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Potential opportunities and impacts of a hydrogen economy for the Australian minerals industry

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ABSTRACT

The hydrogen economy is one of the key areas of interest for the reduction of societal greenhouse gas emissions. However, the potential for impact of hydrogen technologies in the transition to a hydrogen economy will vary across the different industrial sectors depending on the source and usage of current energy sources. This paper presents a broad examination of hydrogen economy opportunities and impacts for the minerals industry in Australia. The usage of hydrogen and fuel cell technology in the mining and metals production sub-sectors has differing potential as metallurgical and heavy-duty mobile energy consumption may not be feasibly substituted with hydrogen. This examination indicates a potential of 12–13% reduction in primary energy usage by the minerals industry, with a resulting reduction in greenhouse gas emissions of 9–12% without carbon capture and storage (CCS), or 53–60% reduction with CCS. Other impacts on the industry may include an increased demand for minerals to produce fuel cells, catalysts and infrastructure. Minimal local reserves of platinum group metals are likely to be the limiting capacity factor.

1. Introduction

The hydrogen economy presents a challenging target for research and development into the reduction of societal greenhouse emissions. There is currently extensive research into fuel cell technology and hydrogen storage, and the various technical challenges in the life cycle of production and utilisation of hydrogen. The individual characteristics of each sector of the economy however, mean that the impacts and potential for implementing a hydrogen economy will be different. This paper takes a near-term, transitional, fossil fuel-based hydrogen economy scenario for Australia, and examines the potential implications for the minerals sector within this scenario.

The minerals industry is a key sector in Australia, supplying approximately 2% of jobs and $120 billions of value added to the economy [1,2]. It also utilises approximately 18% (1030 PJ/yr) of Australia's total energy consumption [3], and contributes greater than 12.3% of the country's total greenhouse gas emissions (GHGs) [4]. Although there is potential for the minerals industry to reduce its environmental impact, observations of declining ore grades [5] and the corresponding increase in energy intensity required in mineral extraction imply an even greater necessity for energy efficiency gains to ensure the sustainability of the industry.

Furthermore, there will be demand for products from the minerals industry. Platinum group metals (PGM), nickel and other metals are used widely as electrode and catalyst

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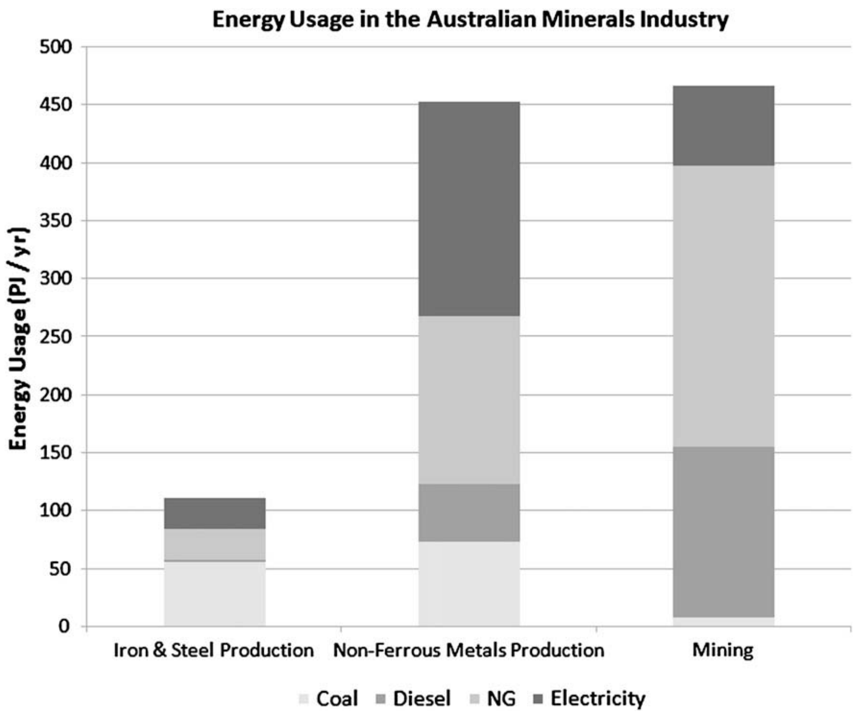

Fig. 1 – Energy usage in the Australian minerals industry by type [3].

materials in the production of hydrogen and fuel cells. Some assessment of the availability and projected requirements of these metals have been performed on a global scale [6,7] which can give an indication of potential impacts in Australia. Energy minerals, especially coal in the Australian context [8], would also be affected by the introduction of a hydrogen economy. Increase or decreased demand for coal for gasification to produce hydrogen or electricity, and the potential use of other uneconomic coal seams for carbon storage are two areas that could particularly impact on the Australian minerals industry.

Previous examination of hydrogen economy opportunities for Australia has shown that fossil fuels are the most likely early sources of hydrogen, due to the abundance of fossil fuels, the strength of the fossil electricity industry and the availability of proven, cost effective technology in the form of natural gas steam reforming and coal gasification [8].

Most of the current works on hydrogen fuel cells for mobile applications are focussed on light duty vehicles, and hydrogen polymer electrolyte membrane fuel cells (PEMFC) are identified as the key technology. Heavy-duty mobile applications of fuel cell technology, as required for the minerals industry,

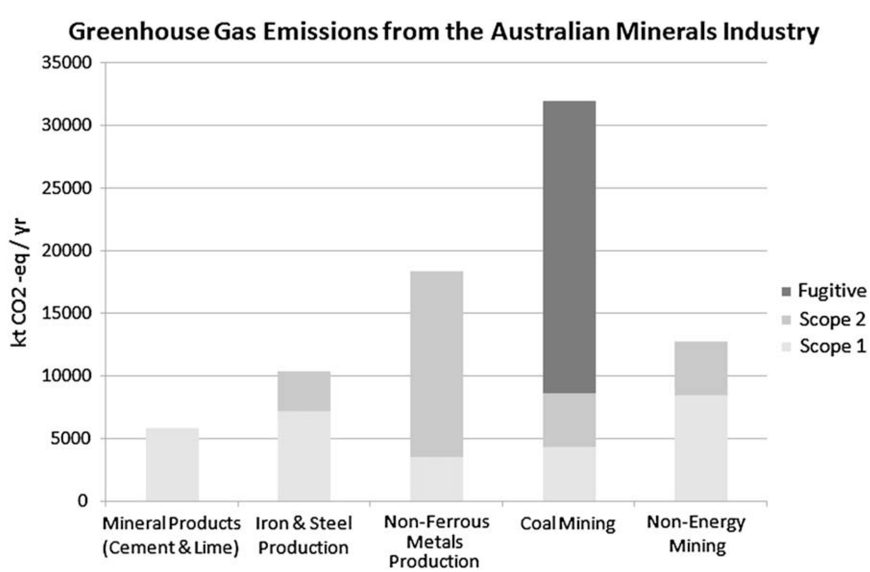

Fig. 2 – Greenhouse gas emissions from the Australian minerals industry by source [4].

Table 1 – Efficiencies utilised in the hydrogen economy scenarios.

Process efficiency	Natural gas steam reforming	Coal gasification
H_2 production efficiency (% HHV[a])	80	60 (H_2 production)
H_2 utilisation efficiency (% HHV)	50 (PEMFC), 70 (SOFC/GT)	50 (PEMFC), 70 (SOFC/GT)
Overall mobile efficiency (% HHV)	40	30
Overall stationary efficiency (% HHV)	56	42

a Higher heating value.

have not been widely examined, and there are indications that the cost is prohibitive where other factors (such as direct emissions concerns) are not in play [9]. Achieving the required operational range for freight and haulage operations is also a limiting factor, as cost-effective high-density hydrogen storage is not currently available. On-board reforming and high temperature fuel cells could find a niche application in mine haulage operations, if cost and design factors are overcome. Of the research into heavy-duty applications that have so far been completed, applications to locomotives [9–12] and significant work focussed on underground mining applications of fuel cells [9,13–16] are of particular interest in the current examination.

2. Minerals industry opportunities from a hydrogen economy

The opportunities and impacts of a hydrogen economy on the minerals industry are divided into two categories for the purpose of this work – firstly, the direct energy and greenhouse gas reduction impact on the minerals industry itself, and secondly, other potential indirect or flow-on effects of a broader implementation of hydrogen technologies on minerals operations and markets.

2.1. *Energy and greenhouse impacts*

Currently, the minerals industry utilises approximately 18% of Australia's total energy consumption [3], and produces 12.3% of the total greenhouse gas emissions [4] through direct metallurgical, on-site fuel usage and indirectly through offsite electricity production. The breakdown of energy and emissions in terms of the minerals industry sub-sector[1] and location of emissions or energy source are given in Figs. 1 and 2.[2,3] The major sources of energy utilised in mining are natural gas and diesel (52% and 32% of mining energy usage respectively), which corresponds to the largest proportion of GHGs from on-site fuel usage except in the case of coal mining, in which fugitive emissions of methane from coal are particularly significant. On the other hand, production of metals has a much larger proportion of electricity in the energy mix (24.6% for iron & steel and 41% for non-ferrous metals), which corresponds to the high energy intensive refining and smelting processes utilised in the industry [17]. In the mining sector, it is assumed for the analysis described here that natural gas and diesel are used largely as a combustion fuel for mining equipment (although some of the diesel will be used for blasting)[4], whilst in metals production it is used predominately as a metallurgical or direct heating agent. Although hydrogen can be combusted to provide heat, if the hydrogen is assumed to be derived from fossil fuels then the conversion step from fossil fuel to hydrogen reduces the overall efficiency of primary energy usage, and would likely[5] result in no overall net benefit. Hence the majority of mining related energy usage is assumed to be substituted with hydrogen fuel cell powered operations, whilst in the metals production phases, only electricity usage is assumed to be substituted.

In this analysis a transitional hydrogen economy scenario is used, in which fossil fuels are assumed to be the major source of hydrogen and electricity. It is assumed that hydrogen is produced from coal gasification and natural gas steam reforming, and stationary electricity is produced from integration with hydrogen fuel cells (Integrated gasification fuel cell cycle (IGFC) or Natural gas reforming fuel cell cycle (NGFC)). Mobile applications are assumed to utilise hydrogen-fed PEMFC, whilst stationary applications utilise Solid Oxide Fuel Cells combined with a gas turbine (SOFC/GT) to enhance efficiency. All electrical operations are therefore assumed to be hydrogen-run, with subsequent efficiency improvements. No CO_2 is assumed to be captured and stored in the initial examination. Table 1 indicates the efficiencies of production and utilisation assumed in this analysis, and the corresponding fuel cycle efficiency for mobile and stationary operations. These are compared with modern diesel combustion engine efficiency of 40% [18], natural gas combined-cycle efficiency of 50%, natural gas engine efficiency of 42% [19–21], conventional coal power station efficiency of 36% [22] and the Australian national grid efficiency of 32.9% [3].

For mobile applications, Scenario A assumes that underground mine operations are able to utilise fuel cells, but open cut operations would continue to operate on diesel as fuel cells would be too expensive. Estimates based on the data of Mudd [5] indicate that approximately 80–90% of Australian mining (by tonnage) is open cut[6]. Taking 80% as a conservative

[1] The sub-sector breakdown is not reliably available at the same level of detail for energy use as for greenhouse gas emissions.

[2] Minor energy sources are not considered in this study.

[3] Scope 1 emissions are direct combustion production onsite; Scope 2 emissions are from electricity generation offsite.

[4] Transport of product and consumables offsite is not examined here, as it is accounted for by the transport sector, although it is recognised as an issue of potential importance, with the road and rail freight sector utilising approximately 150 PJ of fuel each year (not specifically for minerals).

[5] Uncertainties around distance of transport and necessary equipment design variations make an absolute assessment impractical at this point.

[6] Minerals production by mass is dominated by iron ore and coal, which are both dominated by open cut production in Australia.

Table 2 – Fuel usage and substitutability assumption summary.

Energy source	Mining			Metals Production		
	Current usage (PJ)	Hydrogen economy substitutability		Current usage (PJ)	Hydrogen economy substitutability	
		Scenario A	Scenario B		Scenario A	Scenario B
Coal	7.8	100%	100%	128.9	0%	0%
Natural Gas	242.2	20%	100%	171	0%	0%
Diesel	147.5	20%	100%	51	0%	100%
Electricity	69.4	100%	100%	212.7	100%	100%

Table 3 – Resultant reduction in primary energy usage and greenhouse gas emissions in the minerals industry under hydrogen economy scenarios.

Sector	Primary energy usage (PJ)			Greenhouse gas emissions (kt CO_2-eq/yr)		
	Current[a]	Scenario A	Scenario B	Current[b]	Scenario A	Scenario B
Mining	608	−7.9%	−6.3%	64,417	−5.5%	−1.3%
Metals Production	997	−15.9%	−15.9%	78,114	−17.1%	−15.9%
Minerals Industry	1606	−12.9%	−12.3%	142,530	−11.9%	−9.3%

a Primary energy usage is calculated from the known fuel usage figures and back-calculation of grid electricity mix.
b Greenhouse emissions differ from earlier figures because energy usage figures for gas extraction were unable to be extracted from the mining figures, and metals production contains energy usage for forging and casting. Earlier quoted figures are assumed to be more accurate on a sub-sectoral basis, but the figures shown here are appropriate for correlation with the energy usage calculations in the scenario analysis.

figure, Scenario A allows for 20% of diesel and natural gas usage in mining to be converted to hydrogen. Scenario B assumes that all diesel and natural gas operations can be converted to fuel cells, and hence obtain an efficiency and greenhouse gas benefit. Table 2 summarizes the substitutability of energy sources assumed in the scenarios. In both scenarios, diesel and coal are assumed to be substituted with coal-derived hydrogen, whilst natural gas is substituted with natural gas-derived hydrogen. This assumption allows for current fuel-delivery infrastructure to be retained for onsite hydrogen production (i.e. natural gas pipelines and train or truck-based delivery of diesel and coal).

In order to correlate greenhouse gas emissions and energy usage as closely as possible, the Australian electricity grid efficiency of 32.9% [3] is used to back-calculate the primary energy usage to produce the electricity used in the minerals industry. Current electricity production is dominated by coal (84%) and natural gas (11%)[7], which are also leading sources of hydrogen, so the electricity mix is simplified for this analysis to consist entirely of coal (88%) and natural gas (12%). The primary energy balances of coal, natural gas and diesel were then derived for each scenario. Greenhouse gas emissions factors from the Australian Government Department of Climate Change [23] for combustion of coal (88.43 kt CO_2-eq/PJ), natural gas (51.33 kt CO_2-eq/PJ) and diesel (69.5 kt CO_2-eq/PJ) were utilised in estimating emissions reduction from the energy balances. As a result of converting to a hydrogen economy under the above assumptions, the resulting reductions in greenhouse gas and primary energy are shown in Table 3.

The difference in energy reduction and GHG reduction in the mining sector is mostly attributable to the fugitive emissions from coal mining, which is not affected by the energy efficiency gains. The substitution of diesel for coal-based hydrogen production for fuel cells results in an increase of GHG emissions, due to the efficiencies assumed (40% for diesel and 30% for coal-derived hydrogen fuel cells), and the higher emissions from coal as compared with diesel combustion. The assumption that all diesel fuel substitution will be taken up by coal-derived hydrogen is compared with alternative substitution regimes in Figs. 3 and 4. The alternative regimes assume that diesel is replaced with hydrogen sourced from natural gas and coal at current electricity grid ratios, or from natural gas alone. The resultant reduction in emissions across the industry is enhanced, in line with expectations, as shown in Table 4.

Integrated gasification plants are advantageous in providing a high concentration CO_2 stream for capture and storage. If 90% CO_2 capture and storage on coal hydrogen and power plants are assumed (on the original assumptions), the greenhouse emissions reductions improve dramatically, as shown in Table 5. These emissions reductions are approaching the levels proposed by various nations as 2050 targets however, the energy intensity increase suggested by decreasing ore grades would diminish the overall reduction.

2.2. *Resource impacts and opportunities*

With the development of hydrogen technology there are numerous opportunities and impacts that could arise for the

[7] This analysis is based on a near-term scenario, not including other promising hydrogen production methods or electricity sources such as nuclear (which has little current political backing) and renewable (which are relegated to mid/long term sources due to cost factors).

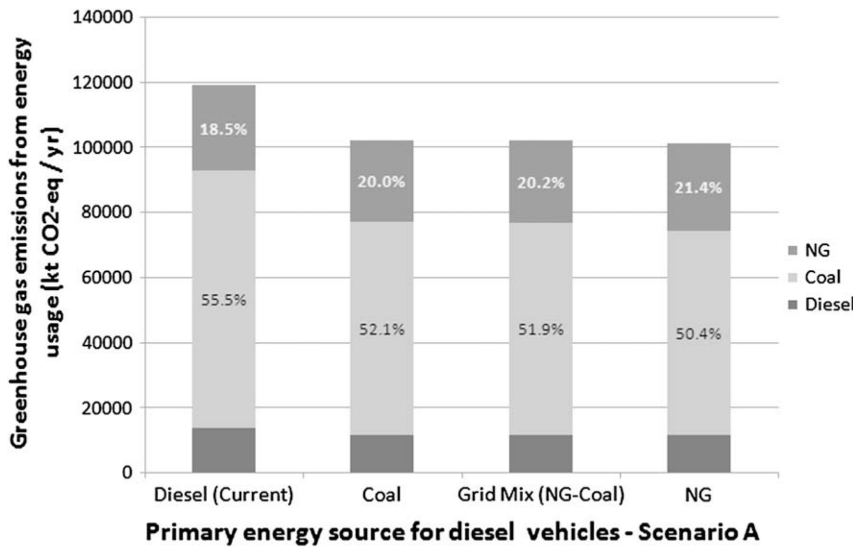

Fig. 3 – Comparison of alternative diesel substitution regimes for minerals industry in Scenario A (percentages indicate the contribution of primary energy source to total minerals industry greenhouse gas emissions).

minerals industry, outside the direct reduction of greenhouse gas emissions. A broad technology and infrastructure analysis would reveal more details of the potential impacts and benefits, some of which are examined here.

Coal gasification replacing diesel fuel and current coal-fired power plants under the previous scenario would lead to a decrease in coal used for the minerals industry, and for electricity in the wider economy (1370 PJ/yr reduced to 950 PJ/yr). However, with the total substitution of hydrogen for petroleum products for transport and other applications, the coal demand would increase by 1680 PJ/yr, or an overall increase of 2100 PJ/yr (approximately 25% of current saleable coal production).

If a new generation of electricity and hydrogen plants replaces existing coal-fired power stations, there is also an off-shoot opportunity for the minerals industry to provide carbon storage services. Bradshaw et al. indicate that the potential for CO_2 storage in coal seams during enhanced recovery of coal bed methane is in the order of 4700 bcm (approximately 24.5 Gt CO_2) [24]. This could potentially store all of Australia's carbon emissions for the next 40 years (or significantly more if only the emissions that could be captured were considered).

Currently, many of the mining and minerals operations have natural gas supply pipelines and access to grid electricity. Therefore, under the current assumptions of hydrogen source, the infrastructure required for implementation would largely be limited to new generation offsite power stations and onsite reforming plants, distribution and refuelling stations. Further analysis and optimisation, such as that performed by Ogden et al. and Johnson et al. [25,26] to identify economically optimal

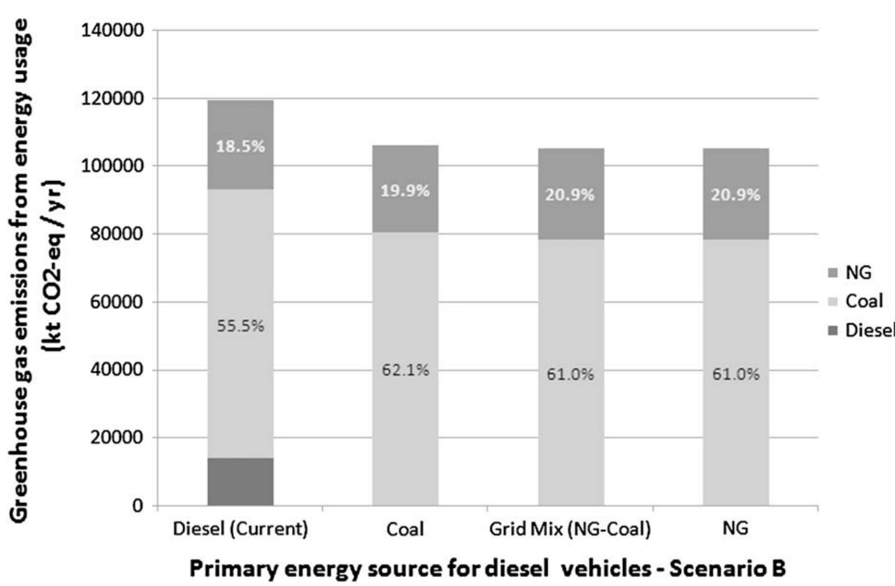

Fig. 4 – Comparison of alternative diesel substitution regimes for minerals industry in Scenario B (percentages indicate the contribution of primary energy source to total minerals industry greenhouse gas emissions).

Table 4 – Comparison of reduction of greenhouse gas emissions using different natural gas - coal mixes for producing hydrogen to substitute for diesel.

Primary source of hydrogen	Greenhouse Gas Emissions Reduction	
	Scenario A	Scenario B
Coal[a]	11.9%	9.3%
Electricity Grid Mix	11.9%	9.9%
Natural gas	12.6%	9.9%

a Original assumption.

hydrogen distribution networks would be an important step in quantifying and confirming this conclusion. The added element to this suggested optimisation (not addressed by previous authors [25,26]) would be that current infrastructure re-use would be valued – as an incentive to the industry, a facilitator to implementation and a key economic and environmental imperative. Utilisation of metals in creating the infrastructure to fuel the wider economy could also be an area for market expansion for the minerals industry.

Other significant areas of interest to the metals industry would be the supply of catalyst and other materials for production of fuel cells. Pehnt [27] has done earlier work on the life cycle assessment of an SOFC, which is used in Table 6 as an example of potential demand for metals for stationary electricity production alone. It is apparent from Table 6, that alumina is the limiting mineral, based on current production (assuming no decrease in current demand). However, given that fuel cells would be produced over a number of years, and much of the material could be recycled, there would likely be no significant impact on availability of alumina. There are limitations to this assessment, in that it does not include Nickel requirements as catalysts for steam reforming, and the only element examined is the fuel cell, however it does give an indication of some of the order of magnitude of impacts from this single area of hydrogen technology. The consideration of reserves and current market displacement are also an area of potential research not examined here. Further requirements for Palladium and Platinum in separation membranes and catalysts would severely limit the potential for local sourcing of materials for an Australian hydrogen economy, as the current production of Palladium is 0.7 t/yr, whilst Platinum is not produced at all in significant quantities. A further assessment of potential expansion of alumina production (currently one of the key contributors to Australia's greenhouse emissions) would enable a clearer assessment of that particular mineral's contribution to the benefits of a hydrogen economy.

Table 5 – Reduction in greenhouse gas emissions from coal gasification with carbon capture and storage.

Sector	Greenhouse Gas Emissions Reduction	
	Scenario A	Scenario B
Mining	27.7%	38.0%
Metals Production	74.2%	78.1%
Minerals Industry	53.2%	60.0%

Table 6 – Amount of metals required to produce the current Australian electricity demand based on SOFC.

	Mineral Product					
	Ni	Al_2O_3	MnO_2	ZrO_2	Fe	Cr
Mass of Mineral for 24 kW SOFC	12.78	8.1	1.8	14.95	11	0.253
Australian Mineral Production (t/yr)	173,686	18,506	441,177	328,597	8,010,000,000	42,425
Mass of Mineral Required (t)						
- Minerals Industry	5959	3777	839	6971	5129	118
- Total Australian Electricity Production	16,983	10,764	2,392	19,867	14,618	336
Percentage of Annual Australian Production (%)						
- Minerals Industry	3.4	20.4	0.2	2.1	0.0	0.3
- Total Australian Electricity Production	9.8	58.2	0.5	6.0	0.0	0.8

Some additional considerations that have not been addressed here, but could be of interest in a full sectoral life cycle assessment are:

- Expanded light metals markets from increase in their use to improve efficiency in a new generation of fuel cell cars
- Effect on recycling markets of taking existing vehicles off the road
- Water production in the fuel cell, and the possibility of its capture and re-usage as process or potable water (especially at remote mine sites).

3. Conclusions

This paper offers an initial examination of potential for a hydrogen economy to impact on the minerals industry. The examination indicates that, given current energy mix and efficiency factors, there is significant potential for a hydrogen economy to reduce energy usage by between 12 and 13%, and decrease corresponding greenhouse gases by between 9 and 12%. It is important to note that the potential for impact is dependent on the sectoral mix of energy sources, as is indicated by the difference in mining and metal's production impacts. When coal gasification is assumed to capture 90% of the emitted CO_2, there is a much greater benefit, indicating that this technology is important to making hydrogen a feasible alternative. The reduction in greenhouse gas emissions is based solely on operational emissions, but a life cycle assessment of hydrogen production, distribution and utilisation infrastructure could decrease the potential for benefit, especially if energy intensive materials such as alumina are required in large amounts.

The minerals industry is unique, in that it is in the position of supplier and user of materials and fuels to support a hydrogen economy. As such, further investigation, especially into the demand side of the hydrogen economy, is warranted in order to assess future potential for the industry. Metals production for fuel cell applications appears at first examination to be limited (especially in Australia) by the availability of scarce catalyst materials such as Platinum, while other mineral compounds are largely available from current production. Potential for the industry to provide services such as carbon storage is also worthy of further investigation – especially in the light of potential trade-offs between coal usage for power/hydrogen and alternative usage for coal bed methane and carbon storage.

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