The Potential Significance of the Australian Hydrogen Industry: An Input-Output Analysis Approach

By

O′CONNOR, Justin Edward

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Committee in charge:

Professor Kim, Dongseok, Supervisor ____________________

Professor Tabakis, Chrysostomos ____________________

Professor Baek, Jisun ____________________

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ABSTRACT

THE POTENTIAL SIGNIFICANCE OF THE AUSTRALIAN HYDROGEN INDUSTRY: AN INPUT-OUTPUT ANALYSIS APPROACH

By

Justin Edward O'Connor

As countries worldwide seek to decarbonise their economies, global interest in hydrogen as a versatile, carbon-free energy solution is strong and growing. Australia has intentions to become a major hydrogen producer and exporter, leveraging its abundant renewable energy resources and strong trade partnerships, especially across Asia. To achieve this ambition, it will be necessary for state and federal governments to justify substantial investment, funding, and policy attention toward scaling up the presently small hydrogen industry in Australia. To inform such justifications, this paper uses an input-output (IO) analysis approach to estimate the economic contributions to GDP and employment resulting from an expanding hydrogen industry out to 2040. This thesis uses scenario-based demand forecasts and proxy IO data to represent the two most important production methods of hydrogen: steam methane reforming (SMR) and electrolysis. The results indicate that the hydrogen industry has the potential to make significant contributions to Australia, with the most optimistic scenario projecting over $14 billion in GDP and support of almost 57,000 jobs by 2040. Another important finding of this paper is that per unit of hydrogen produced, there may be additional gains to GDP and employment through carbon-free, electrolysis-produced hydrogen, over the fossil-fuel based SMR, adding an economic justification to the environmental case for an accelerated transition toward so-called ‘green hydrogen’. As the first academic paper addressing the economic impact of the Australian hydrogen industry, the detailed descriptions of the data and methodology applied offer a foundation which future research will build upon. Future research priorities include detailed surveys of hydrogen industry inputs and uses, along with estimations on the extent to which fossil fuels will be substituted by hydrogen, with intention of calculating the net economic impact of the transition to an Australian hydrogen society.

Keywords: hydrogen, energy, Australia, input-output, economic impact analysis, gross domestic product, employment, electrolysis, exports, fuel cell electric vehicles

Dedicated to Lachlan, for a greener future.

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1. Introduction

As countries worldwide seek to decarbonise their economies, interest in hydrogen as a versatile, carbon-free energy solution is strong and growing. Despite the small size of the present-day hydrogen industry in Australia, the National Hydrogen Strategy (COAG Energy Council, 2019) sent a strong message of state and federal governments' intention for Australia to become a 'major player in a global hydrogen industry by 2030' (p. 83), particularly as an exporter. This ambition is based on Australia's rich resource base, strong trade partnerships, and experience in the 1970s of developing its liquefied natural gas (LNG) industry from infancy to becoming one of the largest LNG exporters in the world (Deloitte, 2019; PWC, 2020). The significance of such comparisons between the hydrogen and LNG industries are revealed by the economic contribution of the latter: over AUD$31 billion[1] in 2015–16, or roughly two per cent of GDP (CSIRO, 2017). However, just as with the Australian LNG industry, achieving the desired level of growth will involve significant and ongoing investment, innovation, and policy support. Furthermore, to make such investments, political discourse on the energy transition in Australia has required that environmental justifications be paired with compelling economic cases for change. As such, this paper responds to public and private sector demand for reasonable estimates on the potential economic contribution of the Australian hydrogen industry out to 2040.

Research estimating the impacts of various aspects of the hydrogen industry have been conducted across numerous countries, including Australia. While some studies examine the impacts of hydrogen across the range of its potential applications and production methods (Deloitte, 2019; Smith et al., 2017; Wietschel & Seydel, 2007), others focus on specific production methods,

[1] AUD – Australian dollars. All dollar figures cited in this paper will refer to Australian dollars unless specified otherwise.

such as biohydrogen (Lee, Lee, & Chiu, 2011; Lee, Lee, & Veziroglu, 2011) or naphtha-reforming (Hienuki, 2017), or specific uses, such as in fuel cell vehicles (Chun et al., 2014) or for export (ACIL Allen Consulting for ARENA, 2018). Only two reports deal specifically with the Australian hydrogen industry (ACIL Allen Consulting for ARENA, 2018; Deloitte, 2019), both of them produced by private consulting firms commissioned by government. There are currently no academically published estimates of the hydrogen industry's economic potential. One disadvantage of the lack of academic studies is that, due to the consulting firms' use of propriety information, important assumptions and inputs to their models are not published along with their results. The lack of transparency of their models therefore makes it difficult to verify and critique the results of their analysis. The aim of this paper is to address this issue by providing detailed and transparent descriptions of the data and methodology used to produce its estimates.

This paper presents an input-output (IO) analysis approach to estimating the GDP and employment contribution of the Australian hydrogen industry. IO analysis uses IO tables, which show interindustry relationships based on empirical economic survey data (Miller & Blair, 2009). An advantage of IO analysis is that although it extends IO tables, it does not depart from empirical data to the same degree as other approaches, particularly computable general equilibrium (CGE) models, which depend on many more input estimates and assumptions (Rose, 1995). Therefore, the relative simplicity of IO analysis, while adding certain limitations, improves the transparency of the results and methodology, making it ideal for the purpose of this paper: to provide transparent economic contribution estimates for Australian hydrogen and a detailed explanation of the methodology used to produce those estimates.

The first chapter of this thesis, Background, outlines important technical and economic aspects of the hydrogen industry, especially those necessary to understanding key methodological choices made in this analysis. The literature review follows, discussing the various approaches made by international and Australian research on the economic contribution of the hydrogen industry. The next two chapters, Data and Methodology, provide detailed explanations of the inputs to and computations of this analysis. Data describes the IO tables that form the basis of this analysis and provides detailed information on the scenario-based hydrogen demand estimates and industry proxies used to simulate the effect of a new hydrogen industry in the Australian economy. Methodology explains how the proxies were introduced to the IO tables, based on 'new industry impacts' analysis (Miller & Blair, 2009, p. 633), and describes the computation of GDP and employment estimates using demand shock analysis (Miller & Blair, 2009, p. 21). The estimates produced under each scenario are presented in Results, illustrating the direct and indirect GDP contribution of hydrogen to the economy, and the sectoral composition of gains in employment. The Discussion chapter examines the implications of the results for policy and investment and proposes a research agenda for future IO analyses of hydrogen industry economic effects. The paper concludes with recommendations for hydrogen industry researchers and policymakers concerned with achieving the aspirations of Australia's National Hydrogen Strategy (2019).

2. Background

Hydrogen is the most common element in the universe but rarely found naturally in its gaseous, molecular form, H_2. It can however be derived from other substances like natural gas (methane) or water. While hydrogen can be used for energy purposes, the extraction of H_2 from other substances requires the input of energy, making hydrogen an energy ‘vector’ or ‘carrier’ (as opposed to an energy source). Hydrogen energy can be released as heat through combustion or as electricity, as occurs in a fuel cell. It has strong potential in energy markets because: it can store energy longer than batteries; it can be transported as a gas or liquefied form; it is efficient, with roughly three times the energy per unit of mass compared to gasoline; and it can be easily blended (for example, in gas networks) or converted to other substances (such as ammonia), making it extremely versatile. Perhaps most importantly to growing global interest, the use of hydrogen for energy releases no carbon by-product, only water.

To mitigate the effects of climate change, economies around the world are seeking to decarbonise. In the search for cleaner forms of energy, hydrogen is being touted as an important energy solution for many applications. The countries with the largest anticipated demand for hydrogen are concentrated in Asia, including China, South Korea, Japan, and Singapore. All these countries are major energy importers and trading partners of Australia and have announced plans to significantly expand their use of hydrogen in fuel cell vehicles- both passenger and heavy- and as a replacement fuel for liquified natural gas. In Australia, planned applications for hydrogen are in public transport, steel making, blending into gas networks, storage of excess renewable energy, and significant production for export. To service both domestic and international demand for hydrogen, Australia intends to take advantage of its abundant land, renewable energy, and natural gas resources. Exactly what mix of those resources will be used depends on the method of hydrogen production that becomes the preferred approach.

The two production methods of hydrogen that have garnered the most attention are reforming of fossil fuels and electrolysis of water. Fossil fuel-based hydrogen, called ‘grey’ hydrogen, is presently the main form of global production. Of fossil fuel-based methods, the main production processes are steam methane reformation (SMR) and coal gasification (CG)[2]. SMR is currently the dominant method of producing hydrogen, with Grand View Research (cited in Deloitte, 2019) estimating that nearly 80% of global hydrogen is produced through SMR. Another approximately 15% of hydrogen production is also fossil fuel-based, employing CG. These figures approximately represent the same proportions as Australia’s current hydrogen production (Deloitte, 2019). Although the hydrogen produced by these methods can be used cleanly, the extraction process releases carbon dioxide, which is leading to vast and growing amounts of research and investment into electrolysis production. Electrolysis splits water into hydrogen and oxygen gases using electricity and typically some kind of catalyst or membrane. It represents only 5% of present-day hydrogen production. If the electricity used is produced from renewables like solar or wind power, both the production and use of hydrogen effectively involves zero carbon emissions. Hydrogen produced in this manner is called ‘green’ hydrogen. Although electrolyser-produced hydrogen is currently not cost competitive with SMR-produced hydrogen[3], rapidly falling renewable electricity prices- the main source of cost in electrolysis- and the global proliferation of carbon taxes or emissions-trading schemes have lead to expectations that green hydrogen will

[2] Hydrogen (or biohydrogen) can also be produced from gasification of biomass, however current production levels of biohydrogen are negligible (Kuba, 2018).

[3] Given that SMR is currently by far the dominant form of hydrogen production, all Australian hydrogen manufacturing that is produced by fossil fuels (SMR or CG) will henceforth be referred to as Hydrogen (SMR). In contrast, hydrogen produced by any means of electrolysis will simply be referred to as Hydrogen (Electrolysis). Where this paper refers to ‘the hydrogen industry’ without clarification, it will refer to hydrogen produced by all means of production.

become both the environmentally and economically preferred form of hydrogen, potentially even within this decade (Bloomberg New Energy Finance, 2020; Longden et al., 2020).

Australia has strong potential to become a major producer and exporter of hydrogen over the coming years and decades. Currently, Australia produces a relatively small amount of hydrogen mainly as a feedstock to ammonia production. Indeed, the size of the hydrogen production industry in Australia is so small that it does not presently feature as a standalone industry in Australian IO tables. However, though not a major producer of ammonia or hydrogen at present, economists and thinktanks globally identify Australia as capable of capturing a substantial portion of global demand, especially in Asia (COAG Energy Council, 2019; Deloitte, 2019; PWC, 2020). Confidence in the Australian hydrogen industry's growth potential is based on low cost, abundant renewable energy, strong trade relationships with the largest future hydrogen importers like Japan, South Korea, China and Singapore, and a demonstrated reputation for industrialising the production of commodities, with natural gas as a primary example (Deloitte, 2019; PWC, 2020). As Australia and other economies prepare for and implement major energy transitions, such as that proposed by hydrogen energy, rigorous estimation of the resulting economic benefits have become an increasingly critical area of research. Both international and Australian research conducting such estimations for the hydrogen industry are reviewed in the following chapter.

3. Literature Review

Globally, the number of studies estimating the economic impacts of a new hydrogen industry is small but growing. Overseas there are a number of peer-reviewed journal articles using IO analysis at the national or regional level to analyse the economic impact of hydrogen for the EU (Wietschel & Seydel, 2007), Japan (Hienuki, 2017), Korea (Chun et al., 2014), Taiwan (Lee & Lee, 2008), the US and China (Lee, Lee, & Chiu, 2011). Smith et al. (2017) published a report for the hydrogen and fuel cell research hub, H2FC Supergen, that applied IO analysis to assess the GDP and employment impacts of hydrogen on the UK economy. In Australia, there have been two such reports, both produced by private consulting firms (ACIL Allen Consulting for ARENA, 2018; Deloitte, 2019). ACIL Allen was commissioned by the Australian Renewable Energy Agency (ARENA) and produced both hydrogen demand forecasts and GDP and employment estimates using IO analysis. Deloitte was engaged by Australia's National Hydrogen Strategy Taskforce and the Council of Australian Governments (now, the National Cabinet) to produce updated, scenario-based hydrogen demand forecasts and economic impact estimates, for which it uses its own CGE model. Review of the various economic impact analyses of hydrogen from Australia and other countries yields two important features for comparison: firstly, the scope of the studies, and secondly, the method by which the structure of the hydrogen industry was estimated within each study's model. These features will each be considered in turn, followed by in-depth analysis of the two Australian reports to highlight this study's contribution clearly.

The scope of hydrogen industry economic impact assessments varies, with some studies examining the impact of hydrogen only from specific production sources or highlighting only specific applications of hydrogen. Lee, Lee, & Chiu (2011) and Lee, Lee, & Veziroglu (2011) focus on the impacts of hydrogen produced from biomass (called 'biohydrogen'). There is some interest in the United States and the EU for including biohydrogen in the overall mix of hydrogen production sources, however, its contribution- presently negligible- is anticipated to remain considerably smaller than SMR or electrolysis-produced hydrogen (Kuba, 2018). Hienuki (2017) focuses their analysis on hydrogen produced through naphtha-reforming, a fossil fuel-based method, and extend their IO analysis to calculate the size of resulting greenhouse gas emissions. All other studies reviewed (ACIL Allen Consulting for ARENA, 2018; Chun et al., 2014; Deloitte, 2020; Smith et al., 2017; Wietschel & Seydel, 2007) consider hydrogen produced by any means, without distinguishing between in the economic effects of different production modes. This thesis captures the vast majority of hydrogen production and offers a new approach by separating fossil fuel-based SMR and renewables-based electrolysis to highlight differing economic impacts resulting from uptake of each production method.

Extant research also differs in consideration of the applications or uses for hydrogen. Demand for hydrogen and hydrogen-powered fuel cell electric vehicles (FCEV) have been the focus of studies in Korea (Chun et al., 2014) and Japan (Hienuki, 2017), where major car manufacturers have developed and released light and heavy FCEV models. Smith et al. (2017) also anticipate considerable future demand for FCEV in the UK, and therefore estimate the impacts of reduced expenditure on refined fuels as consumers switch to hydrogen-powered cars. Their results suggest that as refined fuels sales are substituted with hydrogen, there will be net GDP and employment gains to the UK economy (p.130). The Australian ACIL Allen (Consulting for ARENA, 2018) report focuses exclusively on hydrogen produced for export in both its demand forecasts and IO analysis of economic impacts. While the economic contribution of hydrogen exports is expected to be large, it is generally agreed that Australia will need to first cultivate strong domestic demand, through blending into gas networks and public transport for example, to boost economic efficiencies before engaging seriously in global export markets (Deloitte, 2019; PWC, 2020). This thesis, Deloitte (2019), Lee, Lee, & Chiu (2011), Lee, Lee, & Veziroglu (2011) and Wietschel & Seydel (2007) include all sources of hydrogen demand into their estimates of economic contribution. For this thesis, this is partially achieved by using the hydrogen demand forecasts released by Deloitte (2019, 2020), which are the most recent forecasts for Australia. The other key factor in this paper's inclusion of all hydrogen demand sources is its approach to estimating the structure of the hydrogen industry.

Given the relatively small size of hydrogen industries in each of the countries of each study, it was necessary for each paper to estimate the structure of the hydrogen industry. Researchers used varied approaches to estimate the proportions of intermediate inputs (the 'input' structure), value added (taxes, operating surplus and wages) and sales (the 'distribution' structure) of a mature hydrogen industry. An approach taken by some papers involved surveying expert technical and economic opinions to produce these estimates (Chun et al., 2014; Lee, Lee, & Chiu, 2011; Lee, Lee, & Veziroglu, 2011; Wietschel & Seydel, 2007). This approach has the advantage of a foundation in expertise of current and future trends for an emerging industry. However, there are difficulties in reconciling differences of opinion between experts, particularly those of different fields (economics, engineering, manufacturing etc). Despite conducting an IO analysis, ACIL Allen (Consulting for ARENA, 2018) did not publish how it estimated the input structure of the hydrogen industry. Deloitte (2019) publishes some of the inputs and assumptions to their complex CGE model but withholds substantial details as their proprietary information. This reflects the strength and weakness of CGE models generally: increased sophistication allows them to overcome some limiting assumptions from approaches like IO analysis, however the level of added complexity is at the discretion of the modellers and can obscure exactly how results are obtained

(Rose, 1995). As a result, verification and critique of the methodology and results of both Australian hydrogen reports is extremely difficult.

On the other hand, Smith et al. (2017) use existing industries in the IO table as proxies, based on similarities with the hydrogen industry. They identify two possible candidate industries- manufacturing of gas and electricity generation- that correspond with SMR and electrolysis forms of hydrogen production. This is partly because SMR and electrolysis respectively have natural gas and electricity as their major inputs. The distribution structure of the gas industry is also posited to be appropriate as hydrogen may utilise existing gas distribution infrastructure (Smith et al., 2017, p. 37). IO table proxies used in this way are simplified predictions of an emerging industry but have the benefits of being easily verifiable in publicly available data, a basis in empirical survey data (that used to compile the IO table), and preparation of the data for IO analysis is straightforward. Based on these advantages, this paper uses the proxy approach to estimate the structure of the Australian hydrogen industry. As 'hydrogen manufacturing' is already contained within the larger 'Basic Chemical Manufacturing' industry (ANZSIC 2006), this makes it a natural proxy candidate for the dominant method of hydrogen production: SMR. For the electrolysis-produced hydrogen structure, the approach of Smith et al. is followed, and the 'Electricity Generation' industry is used as the proxy. Details of these proxies are discussed in the next chapter.

Economic impact assessments diverge in the scope and estimation methods of the hydrogen industry. This paper is comprehensive in covering the two major hydrogen production methods- SMR and electrolysis- and all projected domestic and export sources of hydrogen demand. By using proxies to estimate two separate hydrogen industries based on SMR and electrolysis, it goes further than existing reports by examining the distinct economic impacts that result from the different modes of production. This thesis also contributes to Australian hydrogen impact assessments by providing full disclosure of the data used and the methodology applied to produce its estimates. The aim is that by providing greater transparency around key methodological decisions, especially regarding inputs and proxies, the GDP and employment projections will be verifiable, and the IO analysis conducted in this paper will be open to critique and refinement. The following two chapters, Data and Methodology, support this aim by providing details of the inputs and IO analysis of this paper.

4. Data

The previous chapter reviewed Australian and international economic impact estimations of the hydrogen industry, presenting key differences in the data used and the transparency of analytical decisions. This chapter and the subsequent chapter on methodology describe the data sources used and detail the steps taken in the impact analysis, respectively. The Data chapter sections that follow provide descriptions of the Australian IO tables and the data necessary to examine the Australian hydrogen industry through IO analysis. Such data includes proxies of the input and sales structures of the Australian hydrogen industry and descriptions of these proxies in terms of industry multipliers, and forward and backward linkages. The scenario-based hydrogen demand estimates used, based on those published by Deloitte (2019, 2020), and projections of hydrogen production costs (Bloomberg New Energy Finance, 2020; Longden et al., 2020) are also described. Understanding the nature of and assumptions inherent to the data used in economic impact analyses is critical to appropriately interpreting analysis results. To that end, regarding estimation of the economic impact of the hydrogen industry, this chapter explains this paper's improvements upon current research in the scope and transparency of the data applied and identifies limitations to the results produced.

4.1 Australian Input-Output Tables

IO tables are a form of regional or national accounting that describes the sale and purchase relationships between the producers and consumers in an economy (Miller & Blair, 2009). In Australia, the tables are published every few years by the Australian Bureau of Statistics (ABS) following the general format of IO tables. An industry's sales of its product are found along the rows of an IO table, with the first two quadrants representing intermediate demand and final demand (household and government consumption, capital expenditure and exports) respectively.

The inputs to production of an industry's products are found down the columns of an IO table, with the first quadrant representing intermediate inputs and the third quadrant representing primary inputs to production (competing imports and value-added components, including wages and salaries, gross operating surplus and taxes) (McLennan, 1995). In Australian IO tables, the sum of Total Industry Uses (i.e., intermediate demand) and Final Uses (i.e., final demand) is called Total Supply. Total Supply must equal Australian Production, sometimes called 'total input', which is the sum of immediate inputs and the primary inputs to production.

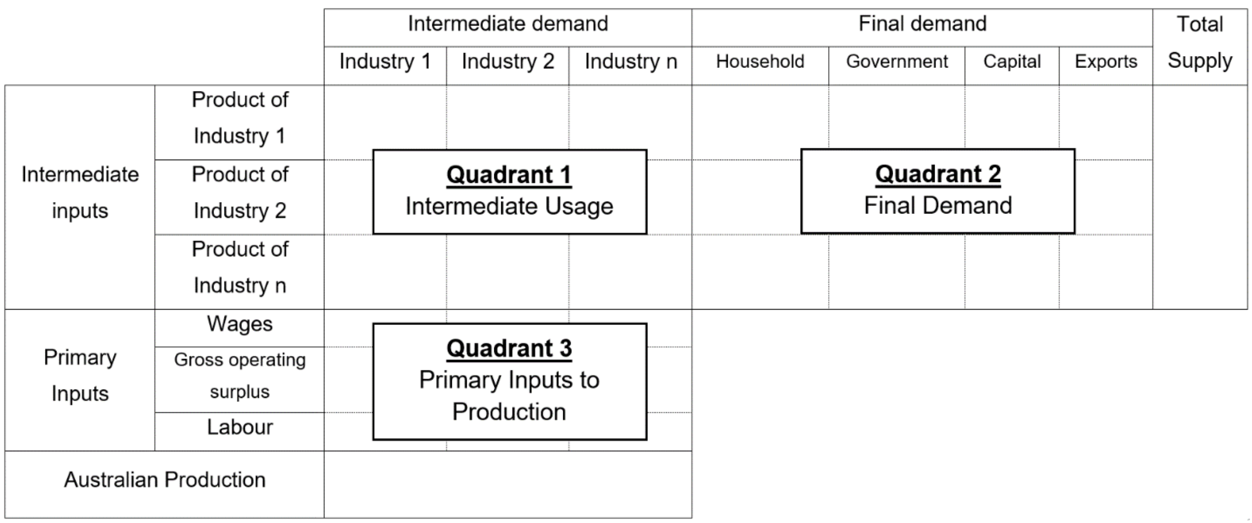

Figure 1 Simplified schematic view of an Australian input-output table

This analysis uses the ABS-published Australian IO tables for domestic production (referred to as 'industry by industry flow table [direct allocation of imports]'), imports, and employment (ABS, 2020a). The latest tables were published in May 2020, and the reference period is the 2017-18 financial year[4]. The delay between reference period and publishing is due to the large scale of the data collection and the complexity of compiling the data into the standard tables. For calculating multipliers- the average economic effects of unit changes in output- the proportions of input values for each industry (column) are assumed to be fixed. Ostensibly, the delays in

[4] The Australian financial year runs from July 1st to June 30th of the following calendar year.

publishing the table could appear to be problematic to the accuracy of such input structures due to technological changes in production over time. However, in most industries technological change does not occur rapidly, and thus standard IO tables and the multipliers generated from them can provide reasonable indications of economic impact resulting from output increases in an industry's product (McLennan, 1995; Miller & Blair, 2009). It is important to understand however the interpretation of an 'industry' and 'product' within an IO table.

IO table data is collected through surveys and organised in accordance with standard IO principles. One important organizing principle is the assumption that each firm produces one product, and firms of the same industry produce the same product (Miller & Blair, 2009). Therefore, it is implied that within each industry (column) there is only one method of production (the principle of homogeneity of inputs) and one pattern of product (row) usage or sales (the principle of homogeneity of disposition) (ABS, 2020b). Where an industry's input meets the same industry's sales, this is typically referred to as the intraindustry sales, representing the sales and purchases between firms of the same industry. These principles are important to present aggregates of the input and distribution structures of many industrially common firms, while also maintaining meaningful distinctions between each industry. The principles are particularly relevant for the proxy selection and aggregation procedure used in this research and are referred to again in subsequent chapters. The next section discusses in detail the data that was used to include the hydrogen industries in the IO table, and evaluates the effectiveness of the approach taken.

4.2 Input-output related data on the Australian hydrogen industry

As discussed earlier, the relatively small size of the present-day hydrogen industry globally means that it does not feature in IO tables as a standalone sector. For that reason, to conduct a new industry analysis and then a demand shock analysis (Miller & Blair, 2009, p. 636), it is necessary to obtain reliable estimates for three aspects of the hydrogen industry- input structure, distribution structure, and intraindustry sales. For an IO table with an $n \ x \ n$ intermediate usage matrix, these three aspects correspond with adding $n + n + 1$ estimates in total (Miller & Blair, 2009, p. 636). Therefore, given that the original intermediate usage quadrant of Australian IO tables is 114 x 114, this means 229 (= 114 + 114 + 1) new estimated values are required to add a single new industry. However, this paper adds two new industries, one for each method of hydrogen production. Therefore, due to addition of the first proxy, which expands the size of the original table to $(n + 1) \ x \ (n + 1)$, or 115 x 115, the second hydrogen proxy requires 231 (= 115 + 115 + 1) new estimated values. In other words, in total, adding the two hydrogen industry proxies requires 229 + 231 new estimated values. The size difference of two between the industry proxies represents each new hydrogen industry's sales to the other new hydrogen industry, or the two hydrogen proxies' interindustry sales, which must also be estimated. The sources and assumptions of all estimates used in this paper are detailed for each production method of hydrogen in the following sections.

4.2.1 Estimating the steam methane reformation produced hydrogen industry

The Australian and New Zealand Standard Industrial Classification (ANZSIC) 2006 indicates that 'hydrogen manufacturing' is contained within Group 181 'Basic Chemical Manufacturing'[5]. This corresponds with the Input-Output Industry Group (IOIG) 1803 of the same name. Given that IO tables are compiled under the principles of homogeneity of inputs and homogeneity of disposition (i.e., similar patterns of product usage), it is reasonable to assume that an approximation of the hydrogen manufacturing component within the Basic Chemical

[5] Appendix B contains details and concordances of the ANZSIC divisions and IOIG numbers. Any number alongside the acronym 'IOIG' is reference to the numerical code used for that industry group.

Manufacturing industry can be disaggregated out and used as an estimate of the 'hydrogen manufacturing' industry. Importantly, the input and distribution structure should be proportional to maintain the homogeneity principles (UN, 1999). Using data from the Observatory of Economic Complexity (OEC) (n.d.), the size of Australian hydrogen manufacturing is approximated at five percent of the total Basic Chemical Manufacturing industry. The calculations as applied to the IO tables are detailed in the Methodology chapter. Given the current dominance of SMR produced hydrogen, the resulting row and column from this disaggregation- hydrogen production- serves as the input and distribution structure of SMR-produced hydrogen.

4.2.2 Estimating the electrolysis-produced hydrogen industry

Hydrogen produced from electrolysers comprise only a small portion of current hydrogen production, estimated at around 3-4% (Deloitte, 2019). The input structure and employment requirements of producing hydrogen from electrolysis will be considerably different from that of SMR-produced hydrogen. As such, the analytical decision was made to estimate a separate industry and product for Hydrogen (Electrolysis). To do this, this paper adopts the approach taken by Smith et al. (2017) and uses 'Electricity Generation', IOIG 2601, as a proxy for the electrolysis-produced hydrogen industry. Their case for this proxy is that electricity is a major input to electrolysers, and both hydrogen and electricity are carriers rather than sources of energy and thus they are both 'produced using energy from a natural resource to realise a delivered energy service' (p. 37). As in Smith et al. (2017), the production input structure of the Electricity Generation industry and the proportion of value-added and employment generated per AUD$ million of Electricity Generation industry output are maintained for the Hydrogen (Electrolysis) proxy. It should be noted that ideally, the precise input structure of electrolyser-produced hydrogen would be obtained through industry surveys and then applied to the analysis. Future research addressing the impacts of the Australian hydrogen industry should address this as a priority.

While the input structures (columns) of each hydrogen industry will be different, given that the same product- hydrogen- is made, it is assumed that the distribution structure (rows) of each hydrogen industry will be identical. This includes the value for intraindustry demand. This is because it is reasonable to assume that the applications of hydrogen will not differ significantly because of production method changes alone. As such, the distribution structures (rows) for each industry are based on the SMR-produced hydrogen industry distribution structure, which is based on the Basic Chemical Manufacturing industry. Finally, considering that future applications of hydrogen- in intermediate and final demand- will continue to diversify and grow, however, future research ought to investigate how the distribution structure for hydrogen will change over time. The calculations applied to the IO tables for the Hydrogen (Electrolysis) proxy are detailed in the Methodology chapter.

4.2.3 New hydrogen interindustry sales

Lastly, the final two values requiring estimation are each new hydrogen industry's sales to the other new hydrogen industry. These values can not be reasonably estimated by this study and as such are set to zero. This results in some underestimation of the economic impacts of the hydrogen industry. One approach taken when such sales estimates are missing is the final demand approach to new industry analysis (Miller & Blair, 2009, p.634). Miller and Blair describe the method as adding a new column only- no new row- to the IO table, implying that the new industry exports all its product, selling none as intermediate input to other industries. In reality, this is almost always an underestimation of new industry impacts and certainly would be with respect to hydrogen in Australia. The alternative method to the final demand approach to new industry analysis is closer to this paper's approach: full inclusion in the technical coefficients matrix (Miller & Blair, 2009, p. 636). By including estimates of the distribution structures of each new hydrogen industry, this paper avoids the substantial underestimation of the final demand approach, at the cost of some minor underestimation.

Another approach would be to combine the two columns and rows to create a unified hydrogen industry. In this approach, hydrogen interindustry sales would simply be contained within the intraindustry estimation. In addition to removing this hydrogen interindustry estimation issue, another argument for this approach is that because they produce the same product, the distribution structure is the same and thus they can be combined in accordance with the principle of homogenous disposition. The counterargument is that, given their different input structures, the principle of homogenous inputs would be violated. In the absence of a universally agreed upon hierarchy between these principles, I take the view that the advantages of being able to analyse the differences in economic impacts on GDP and employment resulting from very different methods of producing of hydrogen outweigh the case for including a single hydrogen industry. The next subsection describes the similarities and differences between each hydrogen proxy from an IO analysis perspective. This initial discussion of the proxy data offers insights into anticipated differences in economic impact that may result as hydrogen production gradually shifts from SMR to electrolysis.

4.2.4 Comparison of hydrogen proxies

This subsection compares the two hydrogen industries based on their input structures, key multipliers, demand ratios, and backward and forward linkage effects. These measures are relevant to IO analysis as they offer preliminary metrics of each industry's economic impacts, in terms of size and spread, resulting from changes to that industry's level of output. Each measure was calculated after inclusion of the hydrogen industry estimates into the Australian IO tables and aggregation of this augmented table from 116 industries and products to 21, comprising the 19 divisions of the Australian and New Zealand Standard Industrial Classification ANZSIC (2006) and the two new hydrogen industries.

4.2.4a Input structures

By dividing each intermediate input and total value-added by the total input of each hydrogen industry, the proportions of each input can be obtained. This is referred to as the input structure or sometimes as the 'production mix'. Table 1 displays the input structures for SMR-produced hydrogen and electrolysis-produced hydrogen. The input share percentages represent both domestic and imported inputs for each industry to emphasize the 'technology of the production system' (West, 1999, p. 18) for hydrogen in each industry, regardless of where inputs are purchased from. Comparison of each industry's input structure highlights differences in both the spread of the inputs (how many different products are significant in producing hydrogen by each method) and the composition (which products are significant in producing hydrogen by each method).

Regarding the spread of inputs, the main inputs to Hydrogen (SMR) are spread more widely than Hydrogen (Electrolysis). In Hydrogen (Electrolysis), almost two-thirds of total input are served by the highest four industries' products: Electricity, Gas, Water and Waste Services (D), Mining (B), Financial and Insurance Services (K), and Manufacturing (C). In contrast, the eleven largest inputs of Hydrogen (SMR) must be considered to account for the same proportion of its total input. The difference in spread, in addition to providing support for including two different hydrogen industries, indicates differing breadth in the dependency of each hydrogen industry on other industries' products.

Table 1 Inputs to production as percentage of total input: SMR and Electrolysis

Input to production	Share		
	SMR (A)	Electrolysis (B)	(A)-(B)
Total Input	100.0%	100.0%	0.0%
Total Intermediate Input	70.7%	78.9%	-8.2%
Agriculture, Forestry and Fishing (A)	1.7%	0.0%	1.7%
Mining (B)	15.2%	19.1%	-3.9%
Manufacturing (C)	20.7%	5.3%	15.4%
Electricity, Gas, Water and Waste Services (D)	5.7%	24.2%	-18.5%
Construction (E)	0.5%	2.8%	-2.3%
Wholesale Trade (F)	4.3%	0.9%	3.4%
Retail Trade (G)	0.9%	0.3%	0.6%
Accommodation and Food Services (H)	1.3%	0.3%	1.0%
Transport, Postal and Warehousing (I)	6.7%	3.1%	3.6%
Information Media and Telecommunications (J)	1.5%	1.0%	0.5%
Financial and Insurance Services (K)	2.1%	16.0%	-13.9%
Rental, Hiring and Real Estate Services (L)	0.7%	0.8%	-0.1%
Professional, Scientific and Technical Services (M)	3.5%	2.1%	1.4%
Administrative and Support Services (N)	1.1%	1.1%	0.0%
Public Administration and Safety (O)	2.0%	0.3%	1.7%
Education and Training (P)	0.1%	0.0%	0.1%
Health Care and Social Assistance (Q)	0.8%	0.0%	0.8%
Arts and Recreation Services (R)	0.0%	0.1%	-0.1%
Other Services (S)	0.4%	0.6%	-0.2%
Hydrogen (SMR)	0.5%	0.0%	0.5%
Hydrogen (Electrolysis)	0.0%	0.5%	-0.5%
Value-added (Wages, gross operating surplus etc)	29.3%	21.1%	8.2%

The composition of inputs to each industry is important to understand differences in the wider economic impacts resulting from changes in production. The largest industrial input to each industry differs, with Hydrogen (SMR) requiring Manufacturing (C) (20.7%) products the most, and Hydrogen (Electrolysis), as intended through its proxy selection, requires Electricity, Gas, Water and Wastes Services (D) (24.2%) products the most. This reflects electricity as by far the largest cost in running electrolysers (Longden et al., 2020; Smith et al., 2017). For both hydrogen industries, Mining (B) is the second largest input. Other significant inputs to Hydrogen (SMR) include Transport, Postal and Warehousing (I), Electricity, Gas, Water and Wastes Services (D) and Wholesale Trade (F). The third and fourth largest inputs to Hydrogen (Electrolysis) are Financial and Insurance Services (K) and Manufacturing (C).

Two other notable comparisons of the hydrogen industry input structures are differences in value-added input and the balance of domestic and imported product inputs. Hydrogen (SMR) has a higher proportion of value-added input (29.3%) than Hydrogen (Electrolysis) (21.1%). Ostensibly, this may lead to the impression that an increase in Hydrogen (SMR) production would lead to a relatively higher contribution to GDP (value-added) than Hydrogen (Electrolysis). However, to calculate the total economic impacts it is important to incorporate the economy wide changes, not simply the initial inputs to produce one extra unit, as the next subsection on Key multipliers shows. The comparative size of impacts across the Australian economy that result from production increases can also be partly inferred by comparison of the balance of domestic and imported product inputs. Hydrogen (SMR) sources 56.7% of total input from domestic products and 13.1% from imported products (total intermediate inputs of 69.8%[6]). On the other hand, Hydrogen (Electrolysis) requires considerably more domestic products, 73.3%, and fewer

[6] It should be noted that in the Australian case, value-added and total intermediate inputs (domestic and imported) do not add to the total input for each industry. For example, Hydrogen (SMR) value-added (29.3%) and total intermediate inputs (69.8%) add to 99.1%. The remaining difference (in the example 0.9%) is constituted by 'Competing imports', defined by the Australian Bureau of Statistics as those products which are produced domestically and imported and so supply sources may be substituted. Given that these proportions are small for each industry (for Hydrogen [Electrolysis], only 0.4%), the figures are omitted from this subsection.

imported, 5.2%. Given that demand for domestic products, not imported products, is ultimately what stimulates increases to Australian GDP and employment, comparison of the proportion of input sources suggests that increases in production of Hydrogen (Electrolysis) will have a larger impact on the Australian economy than Hydrogen (SMR). This hypothesis is supported by the comparison of hydrogen industry key multipliers in the next subsection.

4.2.4b Key multipliers

Multipliers describe average economic impacts resulting from a single unit change in the output of a given industry (McLennan, 1995). They can be useful for estimating the impacts on production, value-added and employment. However, as average effects, they can not reflect economies of scale or technical change (McLennan, 1995). Table 2 below shows the multipliers for production (domestic output), value-added, and employment (measured as full-time equivalent [FTE] employment[7]). Alongside the multipliers are the respective ranks of each industry, largest to smallest, to indicate the relative size of a given industry's impact in each field. A single unit in the Australian IO table is AUD $1 million. Calculation of these multipliers is detailed in the Methodology chapter.

[7] Full-time equivalent (FTE) employment is measured as the number of full-time employees plus 50% of part-time employees.

Table 2 Key multipliers for aggregated Australian IO table industries with hydrogen proxies

Industries	**Domestic Output**	**Rank**	**Value-added**	**Rank**	**FTE**	**Rank**
Agriculture, Forestry and Fishing (A)	1.870	9	0.879	12	3.370	16
Mining (B)	1.637	16	0.910	9	2.346	20
Manufacturing (C)	2.025	5	0.779	21	4.381	11
Electricity, Gas, Water and Waste Services (D)	2.094	3	0.908	10	3.071	17
Construction (E)	2.290	2	0.830	17	4.105	12
Wholesale Trade (F)	1.789	12	0.905	11	4.420	10
Retail Trade (G)	1.665	14	0.938	4	8.089	1
Accommodation and Food Services (H)	1.841	10	0.871	14	7.328	2
Transport, Postal and Warehousing (I)	1.872	8	0.871	16	4.543	9
Information Media and Telecommunications (J)	1.936	6	0.871	15	3.871	14
Financial and Insurance Services (K)	1.598	18	0.944	2	2.774	19
Rental, Hiring and Real Estate Services (L)	1.577	19	0.958	1	1.563	21
Professional, Scientific and Technical Services (M)	1.819	11	0.924	6	4.758	8
Administrative and Support Services (N)	1.645	15	0.941	3	3.957	13
Public Administration and Safety (O)	1.674	13	0.931	5	6.055	6
Education and Training (P)	1.470	20	0.921	8	6.573	4
Health Care and Social Assistance (Q)	1.453	21	0.923	7	6.623	3
Arts and Recreation Services (R)	1.905	7	0.823	19	5.714	7
Other Services (S)	1.624	17	0.828	18	6.385	5
Hydrogen (SMR)	2.033	4	0.793	20	2.895	18
Hydrogen (Electrolysis)	2.347	1	0.877	13	3.710	15

It is apparent that both the Hydrogen (SMR) and Hydrogen (Electrolysis) proxies have relatively high domestic output multipliers, ranking fourth and first respectively, though Hydrogen (Electrolysis) is still considerably higher. In contrast, the value-added multiplier for Hydrogen (SMR) ranks relatively low, and Hydrogen (Electrolysis) seven places higher, toward the middle.

Importantly, this implies that for every unit of demand for Hydrogen (SMR) that is substituted with Hydrogen (Electrolysis), there will be an increase in the value-added or GDP contribution to the economy. Lastly, the multiplier for employment is again higher for Hydrogen (Electrolysis) than Hydrogen (SMR), by almost 30% or almost one additional full-time equivalent role per unit of output increase. Given that demand for electrolysis-produced hydrogen is likely to supplant demand for SMR-produced hydrogen in the coming years, an initial interpretation of these multipliers suggests that GDP and employment contributions per unit of hydrogen produced will increase as this substitution occurs.

4.2.4c Backward and forward linkage effects

IO tables allow for measurement of industry linkage effects, which refers to the relationship between industries. Backward linkages are those that affect 'upstream' industries, meaning that it relates to an industry's effect on suppliers of raw materials to that industry. Forward linkages refer to 'downstream' industries, noting an industry's impact on other industries that purchase its products. Table 3 shows the strength and relative rank of each industry's forward and backward linkage effects. Total backward linkage effects, that incorporate the direct and indirect effects of purchases through the economy are calculated using the column sums of the simple multiplier matrix[8] (Leontief inverse),

$$BL_j = \frac{\sum_{i=1}^{n} l_{ij}}{\frac{1}{n}\sum_{j=1}^{n}\sum_{i=1}^{n} l_{ij}}$$

where l is the Leontief inverse and ij represents the ith product of the jth industry.

On the other hand, forward linkages are calculated using the row sums of the Ghoshian inverse[9] as below,

$$FL_i = \frac{\frac{1}{n}\sum_{j=1}^{n} g_{ij}}{\frac{1}{n^2}\sum_{j=1}^{n}\sum_{i=1}^{n} g_{ij}}$$

where g is the Ghoshian inverse and ij are as above (Miller & Blair, 2009).

Both measures are normalised (the denominators of each equation), such that the average backward and forward linkage effect across all industries is equal to one. This allows easier identification of above and below average industries. To further aid interpretation, industries are categorised based on the system outlined in Miller & Blair (2009, p. 559): I) industries that are generally independent of other industries (both linkage effects less than one); II) industries

[8,9] Excellent explanations of the Leontief and Ghoshian inverses and their utility in calculating linkage effects can be found in Miller & Blair (2009, p. 556).

generally depend on interindustry demand (only forward linkage effect greater than one); III) industries generally dependent on other industries (both linkage effects greater than one); and, IV) industries dependent on interindustry supply (only backward linkage effect greater than one).

Industries with bigger backward linkage effects use more raw materials from upstream industries. Industries with higher forward linkage effects tend to experience larger impacts from economic fluctuations. This is because it is likely that the products from such industries are used as raw materials across many industries. On the other hand, industries that provide the raw materials for a small number of industries tend to be less sensitive to economic fluctuations.

Table 3 Australian industry total backward and forward linkage effects

Industries	**BWL**	**Rank**	**FWL**	**Rank**	**Category**
Agriculture, Forestry and Fishing (A)	1.029	9	1.223	5	III
Mining (B)	0.901	16	0.822	15	I
Manufacturing (C)	1.114	5	1.005	12	III
Electricity, Gas, Water and Waste Services (D)	1.152	3	1.316	3	III
Construction (E)	1.260	2	1.022	10	III
Wholesale Trade (F)	0.985	12	1.008	11	II
Retail Trade (G)	0.916	14	0.737	18	I
Accommodation and Food Services (H)	1.013	10	0.747	17	IV
Transport, Postal and Warehousing (I)	1.030	8	1.108	9	III
Information Media and Telecommunications (J)	1.065	6	1.244	4	III
Financial and Insurance Services (K)	0.879	18	1.178	6	II
Rental, Hiring and Real Estate Services (L)	0.868	19	0.861	14	I
Professional, Scientific and Technical Services (M)	1.001	11	1.420	2	III
Administrative and Support Services (N)	0.905	15	1.448	1	II
Public Administration and Safety (O)	0.921	13	0.716	19	I
Education and Training (P)	0.809	20	0.585	20	I
Health Care and Social Assistance (Q)	0.799	21	0.574	21	I
Arts and Recreation Services (R)	1.048	7	0.769	16	IV
Other Services (S)	0.894	17	0.975	13	I
Hydrogen (SMR)	1.119	4	1.122	7	III
Hydrogen (Electrolysis)	1.292	1	1.121	8	III

The data in Table 3 show that both hydrogen proxies share the same category as generally dependent industries (III). Both display above average backward and forward linkages, with Hydrogen (Electrolysis) showing the highest backward linkage effects of all industries (1.292). These backward linkage effects suggest that expansion of the hydrogen industry would, from the perspective of overall productive activity generated, provide above average benefits to the overall economy, and that as demand shifts from Hydrogen (SMR) to Hydrogen (Electrolysis), these benefits will become greater per unit of output. The above average forward linkage effects suggest that, relative to other Australian industries, hydrogen production would be more important to the economy in terms of the overall production activity it could contribute to as hydrogen demand increases. The next section discusses the scenarios used in this analysis to depict different possible futures in which demand for Australian hydrogen grows.

4.3 Scenario-based demand estimates

4.3.1 Scenarios

There is widespread and growing interest in hydrogen, which has been persistent even through disruptions of the COVID-19 pandemic. However, there remains much uncertainty about industry development and future demand. Scenarios offer an approach to navigating such uncertainty by providing plausible and internally consistent 'stories' that model distinctly different pathways and outcomes. A scenario-based approach to estimating demand figures can be preferable to 'high-medium-low' projections through offering internal logic to variations in demand over time, and the potential to add nuance that reflects very possible outcomes. Deloitte (2019, 2020), in their report to the Council of Australian Governments (COAG) Hydrogen Working Group, produced such a scenario-based analysis of Australian and global hydrogen demand growth. Four scenarios were published- described in Table 4- which present different levels of demand for hydrogen, primarily based on international and domestic policy and technological readiness (Deloitte, 2019, p. 47). The influence of policy on hydrogen demand relates to the extent of encouragement of the hydrogen export market through enabling access and removing barriers to its growth. Technological readiness relates to the degree of adoption of hydrogen across its potential applications, particularly in competition with alternatives, such as battery technology. Deloitte (2019) notes that, in including these factors in their scenario designs, the historically dominant factor in demand has been price, and this was also accounted for in developing the scenarios.

Table 4 Deloitte (2019) hydrogen demand growth scenarios

Scenario	**Description**
1. Hydrogen: Energy of the Future (EF)	The most optimistic scenario for hydrogen demand. Globally, economies decarbonise quickly, and hydrogen uptake is widespread and buoyed by production cost reductions and technology improvements. Australia becomes a major global hydrogen exporter.
2. Hydrogen: Targeted Deployment (TD)	Described as a 'moderately positive' scenario. Hydrogen is seen as important and applied in targeted areas across global economies. Production technology improves, production costs decline, and Australia occupies a moderate share of global exports.
3. Business as Usual (BAU)	This scenario assumes that hydrogen use grows globally, but Australia lags. Hydrogen production improves but the lack of domestic demand and supportive policy means that costs remain relatively higher in Australia. Australia exports notably less hydrogen.
4. Electric Breakthrough (EB)	Hydrogen uptake is stunted by the popularity of electrification globally. Advances in battery and charging technology reduces the policy attention and demand for hydrogen. Production of hydrogen only improves slightly, and Australia's hydrogen exports are low.

The Deloitte (2019; 2020) demand estimates were those selected for this paper. This decision was made because they are the most up-to-date and rigorous figures available, and because of the aforementioned advantages of scenario-based estimates for hydrogen demand projections. However, the disadvantages of this approach should also be acknowledged. The increased sophistication of the demand scenarios beyond 'high-medium-low' projections can make comparisons between the resulting economic impacts more complicated. Also, perhaps counterintuitively, the 'story-like' nature of the scenarios can potentially lead to narrower interpretations of domestic and global market signals. Indeed, though the factors included in the scenario development are important and logically consistent, they are neither completely comprehensive nor conclusive in their projections. As such, the temptation to see these scenarios as all-encompassing or definitive should be avoided. Rather, the demand figures ought to be used as preliminary guides to a diverse range of possibilities for hydrogen. The next subsections- Interpolation, Production prices, and Substitution rate- outline how the hydrogen demand estimates used in this analysis were derived from those published by Deloitte (2019, 2020).

4.3.2 Interpolation

The specific demand figures for each scenario are published in Deloitte (2019) and later updated in an erratum (Deloitte, 2020) to correct for a calculation error that underestimated future hydrogen demand in steelmaking. International and Australian domestic demand is quoted in millions of tonnes of hydrogen for the years 2019, 2025, 2030, 2040 and 2050. Based on the published figures and years, exponential interpolation was conducted to obtain demand estimates for the intervening years for each scenario. Only the figures up until 2040 (inclusive) were used in this analysis. This is because despite the relatively slow pace of change in production technology for most industries, the IO assumption of fixed input structures makes the results of demand shock analyses increasingly less reliable as projections extend further into the future.

4.3.3 Production prices

Given that data in Australian IO tables are in units of AUD $1 million, it was necessary to convert the scenario-based demand estimates from millions of tonnes. To do this, rigorous projections of future hydrogen production costs per kilogram were used (Bloomberg New Energy Finance, 2020; Bruce et al., 2018; Longden et al., 2020). The initial price is based on the SMR-produced hydrogen cost of AUD$2.77/per kilogram, which is cited in Australia's National Hydrogen Roadmap, led by the Commonwealth Scientific and Industrial Research Organisation (Bruce et al., 2018). SMR is a mature technology, and therefore production costs over time are not expected to reduce significantly (Longden et al., 2020; Bloomberg New Energy Finance, 2020). For that reason, and because demand is predicted to increasingly shift toward electrolyser-produced hydrogen in the future, the production costs of hydrogen (SMR) become less relevant over time and those of electrolyser-produced hydrogen become more relevant.

Longden et al. (2020) published a working paper on green hydrogen production costs in Australia for the Australian National University's Centre of Climate & Energy Policy. Analysing cost trends in renewable energy and electrolysers, they attempt to answer the question of when green hydrogen will be produced at costs that make it comparatively attractive to SMR or other fossil fuel produced hydrogen. Their analysis finds hydrogen production cost estimates of AUD$2.64/kg for 2025 and AUD$1.89/kg for 2030. Longden et al. (2020) are careful to emphasise there is considerable uncertainty in future cost estimates, citing the possibility of large and rapid cost reductions as the industry scales up. As Longden et al. (2020) do not publish production cost estimates past 2030, the figures produced by Bloomberg New Energy Finance (BNEF) (2020) are used, with a 2050 cost of AUD$1/kg assumed, which is a conservative estimate among BNEF figures which suggest that Australia's exceptional renewable and hydrogen storage resources mean that production costs could be even lower by 2050.

Using the figures for each of the years mentioned above, the decreasing cost of producing a kilogram of hydrogen for each year between 2019 and 2040 were calculated using exponential interpolation. The result is a gradual decrease in price from AUD$2.77/kg in 2019 to AUD$1.42/kg in 2040. As scenarios one (Energy of the Future) and two (Targeted Deployment) assume increasing use of electrolysers and decreasing hydrogen production costs, these gradually declining per kilogram costs are multiplied by one thousand and the interpolated demand figures (in millions of tonnes) to convert them to Australian IO table units (AUD$ millions). Scenarios three and four are similarly pessimistic about the reduction in hydrogen production costs in Australia, predicting little change over time, and therefore a flat rate of AUD$2.64 (within the range of SMR-produced hydrogen costs from Bruce et al. [2018]) is applied in the same fashion. It should be noted that officially, IO tables in Australia use so-called 'basic prices'[10]. However, there are exceptions where output is valued at its cost of production. The use of production prices in this analysis was justified based on the added complexities and uncertainties to projections for the basic price of hydrogen.

4.3.4 Substitution rate

This final subsection details the assumptions underpinning a substitution rate between Hydrogen (SMR) and Hydrogen (Electrolysis). To fit appropriately with the Deloitte scenarios, the scenario-based substitution rates published in Deloitte (2019) are used to divide the

[10] Basic prices are defined by the ABS as 'the amount receivable by the producer from the purchaser for a unit of a good or service produced as output minus any tax payable, and plus any subsidy receivable, on that unit because of its production or sale. It excludes any transport charges invoiced separately by the producer' (McLennan, 1995).

AUD$ million hydrogen demand figures (calculated in the previous section) between Hydrogen (SMR) and Hydrogen (Electrolysis). Deloitte (2019, pp. 94-97) offers analysis of changes in the technology type of hydrogen production to accompany each of the four scenarios. While Deloitte's analysis includes five different kinds of technology type, this analysis finds it sufficient to group them into only two- Hydrogen (SMR), covering all fossil fuel-based hydrogen production (SMR and coal gasification), and Hydrogen (Electrolysis), covering all forms of electrolyser-produced hydrogen technology (alkaline, polymer electrolyte membrane [PEM], and solid oxide electrolyte cell technologies). Using the published figures and linear interpolation, the substitution rates for each scenario are calculated and used to divide total final demand for hydrogen between the two industries for each year (details on these numbers are available in Appendix A). This is then reflected in the results of the demand shock analysis.

5. Methodology

In this chapter, the steps, assumptions and analytical decisions taken during the IO analysis are outlined. It is divided into five sections: insertion of hydrogen industry proxies to the Australian IO tables, aggregation of the tables based on their Australian and New Zealand Standard Industrial Classification (ANZSIC), calculation of the IO multipliers for all industries, descriptions of the scenario-based demand vectors and the demand shock analysis.

5.1 Insertion of hydrogen industries to Australian input-output tables

As this paper involves the inclusion of a new hydrogen industry, the decision had to be made whether to include a single new row and column- a unified hydrogen industry- or two new rows and columns- reflecting the present and anticipated means of producing hydrogen. The former violates the homogeneity of inputs principle (discussed in the Data chapter), as steam-methane reforming [SMR] and electrolysis involve very different inputs to production. The latter violates the homogeneity of disposition principle, as hydrogen produced by any method will have near identical distribution structures. The latter approach of including two new hydrogen industries based on input structure differences was adopted, because this allows the results to reflect differences in economic impacts resulting from a vastly different method of producing Hydrogen (Electrolysis), which is likely to become increasingly popular in coming years.

From a practical standpoint, due to the absence of a hydrogen industry in Australian IO tables, the first procedure undertaken was the inclusion of two new columns (industries) and rows (products) for each hydrogen industry proxy. The two columns and rows added reflect different input structures for the two main hydrogen production methods: steam-methane reforming (SMR) and electrolysis. The practical computation associated with insertion of each industry into the IO table is discussed in the following two subsections.

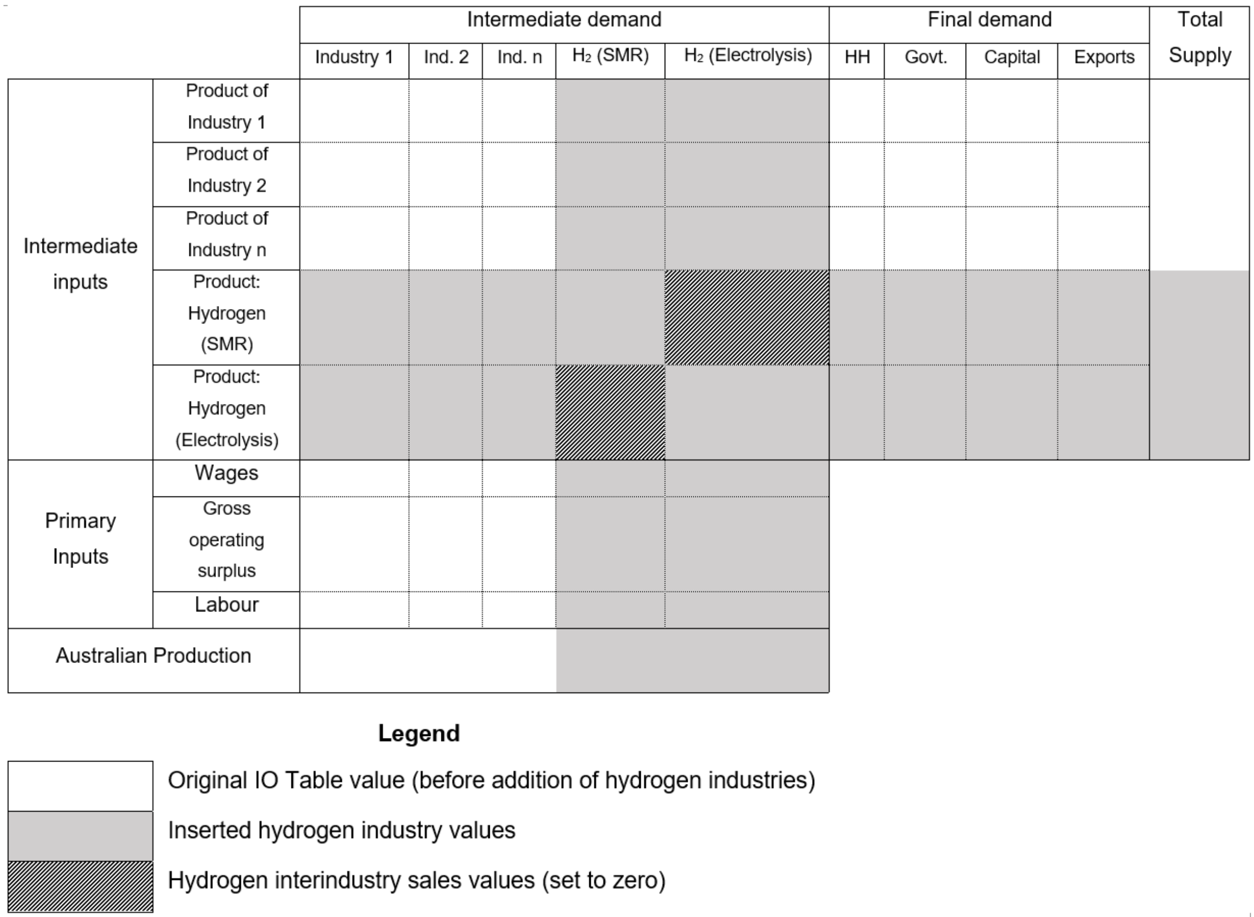

Figure 2 Updated IO table schematic to show insertion of hydrogen industries.

5.1.2 Hydrogen (SMR) – disaggregation of Basic Chemical Manufacturing

The Australian and New Zealand Standard Industrial Classification (ANZSIC) 2006 indicates that ‘hydrogen manufacturing’ is contained within Group 181 ‘Basic Chemical Manufacturing’. This corresponds with the Input-Output Industry Group (IOIG) 1803 of the same name. Given that IO tables are compiled under the principles of homogeneity of inputs and homogeneity of disposition (i.e., similar patterns of product usage), it is reasonable to assume that an approximation of the hydrogen manufacturing component within the Basic Chemical Manufacturing industry can be disaggregated out. Importantly, the input structure and consumption pattern should be proportional to maintain the homogeneity principles (UN, 1999).

Using 2018[11] industry data from the Massachusetts Institute of Technology's Observatory of Economic Complexity (OEC) (n.d.), the size of Australian hydrogen manufacturing is estimated to constitute five percent of the input (column) and output (row) values of the Basic Chemical Manufacturing industry. As discussed in the Background chapter, SMR is currently by far the dominant form of hydrogen production, due to technology maturity and lower production costs, and therefore, for simplicity, it is assumed that all hydrogen manufacturing captured in Basic Chemical Manufacturing is produced via SMR. As such, disaggregation follows the scheme described in UN (1999, p. 215) and the values in the disaggregated Australian IO table are calculated as follows:

$$U^1_{SMR,j} = \pi U^0_{BCM,j}$$

$$S^1_{i,SMR} = \pi S^0_{i,BCM}$$

$$U^1_{BCM,j} = (1-\pi) U^0_{BCM,j}$$

$$S^1_{i,BCM} = (1-\pi) S^0_{i,BCM}$$

where U and S refer to columns (uses) and rows (supply) respectively and the superscripts 0 and 1 denote values before and after disaggregation. Denoting the rows or columns, i refers to the ith industry (column) and j to the jth product (row), SMR refers to the newly disaggregated hydrogen industry (SMR production) and BCM refers to Basic Chemical Manufacturing. π is the estimated size of the Australian hydrogen industry contained within the Basic Chemical Manufacturing industry and set to five percent of the values in the Basic Chemical Manufacturing row and column. After extracting the hydrogen industry, the remaining values for the Basic Chemical Manufacturing are 95% of their original values. Note, this process preserves the balance of the IO tables.

[11] 2018 is the reference year of the IO table used in this analysis.

5.1.3 Hydrogen (Electrolysis) – Electricity Generation-based proxy

New industry analysis (Miller & Blair, 2009) was used to add a second hydrogen industry that uses electrolysis to produce hydrogen. The purpose of this inclusion was to reflect the differences in economic impacts that could result as hydrogen production shifts from fossil fuel-based SMR to renewable energy-based electrolysis. In an IO table of n original sectors, complete inclusion of a new industry requires estimation of $(2n + 1)$ coefficients: a new row and column for the new sector, including intraindustry use of Hydrogen (Electrolysis). The estimation process is described in this section.

As discussed, the input structure (column) of hydrogen produced via electrolysis is different to that of SMR-produced hydrogen. However, given the relatively small scale of the electrolysis-produced hydrogen industry today, details of its input structure have not warranted inclusion in most countries IO tables. As such, this paper adopts the approach taken by Smith et al. (2017) and uses ‘Electricity Generation’, IOIG 2601, as a proxy for the electrolysis-produced hydrogen industry. As in Smith et al. (2017), the production input structure of the Electricity Generation industry and the proportion of value-added and employment generated per AUD$ million of Electricity Generation industry output are maintained for the Hydrogen (Electrolysis) proxy.

Given that each hydrogen production industry, despite using different means, produces the same product- hydrogen- the row values of the Hydrogen (Electrolysis) are assumed to be the same as those for the Hydrogen (SMR) industry. This is because the row values represent the sales of hydrogen. Although the means of producing hydrogen are likely to trend toward renewable energy-based electrolysis, the anticipated applications of hydrogen will not differ significantly as a result of production method changes. Therefore, $S_{SMR,j} = S_{Electrolysis,j}$[12].

With each hydrogen production industry included in the Australian IO tables, the IO tables are then manipulated for the purpose of analysis, beginning with aggregation.

5.2 Aggregation of the IO tables based on ANZSIC division classifications

For ease of analysis and interpretation, the 114 original industries and products of the Australian IO tables were aggregated down to 19, with the two new hydrogen industries and products making a total of 21. As such, subsequent references to matrices of $n \; x \; n$ dimensions, for example, will refer to 21 rows by 21 columns. To maintain the homogeneity principles as much as possible during the aggregation, the concordances between the 114 original IOIGs and the 19 overarching ANZSIC (2006) divisions were applied. The concordances are provided in Appendix C. With the concordances decided upon, aggregation is a straightforward process of adding together the industries (columns) of the same division and then the corresponding products (rows) of the same division. This process is repeated for all 19 divisions.

5.3 Calculation of IO multipliers

To estimate the total impact on all industries in the Australian economy resulting from increasing production by the Australian hydrogen industry, it is necessary to compute IO multipliers. IO multipliers are used to show the average changes in production, value-added, and employment resulting from exogenous changes in final demand. For demand shock analysis, it is

[12] All symbols are the same as in the previous section equations, with $Electrolysis$ denoting electrolysis-produced hydrogen.

necessary to calculate two types of multiplier matrices: first, the technical coefficient (direct requirements) matrix and then, the simple multiplier (total requirements) matrix.

5.3.1 Technical coefficients matrix (direct requirements)

The technical coefficients matrix, A, shows the inputs of each industry (column) expressed as a proportion of total input (called 'Australian Production' in Australian IO tables). Therefore, the coefficients generated represent how much of each industry's input is required to produce one unit of a given industry's output. It is calculated by dividing each input value of the intermediate usage (first) quadrant by the total input for its respective industry (column). The resulting matrix, A, is sometimes called the 'direct requirements' matrix because it represents initial inputs required to produce one additional unit of output (McLennan, 1995). This corresponds with the additional production initially required to satisfy one additional unit of exogenous final demand. In this way, they can be considered as representing the 'first round' of production to meet a unit increase of demand.

There are two $n\ x\ n$ versions of matrix A created: one representing domestic production, A^d, and the other representing imported intermediate inputs to production, A^m. This analysis uses the intermediate usage (first) quadrant of the direct allocation of imports IO table- describing domestic production- to create A^d, and the intermediate usage quadrant of the imports IO table to create A^m. The sum of A^d and A^m represents a 'technology matrix' (West, 1999), wherein the coefficients in each column represent the inputs per unit of output for each industry, regardless of whether those inputs are domestically produced or imported. Subtracting the column sum of this technology matrix from total input divided by itself equals the value-added coefficient vector, A^v:

$$A^d + A^m + A^v = 1$$

Given this relationship, value-added (wages and salaries, gross operating surplus, taxes on production less subsidies) can be thought of the remaining components of total input and its coefficients are calculated in the same way as before: dividing the row of value-added by total input, giving the amount of value-added per unit of output for each industry. The employment required per unit of an Australian industry's output can also be calculated by taking the Employment by Industry figures published by the Australian Bureau of Statistics (ABS) and dividing them by Australian Production (total input) from the IO table. Both the value-added and employment coefficients are converted into $n \, x \, n$ diagonal matrices, with each industry's coefficient value in its corresponding place along the diagonal and zero for all other cells.

5.3.2 Simple multiplier matrix (total requirements)

While the technical coefficients represent the first round of production, they do not capture the additional round of production that would be required to produce the inputs in the first round. Furthermore, that additional round would itself induce another round of production, and so on. The combined effects of all rounds of production- the first round and the 'production induced' rounds- is calculated through the simple multiplier (McLennan, 1995) or 'total requirements' matrix (Miller & Blair, 2009). The simple multiplier matrix is calculated by finding the inverse $(I - A)^{-1}$, with A as the technical coefficients matrix and I as an identity matrix of dimensions $n \; x \; n$.

The matrix $(I - A)^{-1}$ is said to capture the total production requirements in the economy. Final demands for industry products are said to be exogenous, or determined outside of this productive system. Therefore, we can establish the following relationship,

$$X = (I - A)^{-1} * Y$$

where X denotes total output and Y denotes total final demand. Given the assumption of fixed production input ratios, the following also holds:

$$\Delta X = (I - A)^{-1} * \Delta Y$$

Equation 1 Changes in production resulting from changes in final demand

In other words, estimated changes in final demand can be used to calculate changes in total production. While the above is the general case, the simple multiplier matrix, $(I - A)^{-1}$ can be calculated specifically from the technical coefficients matrix for domestic production, A^d. This is called the simple multiplier matrix for domestic production, R^p. This simple multiplier matrix for production can then be multiplied with the technical coefficients matrices for imports A^m, value-added $\hat{V}$ and employment $\hat{L}$ to create their simple multiplier matrices, denoted by R^m, R^v and R^l respectively (Miller & Blair, 2009):

$$R^p = (I - A^d)^{-1}$$

$$R^m = A^m (I - A^d)^{-1} = A^m R^p$$

$$R^v = \hat{V} (I - A^d)^{-1} = \hat{V} R^p$$

$$R^l = \hat{L} (I - A^d)^{-1} = \hat{L} R^p .$$

It then follows that change in imports, $\Delta m = R^m \Delta y^d$,

change in value-added, $\Delta v = R^v \Delta y^d$,

change in employment, $\Delta l = R^l \Delta y^d$.

As such, the change in final demand, Δy^d, with d denoting demand for domestic products, is the last remaining variable needed to conduct demand-shock analysis. Obtaining Δy^d is discussed in the next section.

5.4 Scenario-based demand vectors

With the simple multiplier matrices prepared, the next step in preparation for demand shock analysis is calculating the demand vectors, or Δy^d, in Equation 1.

In this study, Δy^d represents demand estimates for Australian hydrogen for each of the four scenarios until 2040, based on those published by Deloitte (2019, 2020). As discussed in the Data chapter, to prepare the demand vectors using the publicly available data, it was necessary to: (i) interpolate the demand figures for the years between those published, (ii) convert demand figures from physical units (millions of tonnes) to Australian dollars using recent hydrogen production cost projections (Longden et al., 2020), (iii) reflect scenario-based assumptions of substitution of Hydrogen (SMR) by Hydrogen (Electrolysis) over time (Deloitte, 2019), and finally, (iv) insert the resulting demand figures for each hydrogen industry into demand vectors (a summary of the demand figures for each year and scenario can be found in Appendix A). The demand vectors are columns of 21 numbers, each representing a change in final demand. As this study examines the economic contribution of increasing hydrogen demand, all numbers in the column vector are zero, except for rows 20 (SMR-produced hydrogen) and 21 (electrolysis-produced hydrogen).

5.5 Demand shock analysis

The economic impact of increasing demand on the Australian hydrogen industry is estimated using IO demand shock analysis (Miller & Blair, 2009; West, 1999). Demand shock analysis is made possible through the transformation of IO tables described in the previous sections. However, moving from the original IO tables, which are purely accounting statements, to an operational model involves inclusion of new, important assumptions. Firstly, a given industry's input purchases are dependent only on the output level of that industry. The input function is assumed as linear and that there are constant returns to scale. The input structure is assumed as fixed and there is no substitution between inputs (Miller & Blair, 2009). Secondly, there are assumed to be no capacity or resource constraints. In other words, demand increases are met instantaneously, supply is infinitely elastic, and prices are not affected by changes in demand or supply. These are limiting assumptions that necessitate caution in interpreting the results of analysis (West, 1999). Therefore, estimates produced by demand shock analysis should be approached as laying within a range of possible outcomes. To both reflect and address this uncertainty, I use the varying but logically consistent future scenarios presented in Deloitte (2019) and the Australian Hydrogen Strategy (COAG Energy Council, 2019).

The calculations to perform demand shock analysis are based on that of Equation 1, to determine the change in production, imports, value-added and employment resulting from an exogenous demand shock:

$$\Delta X = (I - A)^{-1} * \Delta Y$$

$$R^m = A^m (I - A^d)^{-1} = A^m R^p$$

$$R^v = \hat{V} (I - A^d)^{-1} = \hat{V} R^p$$

$$R^l = \hat{L} (I - A^d)^{-1} = \hat{L} R^p.$$

These calculations were performed for each year (2023-2040) for each of the four scenarios. The result for each is a column vector, with each value showing the impact on each industry due to the demand shock in, respectively, AUD (millions) of production, imports and value-added, and the number of full-time equivalent (FTE) jobs supported. The column sum of these vectors shows the economy-wide impacts for each of these factors. The results of the scenario-based demand shock analysis for the Australian hydrogen are presented in the next chapter.

6. Results

The results of the scenario-based IO analysis in terms of GDP, or value-added, contribution (Table 5) and full-time equivalent (FTE) employment (Table 6) are summarised below. The overall figures are compared first, followed by the industry-by-industry employment breakdowns for each scenario. The acronyms for each scenario included in the column headings of Table 5 are used extensively henceforth.

6.1 Hydrogen's estimated contribution to GDP (value-added)

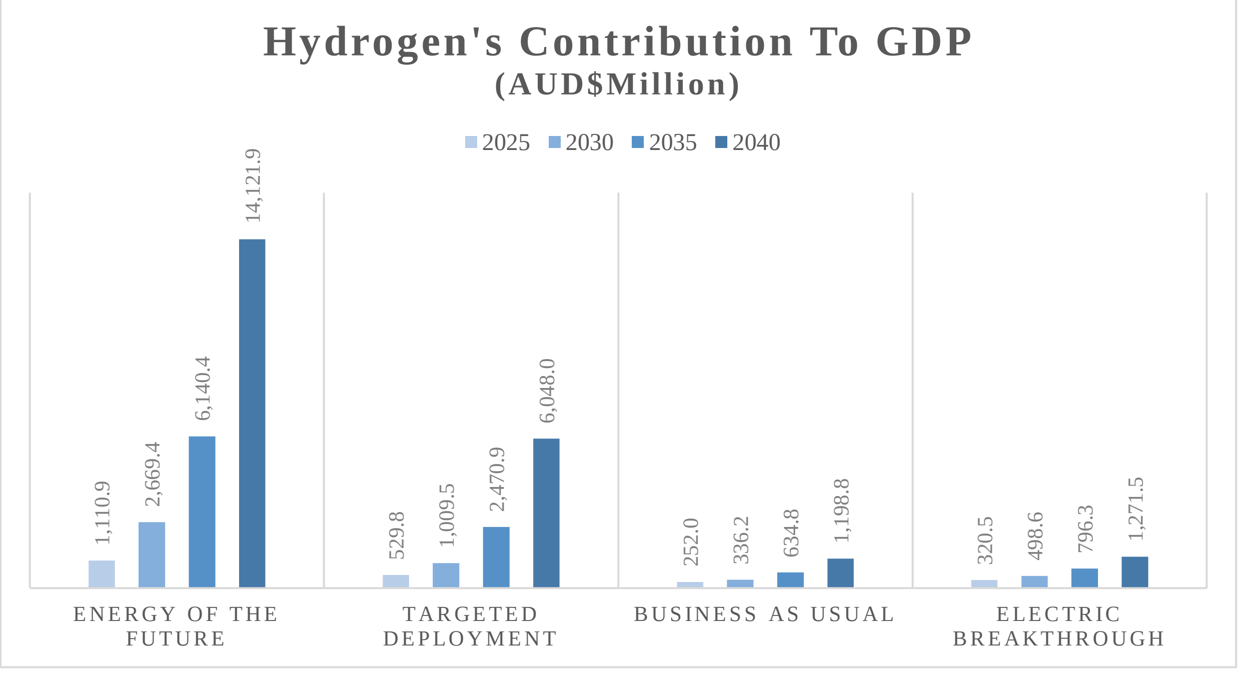

Figure 3 Hydrogen industries' GDP (value-added) contribution (AUD$million), by scenario and year, 2025 to 2040

The first scenario, Energy of the Future (EF), reflects the most optimistic demand outlook for the Australian and global hydrogen industry. It assumes substantial production cost reductions and rapid substitution of Hydrogen (SMR) for Hydrogen (Electrolysis). The GDP estimates produced from IO analysis reflect the optimism of the scenario, with figures for each year more than double the second-highest scenario, Targeted Deployment (TD). Considering the year 2030, this analysis' value-added estimate for EF ($2.67 billion) is relatively consistent with the other important IO analysis addressing the Australian hydrogen industry- ACIL Allen (2018). The figure sits between the ACIL Allen (ACIL Allen Consulting for ARENA, 2018) medium and high hydrogen demand scenarios ($1.67 billion and $3.63 billion respectively). However, estimates for 2040 diverge between this analysis and ACIL Allen's high scenario, at $14.12 billion and $10.01 billion, respectively. Given that the ACIL Allen report does not publish how it approximated the hydrogen industry in its analysis, it is hard to determine the source of this difference. Differences will emerge due to demand estimates differences, including the fact that ACIL Allen only considers the demand for hydrogen exports and not domestic demand.

Table 5 Hydrogen industries' GDP contribution (AUD$million), by scenario, 2025 to 2040

Year	(1) EF Energy of the Future	(2) TD Targeted Deployment	(3) BAU Business as Usual	(4) EB Electric Breakthrough
2025	1,110.9	529.8	252.0	320.5
2030	2,669.4	1,009.5	336.2	498.6
2035	6,140.4	2,470.9	634.8	796.3
2040	14,121.9	6,048.0	1,198.8	1,271.5

On the other hand, the figure is substantially higher than the CGE analysis produced by Deloitte (2019). Deloitte published their EF estimates as the additional GDP above the Business as Usual (BAU) scenario, which for 2030 was $600 million. Even subtracting this analysis' BAU estimate from the EF estimate (henceforth called the 'BAU-adjusted figure'[13])- $2.33 billion- the IO estimate is substantially higher than Deloitte's CGE estimate. Despite using similar demand projections, the considerably higher estimation from this analysis is likely owing to the ability of

[13] BAU-adjusted estimate: this reflects the presentation of estimates chosen by Deloitte (2019). To show only the additional GDP and employment above the Business as Usual (BAU) case, the BAU estimate is subtracted from the original estimate. For example, in the case of the 2030 Energy of the Future (EF) scenario, the BAU-adjusted figure would be: $2,669.4 - $336.2 = $2,333.2 or $2.33 billion.

Deloitte's CGE model to incorporate assumptions about substitution rates, economy-wide resource constraints, and price changes. As such, the higher estimation appears to hold for the EF 2040 GDP figure also. Deloitte projects the figure at approximately $7 billion, compared to this analysis' BAU-adjusted EF estimate of $12.92 billion. Interestingly however, Deloitte's 'unconstrained' EF estimate for 2040, which relaxes constraints on labour and capital mobility, is higher at $20 billion. Their unconstrained model effectively removes the 'crowding-out' effects that are incorporated in their CGE model. As with ACIL Allen, due to the opaqueness of the Deloitte CGE model, it is difficult to account for the differences in GDP estimates precisely.

Targeted Deployment (TD) is a positive but more restrained scenario which features less demand and slower Hydrogen (Electrolysis) uptake than the EF, but more than the BAU and Electric Breakthrough (EB) scenarios. The 2030 and 2040 TD estimates of this analysis ($1 billion, $2.47 billion) sit between the low and medium ACIL Allen estimates for the same years (2030: $806 million, $1.67 billion; 2040: $1.97 billion, $4.29 billion). As with the EF scenario, this analysis' 2030 estimate for TD is considerably higher than Deloitte's: $673.3 million compared to $200 million. For 2040, this analysis projects a BAU-adjusted TD estimate of $4.85 billion, compared to Deloitte's estimate of approximately $1.5 billion.

Business as Usual (BAU) and Electric Breakthrough (EB) represent the more pessimistic scenarios of demand for Australian hydrogen. The Deloitte demand estimates for these two scenarios, as used in this analysis, are similar out to 2040. The key difference is in substitution rates. BAU assumes continued reliance on Hydrogen (SMR), and EB follows the more rapid substitution rates of the EF scenario, with Hydrogen (Electrolysis) becoming the preferred method of production by the mid-2030s. Therefore, this difference in substitution between hydrogen production methods explains much of the difference between the BAU and EB estimates. The

GDP estimates for both scenarios are below the low demand scenarios of ACIL Allen (2018) for all years. In the year of highest demand, 2040, ACIL Allen's low demand estimate is roughly $700 million higher than both BAU and EB estimates for the same year. Deloitte did not publish GDP contribution results for BAU and EB.

6.2 Hydrogen's estimated contribution to employment

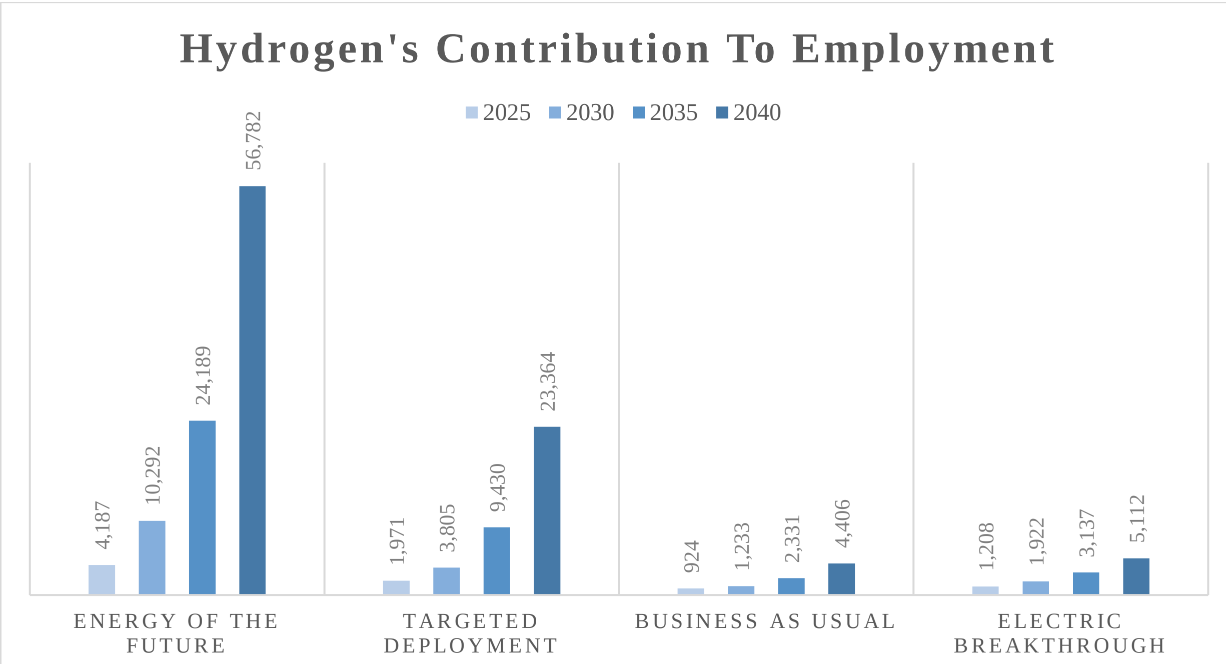

Figure 4 Hydrogen industries' full-time equivalent (FTE) employment contribution, by scenario, 2025 to 2040

6.2.1 Scenario 1: Energy of the Future

The employment contribution estimates of the hydrogen industry in Table 6 reflect the number of jobs economy-wide that could be supported by increased hydrogen output. The EF scenario employment estimates produced by this analysis are considerably higher than those of ACIL Allen (2018). In 2030 and 2040, this analysis finds that 10,292 and 56,782 jobs are contributed by the hydrogen industry, respectively. ACIL Allen's high demand scenario projects 5,754 and 16,024, respectively. As with GDP, this difference can at least be partly explained by the more comprehensive scope of this analysis (i.e., the inclusion of domestic demand) and the use of differing demand estimates. Without the ACIL Allen multipliers it is impossible to draw more precise conclusions for the different results.

Table 6 Hydrogen industries' full-time equivalent (FTE) employment contribution, by scenario, 2025 to 2040

Year	**(1) EF Energy of the Future**	**(2) TD Targeted Deployment**	**(3) BAU Business as Usual**	**(4) EB Electric Breakthrough**
2025	4,187	1,971	924	1,208
2030	10,292	3,805	1,233	1,922
2035	24,189	9,430	2,331	3,137
2040	56,782	23,364	4,406	5,112

In line with expectations, this analysis' employment estimates are also considerably higher than those of Deloitte. The BAU-adjusted EF employment estimates of this IO paper present 9,059 (2030) and 52,376 (2040), compared with Deloitte's estimates: 487 (2030) and approximately 5,200 (2040). The CGE modelling from Deloitte allows for inclusion of labour resource constraint assumptions, which reduce the figure dramatically. Indeed, Deloitte (2019, p. 92) report that their unconstrained estimate of employment was around 16 times higher than their CGE model estimate, at some 273,000 jobs by 2050. The IO analysis assumption of no resource constraints is indeed an extreme assumption, which should give pause to interpretations of these estimates as definitive predictions. Again, however, in the absence of full transparency on the assumptions and computations of their CGE model, it is difficult to fully evaluate the differences in results.

While the figures in Table 6 show the aggregate or economy-wide employment contribution of hydrogen, IO analysis also provides the industry-by-industry breakdown of where employment gains accrue. Table 7 shows this breakdown for the EF scenario. It reveals that the Hydrogen (Electrolysis) industry itself stands to gain the most from increased hydrogen demand.

This is owing to the optimistic demand forecasts and the rapid transition from Hydrogen (SMR) to Hydrogen (Electrolysis), which has a higher employment multiplier. As with the Deloitte (2019) sectoral analysis, service industries accrue the most employment, with this analysis finding similar gains in Professional, Scientific and Technical Services (M); Electricity, Gas, Water and Waste Services (D); and, after Hydrogen (SMR), Financial and Insurance Services (K).

Table 7 Energy of the Future, 2040, industry-by-industry employment contribution of hydrogen industry growth

Industry	**EF 2040**
Hydrogen (Electrolysis)	14,743
Professional, Scientific and Technical Services (M)	4,835
Electricity, Gas, Water and Waste Services (D)	4,801
Hydrogen (SMR)	4,532
Financial and Insurance Services (K)	4,254
Manufacturing (C)	3,585
Mining (B)	3,511
Transport, Postal and Warehousing (I)	3,312
Construction (E)	1,887
Wholesale Trade (F)	1,849
Administrative and Support Services (N)	1,640
Retail Trade (G)	1,389
Public Administration and Safety (O)	1,371
Other Services (S)	1,342
Accommodation and Food Services (H)	1,085
Information Media and Telecommunications (J)	997
Agriculture, Forestry and Fishing (A)	536
Health Care and Social Assistance (Q)	465
Rental, Hiring and Real Estate Services (L)	287
Education and Training (P)	208
Arts and Recreation Services (R)	148

6.2.2 Scenario 2: Targeted Deployment

The TD scenario of this analysis produces similarly high aggregate employment results relative to existing reports. This paper's IO analysis projects 3,805 jobs by 2030 and 23,364 jobs by 2040. The TD estimate is between the ACIL Allen medium and high scenario estimates for 2030 (2,787 and 5,754), however by 2040 it exceeds the high demand scenario estimate, which ACIL Allen puts at 16,024. Again, Deloitte's estimates are far more conservative for the TD scenario of 145 (2030) and just above 1,500 (2040). Even with BAU-adjustment, this analysis' TD figures are 2,572 (2030) and 18,958 (2040).

Table 8 Targeted Deployment, 2040, industry-by-industry employment contribution of hydrogen industry growth

Industry	**TD 2040**
Hydrogen (Electrolysis)	3,636
Hydrogen (SMR)	3,402
Professional, Scientific and Technical Services (M)	2,057
Manufacturing (C)	1,976
Transport, Postal and Warehousing (I)	1,666
Electricity, Gas, Water and Waste Services (D)	1,550
Mining (B)	1,457
Financial and Insurance Services (K)	1,362
Wholesale Trade (F)	993
Public Administration and Safety (O)	757
Construction (E)	697
Retail Trade (G)	694
Administrative and Support Services (N)	691
Other Services (S)	558
Accommodation and Food Services (H)	555

Information Media and Telecommunications (J)	443
Agriculture, Forestry and Fishing (A)	322
Health Care and Social Assistance (Q)	276
Rental, Hiring and Real Estate Services (L)	124
Education and Training (P)	88
Arts and Recreation Services (R)	60

The sectoral breakdown in Table 8 shows that in the TD scenario, like the EF scenario, Hydrogen (Electrolysis) benefits most greatly from gains to employment. However, because of the more conservative pace of electrolyser uptake, the Hydrogen (SMR) industry sees similar gains in employment by 2040. It is notable, however, that the Hydrogen (Electrolysis) industry has higher employment gains than Hydrogen (SMR), even though electrolysis does not become the preferred method of hydrogen production in the TD scenario, constituting only 35% of production by 2040. As with EF, Professional, Scientific and Technical Services (M) gain from overall hydrogen industry growth. However, rather than other services, Manufacturing (C) is the next highest industry, owing to the continued relevance of SMR-produced hydrogen.

6.2.3 Scenario 3 & 4: Business as Usual & Electric Breakthrough

Unlike the GDP estimates, the employment estimates for BAU and EB scenarios differ more meaningfully. In 2030, BAU is projected at 1,233 jobs to the EB projection of 1,922. This gap is maintained through to 2040, where the projections are 4,406 (BAU) and 5,112 (EB), respectively. Given the relative similarity in the size of demand estimates for these scenarios, the higher employment estimates for the EB scenario can be accounted for by the more rapid increase in demand for Hydrogen (Electrolysis) at the expense of Hydrogen (SMR) demand. Compared to the ACIL Allen IO analysis, the BAU and EB scenarios align most closely with the low and medium scenario figures for 2030 (low: 1,439 jobs, medium: 2,787) and 2040 (low: 3,519 jobs, medium: 7,142). As with GDP, Deloitte did not publish employment results for BAU and EB.

The industry-by-industry analyses of the BAU (Table 9) and EB (Table 10) scenarios again show the influence of the rate of substitution between Hydrogen (SMR) and Hydrogen (Electrolysis). The BAU breakdown reflects the ongoing dominance of SMR for hydrogen production, being by far the largest beneficiary of employment increases. The Manufacturing (C) industry, from which Hydrogen (SMR) was originally disaggregated, sees the second largest gains in employment. This is followed by Professional, Scientific and Technical Services (M) and Transport, Postal and Warehousing (I). Hydrogen (Electrolysis) is ranked sixteenth among the 21 industries in the aggregated IO table, reflecting its very limited adoption in the BAU scenario.

In contrast, the rapid uptake of electrolysis assumed under the EB scenario changes the ranking of industries considerably from BAU. As EB shares the same substitution rate as the EF scenario, the industry-by-industry rankings are identical, and the relative sizes of the employment gains are also comparable. Thus Table 10 shows the largest gains for Hydrogen (Electrolysis) by far, followed by the same services industries and Hydrogen (SMR) with similar employment gains. However, due to the smaller size of demand for hydrogen overall assumed in the EB scenario, the gains across industries are substantially lower.

Table 9 Business as Usual, 2040, industry-by-industry employment contribution of hydrogen industry growth

Industry	BAU 2040
Hydrogen (SMR)	1,020
Manufacturing (C)	496
Professional, Scientific and Technical Services (M)	405
Transport, Postal and Warehousing (I)	389
Mining (B)	278
Wholesale Trade (F)	244
Public Administration and Safety (O)	190
Electricity, Gas, Water and Waste Services (D)	188
Financial and Insurance Services (K)	161
Retail Trade (G)	161
Administrative and Support Services (N)	134
Accommodation and Food Services (H)	131
Construction (E)	112
Other Services (S)	107
Information Media and Telecommunications (J)	92
Hydrogen (Electrolysis)	87
Agriculture, Forestry and Fishing (A)	86
Health Care and Social Assistance (Q)	73
Rental, Hiring and Real Estate Services (L)	25
Education and Training (P)	17
Arts and Recreation Services (R)	11

Table 10 Electric Breakthrough, 2040, industry-by-industry employment contribution of hydrogen industry growth

Industry	**EB 2040**
Hydrogen (Electrolysis)	1,327
Professional, Scientific and Technical Services (M)	435
Electricity, Gas, Water and Waste Services (D)	432
Hydrogen (SMR)	408
Financial and Insurance Services (K)	383
Manufacturing (C)	323
Mining (B)	316
Transport, Postal and Warehousing (I)	298
Construction (E)	170
Wholesale Trade (F)	166
Administrative and Support Services (N)	148
Retail Trade (G)	125
Public Administration and Safety (O)	123
Other Services (S)	121
Accommodation and Food Services (H)	98
Information Media and Telecommunications (J)	90
Agriculture, Forestry and Fishing (A)	48
Health Care and Social Assistance (Q)	42
Rental, Hiring and Real Estate Services (L)	26
Education and Training (P)	19
Arts and Recreation Services (R)	13

7. Discussion

The GDP and employment estimates produced by this paper suggest that the contribution of the hydrogen industry to Australia's economy has the potential to be highly significant. It is important however that the estimates reported in the previous chapter be interpreted appropriately, with acknowledgement of the underlying assumptions. Returning to the IO analysis assumption of no resource constraints, in reality, the expansion of the hydrogen industry and the associated GDP and employment are likely to come at some cost to other industries. Therefore, it may be more reasonable to consider the figures of the previous chapter as GDP and jobs supported by the hydrogen industry (directly or indirectly), rather than additional or net benefits to the economy (West, 1999).

Deloitte's (2019, p. 92) CGE model can compute the net changes to the economy, hence the more modest employment impacts across all scenarios. However, their report does not publish all the precise inputs and assumptions used to calculate to the 'crowding out' effects from resource constraints. Future research examining hydrogen's impact on the Australian economy ought to quantitatively examine and report on the proportion of fuels and feedstocks that could be substituted in a future hydrogen economy as technology improves and demand increases. Applications of hydrogen in transport, steelmaking, blending in gas networks and industrial heat will displace fossil fuels like petroleum, natural gas, and coal. Published estimates of the degree of substitution across these applications, especially as proportions of their respective industries, would facilitate estimation of the net effects to the economy as the applications of hydrogen grow.

An important insight from this paper is the suggestion that, on a per unit of hydrogen output basis, electrolysis production contributes more to the Australian economy than SMR production. In the Data chapter, the multipliers for all industries were compared. Comparison of the multipliers showed that electrolysis has notably higher effects than SMR across production, value-added and employment. This finding is in contrast to that of Smith et al. (2017), who found that the multipliers of their hydrogen industry proxies- gas and electricity- were almost identical for value-added and employment.

Whether these results would be reflected in practice depends on the extent to which the two hydrogen industry proxies used in this study accurately reflect the input structures of their respective modes of hydrogen production. The justification for the use of these proxies is outlined in the Data chapter. Ultimately, however, the need for proxies arises from a lack of detailed data on the present and future hydrogen industry, particularly the input and distribution structures. Therefore, it would be worthwhile complementing and updating the proxies used in this analysis through industry surveys and expert opinions. Such research would assist in evaluating this paper's finding. If it is indeed the case that electrolysis generates greater economic benefits than SMR, this would suggest that an economic argument reinforces the environmental case for expediting the use of electrolysis-produced, green hydrogen.

Policymakers concerned with encouraging the growth of the hydrogen industry should therefore focus greater attention on bringing down the costs of green hydrogen. As renewable energy and electrolysers are currently the biggest cost factors in electrolysis (Longden et al., 2020), efforts to increase investment in both is encouraged. One important proposal for achieving this is enforcement of carbon capture and storage (CCS) on SMR, increasing the cost of production, helping electrolyser-produced hydrogen compete. Ongoing development of international green hydrogen certification schemes, guaranteeing renewables-based production, and anticipated international demand for certified green hydrogen are other factors that make electrolysis the more attractive target of existing and future government grants, subsidies and low-cost finance schemes for hydrogen projects (Deloitte, 2019; PWC, 2020).

This analysis also finds that the largest employment gains from a mature hydrogen industry, outside of the hydrogen industry itself, will be predominantly found across service industries. The concentration of employment in service industries is consistent with the findings of Deloitte (2019) and their CGE model analysis. In this analysis, the sectoral breakdown of employment estimates for the scenarios Energy of the Future, Targeted Deployment and Electric Breakthrough (Tables 7, 8 and 10) consistently show the main services benefactors are Professional, Scientific and Technical Services (M); Electricity, Gas, Water and Waste Services (D); and, Financial and Insurance Services (K). This finding may indicate that to cultivate a large hydrogen industry in Australia, future education and training initiatives should be directed toward services, as well as hydrogen industry specific jobs. The Australian National Hydrogen Strategy (COAG Energy Council, 2019, p. 63) anticipates that many of the required technical and professional service jobs will be ‘engineers, technicians, gas fitters, plumbers and builders and other associated trades’. Other important jobs will be in regulatory and legal positions. They foresee that although some skills and experience will be transferable to the hydrogen industry, there will be a need for qualification, licensing, and training to ensure safety across all aspects of working with hydrogen. As such it will be necessary to work with educational providers to ensure that training is up to date with international and domestic standards and codes. This training may itself become an additional export, given Australia’s strong reputation for quality education (COAG Energy Council, 2019).

8. Conclusion

This research aimed to estimate the potential significance of the hydrogen industry to the Australian economy out to 2040. Based on a scenario-based IO analysis, it is estimated that the hydrogen industry has the potential to make significant contributions to Australia, with the most optimistic scenario projecting over $14 billion in GDP and support of almost 57,000 jobs by 2040. While further research into the impact of hydrogen substitution in transport and other sectors will be necessary to estimate the net effects of a mature hydrogen industry, these initial results indicate that the current policy, research, and investment attention being directed toward the hydrogen industry is highly appropriate.

Further, this thesis' novel approach of using individual proxies for both SMR and electrolysis produced hydrogen revealed the suggestion that electrolysis-produced green hydrogen may lead to higher gains in GDP and employment than the dominant fossil fuel-based methods of production. This finding suggests that the case for encouraging investment and cost reduction in electrolyser technology and renewable energy is both environmentally and economically sound. Future research should aim to clarify the veracity of this finding by complementing and updating the proxies used in this paper with surveys of industry and expert opinion.

Finally, this paper confirms the findings of Deloitte (2019) that the largest labour needs arising from a mature hydrogen sector, outside of the hydrogen sector itself, will be found across services industries. This suggests that training and education initiatives accompanying the development of the Australian hydrogen industry should be directed towards increasing the number and skills of services workers.

The largest contribution of this thesis is potentially the detailed description of the data and methodology used to produce its economic impact estimates of the Australian hydrogen industry.

Academic research estimating the impact of hydrogen in other countries and regions undergo peer review before publishing, and some studies provide sufficient data such that their studies could be replicated, and results verified. The two existing Australian reports on the hydrogen industry were both produced by private consulting firms and substantial detail on their methodology is withheld, limiting the reproducibility, verification, and critique of their estimates.

This paper addresses this concern by providing extensive detail on its proxies for the hydrogen industry and the IO analysis applied. The aim of publishing these details is to strengthen understanding of the method behind the headline estimates of GDP and employment, and to promote critique and refinement of these estimates as further research on the hydrogen industry is conducted. In this regard, future research on the input and distribution structure of the hydrogen industry should be prioritised.

In conclusion, this paper offers the most thorough contribution to date on the potential structure and economic impacts of the Australian hydrogen industry. The environmental benefits of transitioning to a hydrogen economy are well-established (COAG Energy Council, 2019; PWC, 2020). The findings of this paper suggest that there is also a compelling economic case for sustained policy support and investment in pursuing the aim of the National Hydrogen Strategy: for Australia to become a 'major player in a global hydrogen industry'.

9. References

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10. Appendices

Appendix A: Scenario-based hydrogen demand estimate details

Scenario	**Year**	**AUD per kg of H2**	**Hydrogen demand assumptions**					
			Total demand (millAUD)	**SMR share**	**Electrolysis share**	**H_2 SMR (millAUD)**	**H_2 Electrolysis (millAUD)**
S1 Energy of the Future (EF)	2025	$2.64	$1,372	81%	19%	$1,112	$261
S1 Energy of the Future (EF)	2030	$1.89	$3,251	67%	33%	$2,171	$1,080
S1 Energy of the Future (EF)	2035	$1.64	$7,371	53%	47%	$3,876	$3,495
S1 Energy of the Future (EF)	2040	$1.42	$16,713	38%	62%	$6,416	$10,298
S2 Targeted Deployment (TD)	2025	$2.64	$660	89%	11%	$585	$75
S2 Targeted Deployment (TD)	2030	$1.89	$1,247	81%	19%	$1,010	$237
S2 Targeted Deployment (TD)	2035	$1.64	$3,029	73%	27%	$2,218	$811
S2 Targeted Deployment (TD)	2040	$1.42	$7,356	65%	35%	$4,817	$2,539
S3 Business as Usual (BAU)	2025	$2.64	$317	97%	3%	$309	$8
S3 Business as Usual (BAU)	2030	$2.64	$422	97%	3%	$409	$13
S3 Business as Usual (BAU)	2035	$2.64	$797	96%	4%	$769	$28
S3 Business as Usual (BAU)	2040	$2.64	$1,505	96%	4%	$1,444	$61
S4 Electric Breakthrough (EB)	2025	$2.64	$396	81%	19%	$321	$75
S4 Electric Breakthrough (EB)	2030	$2.64	$607	67%	33%	$405	$202
S4 Electric Breakthrough (EB)	2035	$2.64	$956	53%	47%	$503	$453
S4 Electric Breakthrough (EB)	2040	$2.64	$1,505	38%	62%	$578	$927

Appendix B: ANZSIC Industry division letter codes

ANZSIC Industry divisions	**Letter code**
Agriculture, Forestry and Fishing (A)	A
Mining (B)	B
Manufacturing (C)	C
Electricity, Gas, Water and Waste Services (D)	D
Construction (E)	E
Wholesale Trade (F)	F
Retail Trade (G)	G
Accommodation and Food Services (H)	H
Transport, Postal and Warehousing (I)	I
Information Media and Telecommunications (J)	J
Financial and Insurance Services (K)	K
Rental, Hiring and Real Estate Services (L)	L
Professional, Scientific and Technical Services (M)	M
Administrative and Support Services (N)	N
Public Administration and Safety (O)	O
Education and Training (P)	P
Health Care and Social Assistance (Q)	Q
Arts and Recreation Services (R)	R
Other Services (S)	S
Hydrogen (SMR)	-
Hydrogen (Electrolysis)	-

Appendix C: Input-Output Industry Groups (IOIG) to ANZSIC Division Concordances

IOIG	IOIG (2015) Descriptor	ANZDIV
0101	Sheep, Grains, Beef and Dairy Cattle	A
0102	Poultry and Other Livestock	
0103	Other Agriculture	
0201	Aquaculture	
0301	Forestry and Logging	
0401	Fishing, hunting and trapping	
0501	Agriculture, Forestry and Fishing Support Services	
0601	Coal mining	B
0701	Oil and gas extraction	
0801	Iron Ore Mining	
0802	Non Ferrous Metal Ore Mining	
0901	Non Metallic Mineral Mining	
1001	Exploration and Mining Support Services	
1101	Meat and Meat product Manufacturing	C
1102	Processed Seafood Manufacturing	
1103	Dairy Product Manufacturing	
1104	Fruit and Vegetable Product Manufacturing	
1105	Oils and Fats Manufacturing	
1106	Grain Mill and Cereal Product Manufacturing	
1107	Bakery Product Manufacturing	
1108	Sugar and Confectionery Manufacturing	
1109	Other Food Product Manufacturing	
1201	Soft Drinks, Cordials and Syrup Manufacturing	
1202	Beer Manufacturing	
1205	Wine, Spirits and Tobacco	
1301	Textile Manufacturing	
1302	Tanned Leather, Dressed Fur and Leather Product Manufacturing	
1303	Textile Product Manufacturing	
1304	Knitted Product Manufacturing	
1305	Clothing Manufacturing	
1306	Footwear Manufacturing	
1401	Sawmill Product Manufacturing	
1402	Other Wood Product Manufacturing	
1501	Pulp, Paper and Paperboard Manufacturing	
1502	Paper Stationery and Other Converted Paper Product Manufacturing	
1601	Printing (including the reproduction of recorded media)	
1701	Petroleum and Coal Product Manufacturing	
1801	Human Pharmaceutical and Medicinal Product Manufacturing	
1802	Veterinary Pharmaceutical and Medicinal Product Manufacturing	
1803	Basic Chemical Manufacturing	
1804	Cleaning Compounds and Toiletry Preparation Manufacturing	
1901	Polymer Product Manufacturing	
1902	Natural Rubber Product Manufacturing	
2001	Glass and Glass Product Manufacturing	

2002	Ceramic Product Manufacturing	
2003	Cement, Lime and Ready-Mixed Concrete Manufacturing	
2004	Plaster and Concrete Product Manufacturing	
2005	Other Non-Metallic Mineral Product Manufacturing	
2101	Iron and Steel Manufacturing	
2102	Basic Non-Ferrous Metal Manufacturing	
2201	Forged Iron and Steel Product Manufacturing	
2202	Structural Metal Product Manufacturing	
2203	Metal Containers and Other Sheet Metal Product manufacturing	
2204	Other Fabricated Metal Product manufacturing	
2301	Motor Vehicles and Parts; Other Transport Equipment manufacturing	
2302	Ships and Boat Manufacturing	
2303	Railway Rolling Stock Manufacturing	
2304	Aircraft Manufacturing	
2401	Professional, Scientific, Computer and Electronic Equipment Manufacturing	
2403	Electrical Equipment Manufacturing	
2404	Domestic Appliance Manufacturing	
2405	Specialised and other Machinery and Equipment Manufacturing	
2501	Furniture Manufacturing	
2502	Other Manufactured Products	
2601	Electricity Generation	D
2605	Electricity Transmission, Distribution, On Selling and Electricity Market Operation	
2701	Gas Supply	
2801	Water Supply, Sewerage and Drainage Services	
2901	Waste Collection, Treatment and Disposal Services	
3001	Residential Building Construction	E
3002	Non-Residential Building Construction	
3101	Heavy and Civil Engineering Construction	
3201	Construction Services	
3301	Wholesale Trade	F
3901	Retail Trade	G
4401	Accommodation	H
4501	Food and Beverage Services	
4601	Road Transport	I
4701	Rail Transport	
4801	Water, Pipeline and Other Transport	
4901	Air and Space Transport	
5101	Postal and Courier Pick-up and Delivery Service	
5201	Transport Support services and storage	
5401	Publishing (except Internet and Music Publishing)	J
5501	Motion Picture and Sound Recording	
5601	Broadcasting (except Internet)	
5701	Internet Service Providers, Internet Publishing and Broadcasting, Websearch Portals and Data Processing	
5801	Telecommunication Services	
6001	Library and Other Information Services	
6201	Finance	K
6301	Insurance and Superannuation Funds	

6401	Auxiliary Finance and Insurance Services	
6601	Rental and Hiring Services (except Real Estate)	L
6701	Ownership of Dwellings	
6702	Non-Residential Property Operators and Real Estate Services	
6901	Professional, Scientific and Technical Services	M
7001	Computer Systems Design and Related Services	
7210	Employment, Travel Agency and Other Administrative Services	N
7310	Building Cleaning, Pest Control and Other Support Services	
7501	Public Administration and Regulatory Services	O
7601	Defence	
7701	Public Order and Safety	
8010	Primary and Secondary Education Services (incl Pre-Schools and Special Schools)	P
8110	Technical, Vocational and Tertiary Education Services (incl undergraduate and postgraduate)	
8210	Arts, Sports, Adult and Other Education Services (incl community education)	
8401	Health Care Services	Q
8601	Residential Care and Social Assistance Services	
8901	Heritage, Creative and Performing Arts	R
9101	Sports and Recreation	
9201	Gambling	
9401	Automotive Repair and Maintenance	S
9402	Other Repair and Maintenance	
9501	Personal Services	
9502	Other Services	