as costs of any trials, further development and market tests. Benefits represent the reduced operating costs and CO_2 emissions relative to traditional diesel fuels.

Therefore, the formula for calculating a benefit cost ratio is defined as economic and environmental benefits (Present Value) divided by all the research, adaptive development and extension costs (Present Value).

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

Where

$PV(B_t)$ is the present value of the benefits at time t

$PV(C_t)$ is the present value of the costs at time t

Time period of analysis

While the DICE program is an ongoing activity, it is necessary to define a particular period for the cost benefit analysis. Given the history of the project, the analysis is based on research activity since 2007/08.

In the program, there are lags between development of the technology and the realisation of benefits after adoption by the industry. In recent years, the lag has averaged 10 years, so that adoption does not take place until the eleventh year after the initial research. On that basis, the benefits are only measured from 2020/21 onwards. In the analysis, the costs from 2007/08 are included.

Given the costs are measured until 2016/17, the benefit must be estimated for the future, since the research done before 2016/17 will have a productive impact for many years. CSIRO's current and growing presence in DICE technology may owe to circumstances where it was one of the earliest providers of such technology. However, over time CSIRO's competitors may have developed similar technology in the absence of CSIRO. The commercial value of first mover advantage is difficult to determine precisely, but given the lack of equivalent technology available at the time that DICE technology was commercialised, we estimated that it would have taken roughly 30 years (until 2050) for other researchers to develop technology that is similar to DICE in the absence of CSIRO.

Costs

Establishing the costs involved throughout the entire inputs to impact pathway is an important exercise of a cost-benefit analysis. This includes both the input costs incurred by CSIRO and its collaborators, as well as any usage and adoption costs borne by clients, external stakeholders, intermediaries, and end users. Wibberley 2014 identified that $75 million from R&D to demonstration and first commercial plant is required.

CSIRO and its research partners contributed $11.15 million and $18 million to the DICE project between 2007/08 and 2016/17 in real terms. These contributions were discounted using a real discount rate of 7%. In our analysis, we assume that the implementation costs is $61.8 million (2016/17 price) from 2015/16 to 2050/51 (Wimberley 2013). Table 6.1 summarise the adjusted all costs for developing and implementing the FGF and Roadmap recommendations.

Table 6.1 Summary of the DICE project costs

	Present value of collaborators costs (2007/08- 2016/17)	Present value of CSIRO costs(2007/08- 2016/17)	Present value of implementation cost (2015/16 to 2050/51)
Total ($m)	$18	$11.15	$61.8
% of total cost	19.8	12.3	68

Source: CSIRO

Note: PV= Present Value

Benefits to 2050/51

We calculated the DICE deployment and counterfactual scenarios to determine the value of the entire research program benefits (where quantification is possible). The counterfactual scenario represents the pathway where the DICE technology is not implemented and a 'status quo' or extension of current trends prevails. Due to data constraints, this analysis focuses on key benefits, namely changes in operating costs, capital costs, fuel costs and GHG emissions.

We acknowledge that the DICE technology is but one of many current proposals for future action by business leaders, politicians, and community groups. Ultimately, only commercial action can enable implementation of the DICE technology. It might therefore be premature, to attribute solely to the research project the expected future benefits. 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 actual uptake/adoption become available.

Table 6.2: Value of the DICE project

	Scenario 1: Deployment of DICE as base load to displace Brown Coal SC($ NPV)	Scenario 2: Deployment of DICE as peak/shoulder load to displace CCGT ($ NPV)
- **With program (A)**	Net cash flow (after tax revenue less net cost)	Net cash flow (after tax revenue less net cost)
- **Without program (B)**	Same as above	Same as above
- **Savings (C= B-A)**	Various	Various

The benefits calculated in the analysis are the net benefits from the program, that is, 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.

Modelling approach

A comparison of national electricity market (NEM) connected power plant scenarios with a range of discount rates, greenhouse gas (GHG) costs, capital costs, variable operating and maintenance (VOM) costs, fixed operating and maintenance (FOM) costs, and fuel costs were undertaken in order to determine the net present value (NPV) of a DICE 200MWe net power plant compared to CCGT 200MWe net and Brown Coal SC 200MWe net.

This model used a discounted cash flow methodology to determine the levelised cost of electricity (LCOE) for each project. The average LCOE for the counterfactual projects (CCGT and Brown Coal) were treated as the average wholesale electricity price applied to the base case projects (DICE) in order to determine the average revenue and NPV for each scenario. In other words, the DICE project NPVs were determined by applying the same wholesale electricity price assumptions to both projects in each comparison.

The following DCF modelling input assumptions are to a large extent based on estimates provided by CSIRO 2016 and the BREE 2012 report. Some input ranges were increased in order to allow for a greater level of uncertainty in the sensitivity analysis. The following cost estimates assume the DICE power plant project and fuel processing plant costs are NOAK (Nth of a kind) and not FOAK (first of a kind). For the DICE and Brown coal SC projects a narrow range of fuel costs were modelled in order to produce similar LCOE estimates to the BREE 2012 report. However, due to the high level of uncertainty in relation to gas prices an additional high gas fuel cost scenario was modelled (see details in table below).

Table 6.2: Key assumptions related to inputs, real terms

Overnight Capital Costs ($/kW net)			
	DICE	CCGT	Brown SC
Low	$ 2,285	$ 1,062	$ 3,788
High	$ 2,363	$ 1,450	$ 4,026
FOM Costs O&M ($/MW/year)			
	DICE	CCGT	Brown SC
Low	$ 27,000	$ 10,000	$ 60,500
High	$ 150,000	$ 20,000	$ 64,000
VOM Costs O&M ($/MWe)			
	DICE	CCGT	Brown SC
Low	$ 8.0	$ 1.5	$ 3.0
High	$ 10.0	$ 4.0	$ 8.0
Fuel Costs ($/MWh)			
	DICE	CCGT	Brown SC
Low	$ 18.0	$ 43.2	$ 7.9
High	$ 21.6	$ 50.5	$ 10.6
Very high		$ 87.0	
GHG Permit $/MWh			
	DICE	CCGT	Brown SC
Low	$ 40.6	$ 21.3	$ 59.4
High	$ 109.2	$ 57.4	$ 159.7
Discount and loan rates (%)			
	DICE	CCGT	Brown SC

Low	7%	7%	7%
High	10%	10%	10%

Source: Estimates derived from CSIRO 2016 and AETA 2012.

The estimated range of average GHG prices are often derived from estimates of the social cost of carbon by 2050. Due to the uncertainty in relation to the direct and indirect GHG costs from the power plant scenarios modelled, a range of carbon prices per tonne similar to those used in AETA 2012 were applied to the projects under consideration and converted into GHG permit costs per MWh in the table below.

The sensitivity analysis of the DICE NPV involved modelling a low and high cost assumption for each of the key inputs while holding all other inputs constant. For instance in one scenario both the DICE and counterfactual projects would be modelled with low cost and discount rate assumptions but would adjust a single assumption (e.g. incorporating a high capital cost) for both power plants. In another scenario both the DICE and counterfactual projects would be modelled with high cost and discount rate assumptions but would adjust a single assumption (e.g. incorporating a low capital cost) for both power plants. This process was repeated for each input in order to produce a broad range of DICE project NPVs.

The modelling outputs are displayed as either negative or positive NPVs for the DICE project under each scenario. The NPV results for DICE ranges from -$477m to $532m.

Table 6.3: DICE NPV relative to CCGT and Brown Coal SC, real terms ($m)

DICE NPV relative to CCGT	
Min	$ (477.60)
Max	$ 202.28
Average	$ (217.16)
DICE NPV relative to Brown Coal SC	
Min	$ 125.84
Max	$ 532.96
Average	$ 315.04

Note: results are based on 32 simulations.

The flows of costs and benefits from 2007/08 to 2050/51 are used to calculate investment criteria. Investment criteria was estimated for both total investment and for the CSIRO investment alone, as reported Table 6.4. The analysis is not designed to produce precise estimates, but rather a “reasonable” range of estimates under a number of different assumptions reflecting uncertainties about DICE costs and adoption profiles.

Table 6.4: Results of cost benefit analysis

DICE NPV relative to CCGT	Program	CSIRO
Min	-7.7	-5.2
Max	3.3	2.2
Average	-3.5	-2.4
DICE NPV relative to Brown Coal SC	**Program**	**CSIRO**
Min	2.0	1.4
Max	8.6	5.9
Average	5.1	3.5

Assuming total costs of $61.8 million and $11.2 million respectively, then BCRs from the research range from -7.7:1 to 8.6:1 ('program in context') and from -5.2:1 to 5.9:1 ('CSIRO in context'). Table 6.4 highlights the uncertainty of potential deployment of DICE technology in base-load operation in Australia. For example, there is a great degree of uncertainty with regards to the competitiveness of DICE relative to CCGT.

Despite the conservative estimates of the potential benefits that might be delivered by the DICE relative to Brown Coal SC, the total estimated benefits comfortably exceed the costs of the research by more than one order of magnitude.

Distribution effects on users

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 coal-based electricity providers. These benefits allow them to either increase production level, or reduce costs for the same level of production.

Externalities or other flow-on effects on non-users

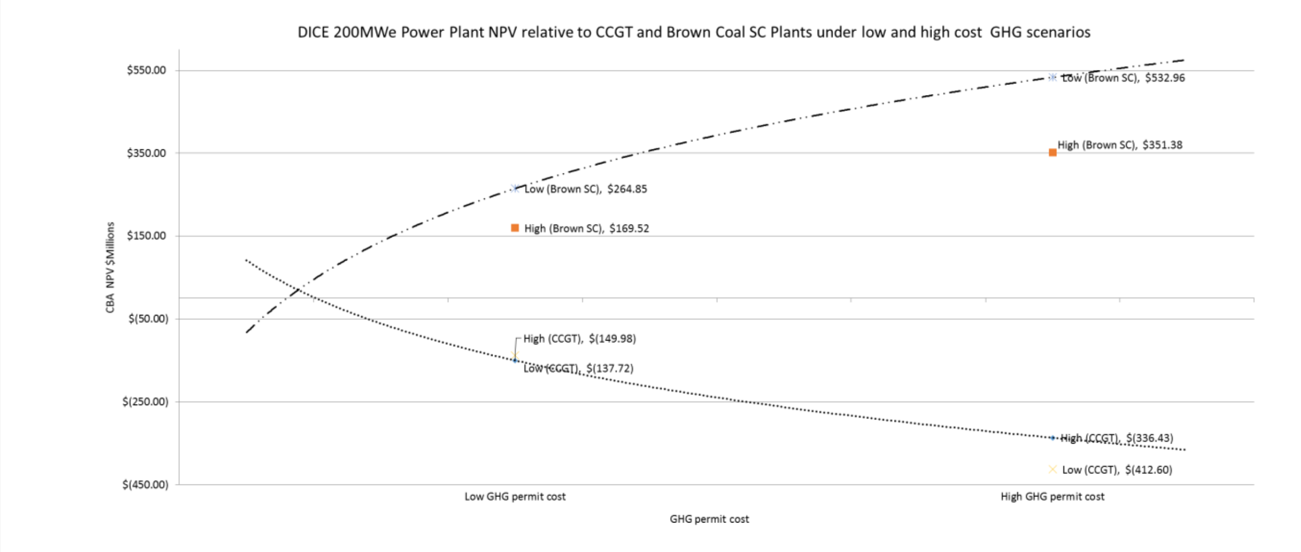
In terms of flow-on effects, some of the benefits assigned to DICE technology producers will be shared along the input supply and market supply chains, including both domestic and foreign consumers. There may be some potential environmental benefits in terms of new pathways to reduce emissions. For example, DICE technology reduces CO_2 intensity of around 20 – 30 per cent for black coal and 30 – 50 per cent for brown coals (depending on whether DICE is used for new or replacement of old coal generation capacity).

7 Sensitivity analysis

While the DICE technology look promising, commercial scale adoption of DICE using CSIRO technology is not certain. The take-up of new technology on a large scale relies on a number of environmental, economic and competition factors. For example the price and availability of substitute rapid response electricity generation, most notably natural gas, and the political and community tolerance for coal electricity generation.

The NPV results reported in section 6 (including max, min and average) provide a summary of the broad range of NPV values produced in the sensitivity analysis. In this section, we analyse the impact of variation in carbon prices. Figure 7.1 highlights the influence on our analysis of changes in key assumptions. The NPV and BCR ratio calculations are particularly sensitive to changes in the attribution rates. For example, the NPVs and BCRs ranges from -$412.60 million to $532.96 million in the high carbon cost scenario compared to $137.72 million to $264.85 million in the low carbon cost scenario These results reflect a broad range of potential outcomes for the technology due to ongoing carbon policy uncertainty and lack of confidence in and coordination of resources for delivering lower emissions.

Figure 7.1: Results of cost benefit analysis under low and high cost GHG scenarios.



8 Limitations and Future Directions

This evaluation uses a mixed methodology to evaluate the research impact arising from the DICE technology. 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 uptake and adoption rate of DICE in electricity generation was based on estimates only as limited information was available about the actual gains over time due to commercial confidentiality. In addition, energy security was not quantified, but were treated as potential impacts, owing to a lack of reliable data.

9 References

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