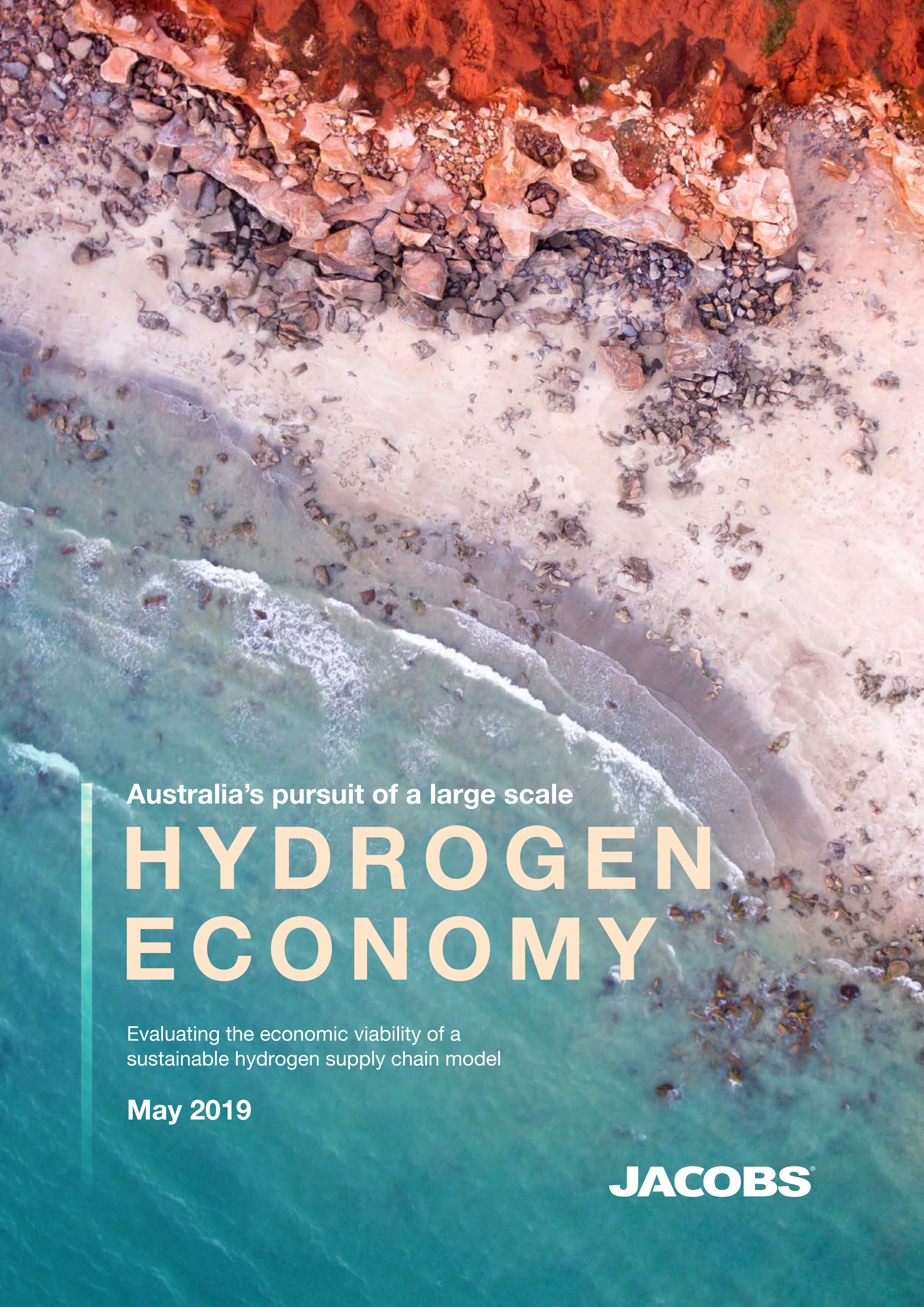
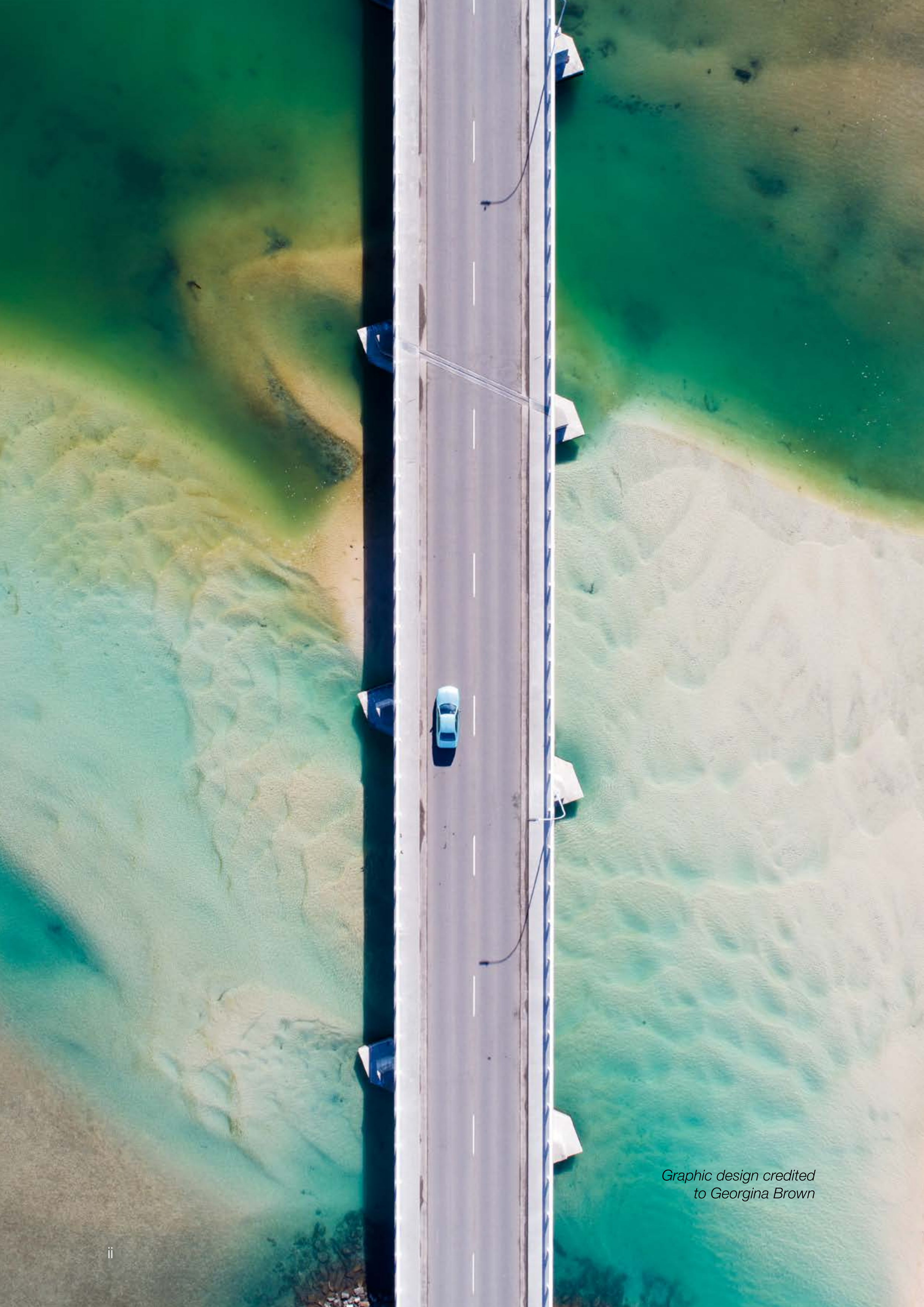


Australia’s pursuit of a large scale
HYDROGEN ECONOMY

Evaluating the economic viability of a
sustainable hydrogen supply chain model

May 2019

JACOBS



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Foreword

What if we could integrate knowledge from the water, power and transport sectors to create a more sustainable Australia?

In 2015 the Australian Government signalled its commitment to reducing carbon emissions and working towards a more sustainable future, signing up to the Paris Agreement on Climate Change and adopting the United Nations' Sustainable Development Goals. The Government has subsequently implemented a range of policy measures in pursuit of 2020 and 2030 carbon emission reduction targets, yet the Intergovernmental Panel on Climate Change 2018 Special Report identifies that we must take greater measures to limit the risk and severity of catastrophic climate impacts.

With its potential to decarbonise a broad spectrum of industries, hydrogen as an alternative energy storage solution is currently receiving renewed attention, including from The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Australia's Chief Scientist. This resurgence is largely due to improvements in hydrogen production technologies and the declining cost of renewable energy, meaning that large-scale zero-emissions hydrogen production may be more viable now than ever before. With excellent renewable energy resources and proximity to large potential export markets in Asia, Australia is well positioned to become a leader in this emerging industry.

Despite the recent focus on hydrogen, industry conversations have largely neglected one critical issue; under the current electrolysis-based supply chain model, production may not be sustainable in the context of Australia's climate and existing energy landscape.

To be sustainable, this supply chain model requires both readily available renewable energy generation and a consistent supply of drinking water; both requirements could be an impediment to sustainable hydrogen production in Australia. While renewable energy developments are increasing across the country, our electricity grid is still dominated by coal-fired generation and our ability to use grid-purchased electricity generated from renewable sources for hydrogen production is limited. Moreover, in a country already facing increasing fears over future water security, the creation of a new industry that relies on drinking water could further exacerbate supply risks. Our pursuit of a large-scale hydrogen economy should not contribute to broader sustainability challenges, including putting additional strain on an already scarce resource.

This raises two pertinent questions: How might we create a more sustainable hydrogen supply chain model for Australia's circumstances, and could such a model prove as economically viable as the current approach?

This paper explores how the current hydrogen supply chain model could be adapted for Australia's environmental conditions and energy landscape by replacing drinking water with recycled water in the production process and evaluating options for sourcing renewable energy generation. In doing so, we will assess whether a truly sustainable hydrogen supply chain model can be employed in Australia without sacrificing economic viability. •

Authors and contributors

As our world undergoes rapid transformation and the challenges we face become increasingly interlinked and complex, we must look beyond individual markets, sectors and industries and engage in meaningful cross-sector conversation and collaboration. It is only in doing so that we can develop innovative solutions that will drive sustainable growth into the future.

This paper has been authored by Jacobs' global network of professionals, who take a cross-sector collaborative approach to address some of the world's most critical challenges and advance conversations that matter.

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Contents

Executive summary

The drive towards a lower-emissions and more sustainable future is gathering pace. At the same time, discussions about hydrogen as an energy storage solution are increasing due, in large part, to its potential to decarbonise many Australian industries and to support economic growth as a new export market. However, Australia's pursuit of a large-scale hydrogen economy could represent a trade-off between environmental sustainability and economic viability if the current electrolysis-based hydrogen supply chain model is adopted.

The current supply chain model requires ready access to a renewable electricity grid and a consistent supply of drinking water. Neither of these conditions are present in Australia, a drought-prone country with an electricity grid composed predominantly of emissions-intensive coal-fired generation. We must determine whether a more sustainable model is possible and how this might compare to the current model on an economic basis.

Developing a hydrogen economy that successfully navigates potential environmental and economic hurdles will require collaboration across the water, power and transport sectors. This paper draws on knowledge from professionals across each of these sectors to investigate and compare the sustainability and economic benefits of a hydrogen supply chain that uses renewable energy and recycled water (the Proposed Model) rather than grid-purchased electricity and drinking water (the Current Model).

The paper does not aim to assess the viability of hydrogen itself; rather it seeks to ascertain the comparative economic viability of a supply chain model that would improve the sustainability of hydrogen if a large-scale Australian economy were to develop. Both models were applied to convert the existing diesel-powered East-West Rail Corridor to hydrogen rail vehicles, and results were assessed via a cost-benefit analysis (CBA). This methodology was used to calculate the Net Present Value (NPV)[1] of adopting both hydrogen scenarios against a 'Business-as-Usual' (BAU) scenario which assumed no transition to hydrogen rail vehicles.

The details of each scenario and the modelling inputs are summarised in *Chapter 2* and *Appendix A* respectively.

Results summary

In terms of economic viability:

- Our results indicated that the Current Model was more economically viable than the Proposed Model, with the electrolyser usage rate representing the key cost driver.
- Power Purchase Agreements (PPAs) were the most viable means of producing zero-emissions hydrogen at large volumes. Reliance on dedicated behind-the-meter or curtailed renewable energy are unlikely to be viable as sole sources of energy for hydrogen production at the scale required to create a functioning large scale hydrogen economy.
- While the source of water did not have a large impact on NPV, using recycled water for hydrogen production could be beneficial due to its availability throughout the year, thus eliminating drinking water supply shortage risks and creating additional commercial opportunities for water businesses.

In terms of environmental sustainability:

- Although the Current Model was not zero-emissions, replacing diesel rail vehicles with hydrogen rail vehicles still resulted in net emissions savings averaging about 232,000 tonnes per annum. However, it is important to note that while the modelling assumed a national emissions reduction policy with targets that would ensure Australia meets its Paris Commitment targets in 2030 and reaches zero emissions by 2070, no such policy is currently in place. Achieving these targets is equivalent to a decline in the emissions intensity of the electricity grid at an average rate of 5% per annum from 2025 to 2065. Emissions created from the Current Model could be substantially higher if this decline is slower than projected.
- Even if no policy is implemented, hydrogen production could effectively reduce its emissions over time by procuring an increasing proportion of energy via PPAs and during periods where there is an oversupply of renewable energy.
- The use of recycled water in the supply chain model would have no adverse impact on Australia's drinking water supply.

In terms of rail freight:

- Sensitivity tests indicated that the price of diesel and cost of hydrogen rail vehicles were major influencing factors on economic viability.
- Though the analysis is high-level and could vary substantially based on project and site-specific factors, an increase in diesel prices of approximately 18% or a reduction in the cost of hydrogen rail vehicles of approximately 30% resulted in a positive NPV.
- Adopting the Current Model to convert the East-West Rail Corridor to hydrogen would result in emissions savings equivalent to taking 49,000 passenger cars off the road every year[2].

Based on these findings, the following recommendations outline means to support large-scale hydrogen projects that do not create a trade-off between environmental sustainability and economic viability. •

Energy recommendations

The current discourse on hydrogen in Australia focuses on its zero-emissions benefits. However, our results indicate that if hydrogen production is scaled up to meet its large range of potential applications, sourcing the electricity required from only zero-emissions energy sources would negatively impact its economic viability.

The following actions should be considered:

1

TAKE A 'STAGED' APPROACH TO ZERO-EMISSIONS HYDROGEN

While producing hydrogen from Australian grid-purchased electricity would create emissions in the short to medium-term, this may be acceptable if the hydrogen produced is able to create more significant emissions reductions in its end-use application. Taking a progressive or 'staged' approach to making hydrogen zero-emissions could therefore still create net benefits from an emissions reduction perspective and enable earlier adoption of hydrogen by making the production process more economically viable. As outlined in Chapter 3, such approaches could take the form of a hydrogen-specific emissions reduction target or enacting policy measures to reduce grid emissions faster than currently projected.

2

EXPLORE FLEXIBLE ENERGY SOURCING OPTIONS TO AVOID LOCK-IN

Most zero-emissions hydrogen projects to date have been small-scale pilots or demonstrations that made effective use of behind-the-meter wind or solar generation. Our findings indicated that this approach is cost prohibitive for large-scale production facilities, locking-in their source of energy at a high cost. There are a number of other downsides to this approach. First, not all locations that are suitable for hydrogen production are likely to have strong renewable energy resources. Second, even where resources are available, it may not be possible to develop renewable energy plants large enough to meet hydrogen demand due to the trade-off between proximity to urban centres and planning restrictions/land availability.

Finally, building dedicated renewable energy plants increases capital and operating costs and may make scaling production difficult and time-intensive given the lead times for building additional generation. Instead, more flexible interim solutions should be considered, such as grid-purchased electricity with emissions offset by renewable PPAs. •

Water recommendations

The role of water in hydrogen production must be recognised and become a component of current and future conversations about the development of a large-scale hydrogen economy. A large-scale hydrogen project using recycled water could serve as a test case for a more sustainable model that reduces potential resource scarcity and climate risks, while providing additional economic benefits. As such, the following actions should be considered:

1

WATER BUSINESSES SHOULD EVALUATE THE POTENTIAL BENEFITS OF HYDROGEN PRODUCTION

Water businesses should evaluate the feasibility of producing hydrogen and consider the potential revenue stream, cost-savings and efficiency gains this would entail for their organisation. It is envisaged that water utilities would find this an attractive prospect, given the current challenge of finding a demand for recycled water that does not result in increased costs for customers.

2

DEVELOP HYDROGEN PRODUCTION FACILITIES THAT USE RECYCLED WATER

Using recycled water to produce hydrogen would eliminate the need to use drinking water resources. The prevalence of wastewater facilities across Australia and their proximity to urban centres would offer flexible siting options. Ideally, hydrogren facilities should be located in areas with the largest number of potential end-users to reduce distribution costs to these users and create economies of scale. Increasing demand for recycled water would also reduce the water quality impacts of discharging recycled water to waterways and oceans, delivering an additional environmental benefit.

3

ADD SUSTAINABLE HYDROGEN AS AN OPTION IN ENERGY STRATEGIES

Cities and towns with medium to large wastewater facilities should incorporate hydrogen production as a potential option into their economic growth and energy strategies. Business cases will be further supported if these locations are adjacent to existing or planned transport hubs and other large potential end-users such as industrial business parks.

4

GOVERNMENT SHOULD ENCOURAGE MORE SUSTAINABLE PRODUCTION METHODS

Government has a role to play in establishing measures that encourage the adoption of hydrogen in a way that supports responsible consumption of scarce resources and in allocating funds to projects that advance this objective.

In summary, if Australia is to become a global leader in hydrogen production, early planning that accounts for the sustainability implications highlighted in this paper is critical as project lifetimes can span multiple decades. Decisions related to hydrogen will require government and industry to engage collaboratively with professionals and academics across multiple disciplines.

Promoting a greater diversity of perspectives in strategic forums such as the Council of Australian Governments (COAG) Energy Council's Hydrogen Working Group will support this aim and encourage the development of innovative solutions that drive sustainable growth in the Australian market. As with any emerging technology nearing commercial deployment, it is vital that a holistic view is applied in early phases of development to identify risks and maximise potential. Overall, taking a view that considers the broader implications of rapidly changing technological, environmental and social trends supports the development of integrated solutions that create a more connected, sustainable world. •

1

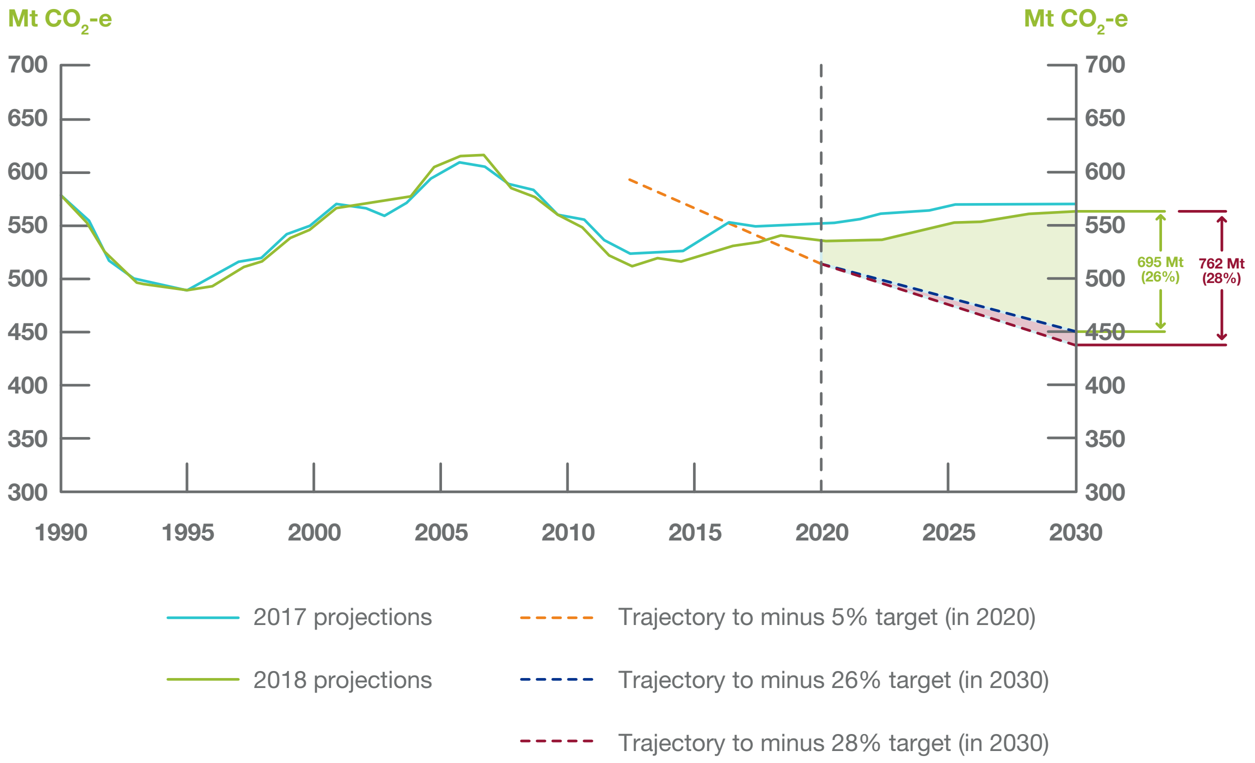
Introduction

Towards a zero-carbon future: the role of energy storage solutions

The Intergovernmental Panel on Climate Change's (IPCC's) 2018 Special Report emphasised the need to rapidly decarbonise emissions-intensive sectors, including energy, agriculture, industrial processes, waste and transport, to limit global warming to 1.5°C[3]. We are making some progress towards this target, with renewable energy generation technologies such as wind turbines and solar photovoltaic (PV) panels already delivering emissions reductions. Taken together, they represent over half of new energy developments globally in recent years and investment in these technologies is growing. However, the world is not yet on track to meet the IPCC's recommended target and greater action is necessary. Australia is a prime example of these trends, with the Department of Environment and Energy's 2018 emissions projections report highlighting that despite increasing renewable energy uptake, the country is not on track to meet its 2030 emissions reduction target of 26-28% below 2005 levels[4].

There are two major barriers to achieving widespread decarbonisation in Australia. First, because the wind does not always blow and the sun does not always shine, transitioning to 100% renewable energy is only possible if we can make these resources reliable. We do not presently have a cost-effective means of storing energy generated from renewable sources for long periods of time, meaning many countries, Australia included, still rely on emissions-intensive fossil fuels to provide consistent energy supply. Second, industries that are not connected to the electricity grid, such as much of the transport sector, cannot access renewable energy without storing it in a portable form.

Figure 1: Australia’s historical and projected emissions trends (1990 – 2030) show a clear gap between projected emissions levels and our emission reduction target.



Source: Figure 4 in ‘Australia’s emissions projections 2018’ report by the Department of the Environment and Energy

Discussions about how to make renewable energy sources more reliable (and accessible) through energy storage have recently surged in Australia. The advantages of energy storage solutions are that they can provide back-up power in the event of black-outs and allow renewable energy use to be optimised. They also make renewable energy transportable, enabling widespread use of zero-emissions electricity by industries not connected to the grid.

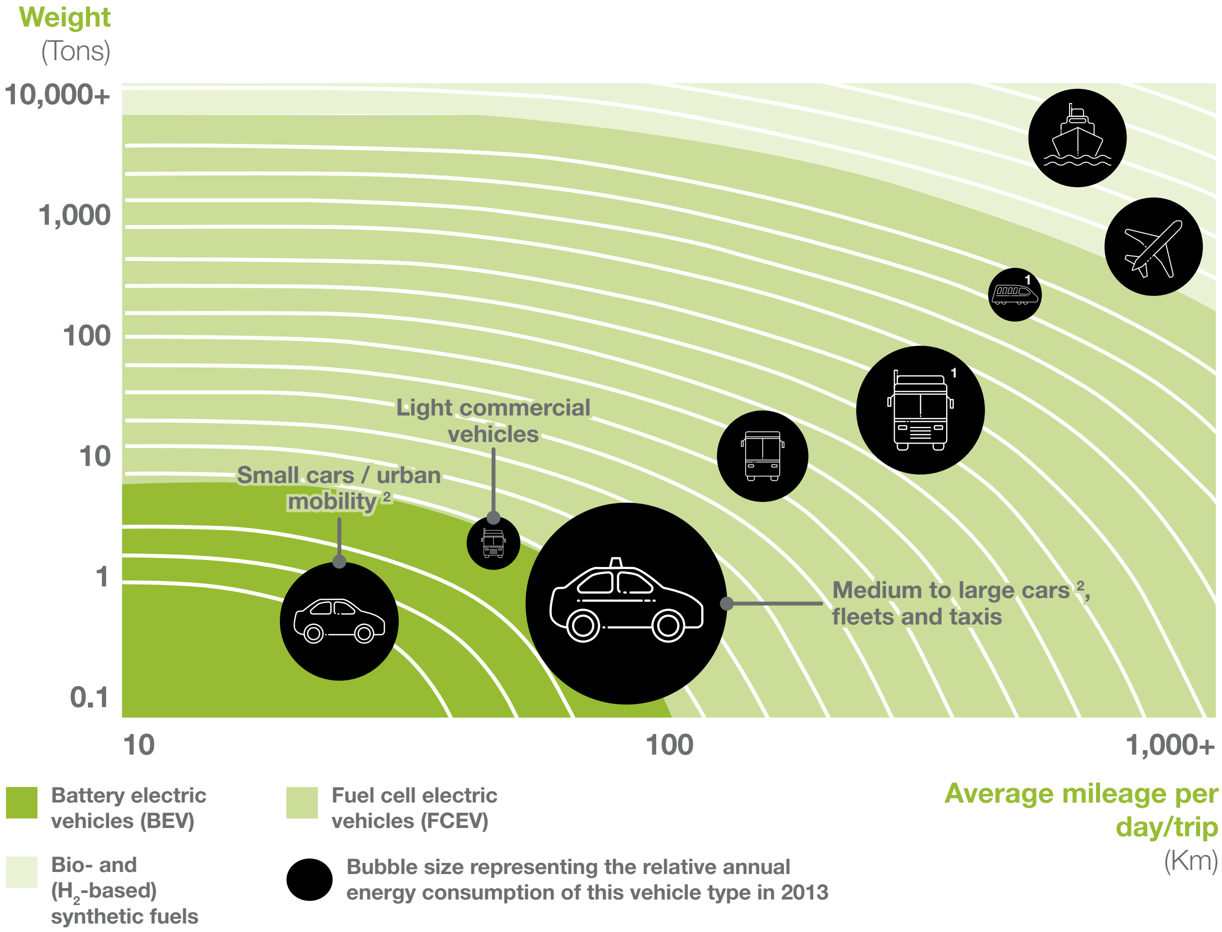
Lithium-ion batteries are arguably the most well-known energy storage technology, in large part due to the recent installation of one of the world’s largest lithium-ion battery systems in South Australia. However hydrogen is currently receiving renewed attention, including from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Australia’s Chief Scientist. This resurgence is largely due to improvements in hydrogen production technologies and the declining cost of renewable energy.

While the efficiency and cost benefits of batteries and hydrogen are often compared, the two technologies have different characteristics and therefore different advantages and potential end-uses. Batteries are heavy, highly efficient and are best suited for use in passenger vehicles and to supply high volumes of power over short timescales.

In contrast, hydrogen in gaseous form is light weight, energy dense and has great potential for use in large-scale, long-distance transport, as a replacement for household natural gas applications and thermal-peaking generators, and as a back-up energy source for lengthy periods (ten hours or more).

To achieve a zero-emissions future, a variety of energy storage technologies are required. Based on its versatile characteristics, hydrogen could play a key role in decarbonising many applications where other energy storage technologies are unsuitable. •

Figure 2: Due to their different characteristics, hydrogen and batteries are suitable for different transport modes, with hydrogen more suited to medium to large-scale vehicles.



1 Battery-hydrogen hybrid to ensure sufficient power

2 Split in A- and B-segment LDV's (small cars) and C+-segment LDVs (medium to large cars) based on a 30% market share of A/B-segment cars and a 50% less energy demand

Source: Toyota, Hyundai, Daimier

Source: Adapted from Figure 5 in Hydrogen Council (2017)[5]

Investment in hydrogen is increasing but is the future 'sustainable'?

Australia is well positioned to become a market leader in zero-emissions hydrogen production if the nation's excellent renewable energy resources are developed. The 2018 Hydrogen for Australia's Future report outlined three opportunity areas for Australian-produced hydrogen: as an export product, to decarbonise domestic industries and to improve energy system resilience[6]. In support, the Federal Government has opened public consultation on a national hydrogen strategy. In addition, multiple State governments have initiated strategies, pilot projects or investment vehicles to develop hydrogen production opportunities, with several cities submitting project ideas with the aim of becoming Australia's first hydrogen city[7].

However, while terms such as 'green' and 'renewable' hydrogen are often used in the media, there are still potential barriers that must be overcome to enable hydrogen production to occur both at the scale required to meet the opportunities described above and deliver on its sustainability-related credentials. •

Figure 3: There are three main opportunity areas for Australian-produced hydrogen

EXPORT

+ Liquefied hydrogen or hydrogen in ammonia form
+ Proximity to large potential export markets (Japan, China, South Korea, and Singapore)

DOMESTIC

+ Replacement for natural gas in heating, cooking, hot water, and industrial applications
+ Transport
+ Industrial processes

ENERGY SYSTEM RESILIENCE

+ Electrolysis as flexible load
+ Stored hydrogen for dispatchable electricity generation
+ Hydrogen for fuel diversification

Sustainability barriers to Australian-produced hydrogen

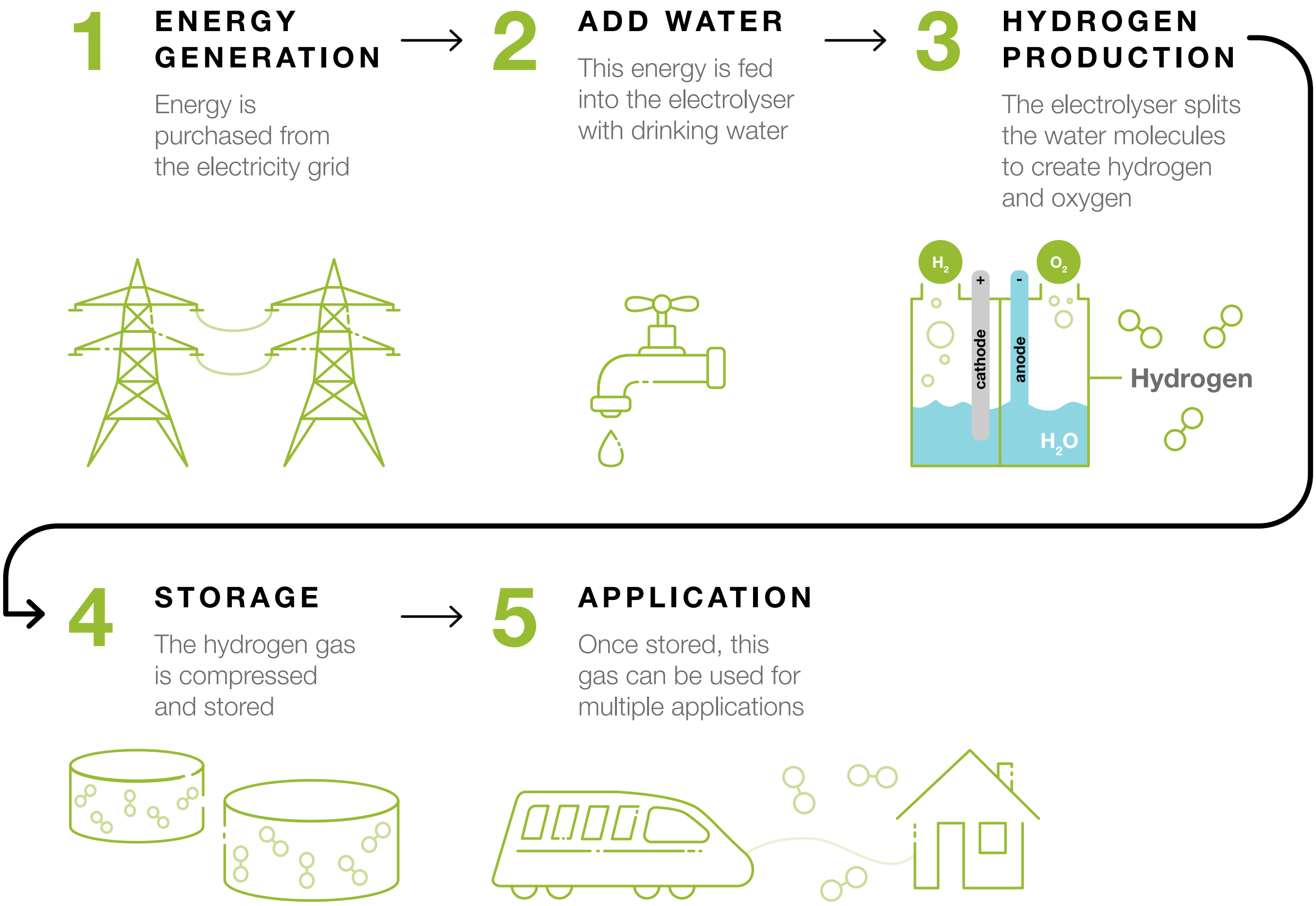
Discussions around developing a large-scale hydrogen economy in Australia often suggest adopting the electrolysis-based supply chain model proposed overseas in regions such as Ontario in Canada and Norway in Europe (see Figure 4). However, this model cannot be readily implemented in Australia.

The model assumes that zero-emissions electricity from renewable energy and a high-volume, reliable supply of drinking water are available.

Neither of these conditions are present in Australia, a drought-prone country where drinking water reserves are already often strained and the electricity system is still dominated by emissions-intensive coal generation.

While industry conversations have discussed means of making hydrogen zero-emissions by pairing production facilities with renewable energy generators, there has been limited discussion to date about whether this is viable on a large scale, or how scaling production would impact drinking water supplies.

Figure 4: The current electrolysis-based hydrogen supply chain model



1 ENERGY GENERATION →

Energy is purchased from the electricity grid

2 ADD WATER →

This energy is fed into the electrolyser with drinking water

3 HYDROGEN PRODUCTION

The electrolyser splits the water molecules to create hydrogen and oxygen

4 STORAGE →

The hydrogen gas is compressed and stored

5 APPLICATION

Once stored, this gas can be used for multiple applications

Access to zero-emissions energy

In countries with electricity systems made up mostly of renewable energy, it is possible to buy electricity from the grid at the cheapest times without creating emissions. In Australia, the cheapest times to buy electricity also tend to be times when coal generation levels are at their highest, meaning hydrogen production facilities that rely on grid-purchased electricity would most likely create more emissions, not less—a fact highlighted recently by researchers at Queensland University of Technology (QUT)[8]. Research from the CSIRO (2018) supports this finding but also indicated that hydrogen produced from grid-purchased electricity would be more cost-effective than from dedicated renewable energy options[9].

So, for now at least, there is a clear trade-off between economic viability and environmental sustainability. Although this may change as more renewable energy projects are built, modelling conducted by Jacobs' Energy Market Insights group in 2019 on the future of the national electricity market has indicated that ongoing investment in renewable energy will require some form of national emissions reduction policy and that coal generation is still likely to make up a large portion of the electricity system for at least the next 20 years. Further analysis is therefore necessary to evaluate the cost of different options for sourcing renewable energy for hydrogen production and to improve their economic viability.

Increasing pressure on water resources

Climate change is already diminishing Australia's water security; rainfall patterns are shifting and the frequency and severity of droughts are increasing. This means that less water is likely to be available for agriculture, urban water supplies and ecosystems across Australia in the future. The additional strain a new hydrogen economy would place on finite water resources must be considered.

To supply the opportunity areas identified previously, hydrogen production would have to be scaled up substantially. We would need to produce approximately 500 million kilograms of hydrogen per year to service the estimated 2030 export market[10], using an additional 5.5 billion litres of water per year. If we also looked to decarbonise some of Australia's domestic industries by replacing the 39 million tonnes of imported diesel and petrol fuel currently used across the country with hydrogen, this would require 99 billion litres of water per year. This would have the same impact on water demand as adding an additional 1.7 million people to Australia's urban population.

While this may seem trivial when compared with the agriculture sector which used about 11 trillion litres of water in 2018, our existing drinking water resources are already stretched. Several major Australian cities are already reliant on energy-intensive desalinated water plants to meet their existing drinking water needs and many farms across Australia are experiencing water shortage issues. Hydrogen usage would be expected to increase every year as our population and export demand grows and the technology becomes increasingly widespread. Ongoing population growth and climate change already represent significant risks to the nation's drinking water reserves and developing a large-scale hydrogen economy represents an irresponsible use of a scarce resource unless an alternative sustainable water source is identified.

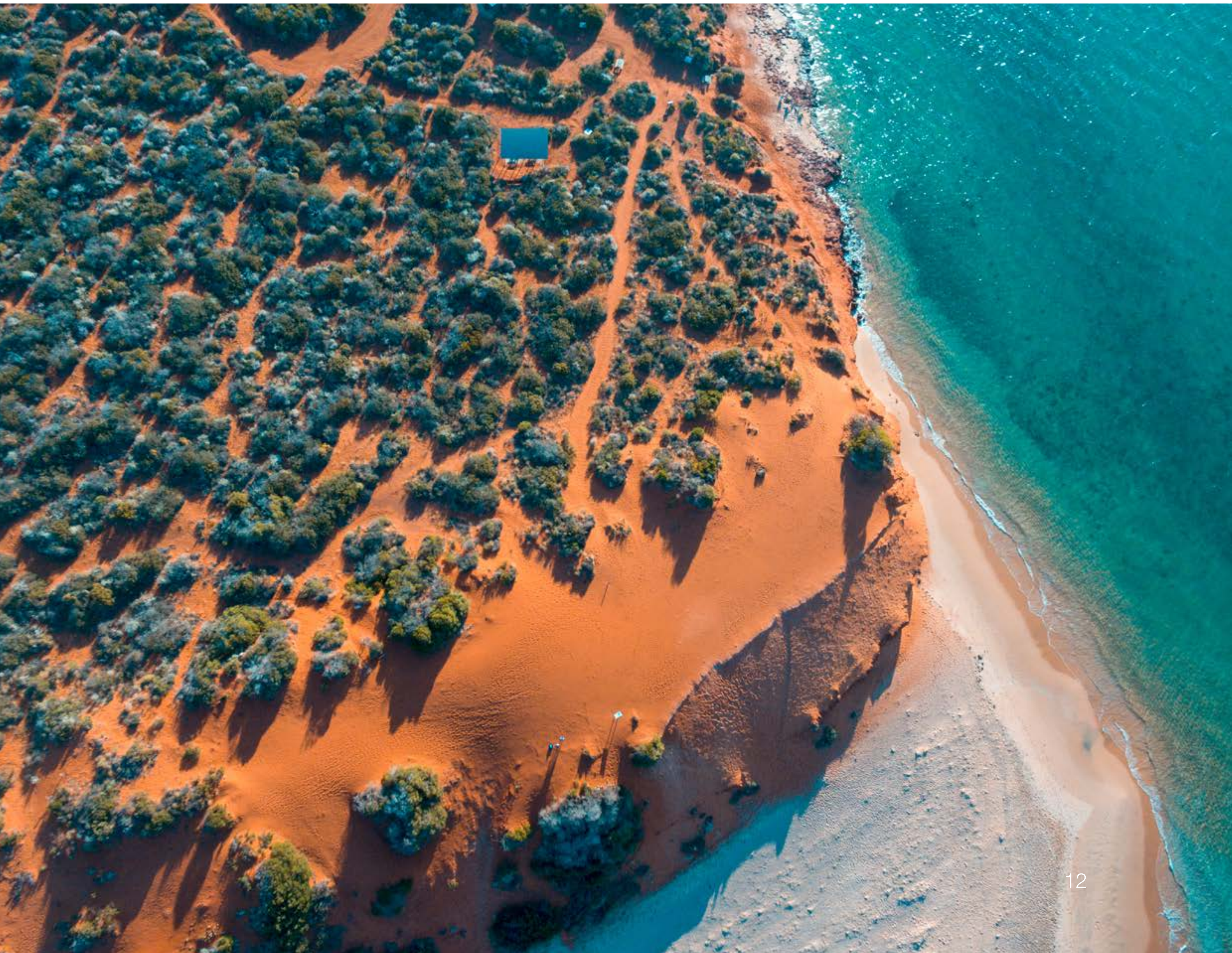
In short, large-scale hydrogen production using the current hydrogen supply chain model is unsustainable in Australia.

Pathway to a more sustainable hydrogen future

The noted sustainability challenges should not deter our progress towards zero-emissions hydrogen, however, we must determine:

1. Whether a more sustainable hydrogen supply chain model can be developed that does not exacerbate water scarcity risks in addition to being zero-emissions
2. Whether that model would prove economically viable compared to the current non-sustainable model

This paper therefore compares the sustainability and economic viability of a hydrogen supply chain which uses renewable energy (behind-the-meter or contracted) and recycled water against the current model which uses grid-purchased electricity and drinking water. •



2

The approach

A more sustainable hydrogen supply chain model

The current process

The current electrolysis-based supply chain model (the Current Model) assumes access to abundant drinking water sources and renewable energy. For reasons already discussed, the model presents potential sustainability challenges in Australia. This section outlines how the Current Model might be adapted for Australian conditions to create a more sustainable solution and whether this approach would prove as economically viable.

To ground the results in a real-world application, both the Current Model and proposed supply chain model (the Proposed Model) are applied to an existing diesel-powered freight line in Australia: The East-West Rail Corridor, an intermodal freight route from Melbourne to Perth.

A new approach

STEP 1: OPTIONS FOR ZERO-EMISSIONS ENERGY

The Australian electricity grid is likely to include a large proportion of coal-fired generation for at least the next two decades. The CSIRO (2018) has identified three potential options for sourcing zero-emissions energy for hydrogen production in the interim:

1. Building dedicated renewable energy plants for the sole purpose of producing hydrogen;
2. Securing a renewable Power Purchase Agreement (PPA) – a contract to buy electricity from renewable energy facilities located anywhere in the market;
3. Using spare or ‘curtailed’ capacity from renewable energy plants which would otherwise not have been used.

Any of these options could feasibly be used to produce hydrogen without creating emissions and each is examined for use in the Proposed Model via sensitivity analysis.

At this stage, it is important to note that there are two main types of electrolyser technology and the choice of technology used will impact sustainability and economic feasibility outcomes. Alkaline Electrolysers (AE) are a mature electrolysis technology but must be run continuously. Proton Exchange Membrane (PEM) electrolysers are a more recent technology that can be switched on and off quickly without the need to operate continuously. Not only can PEM electrolysers produce hydrogen at times when variable renewable generation such as wind or solar is available, they have a smaller installation footprint and are modular in nature, meaning that electrolyser capacity can be scaled up progressively to reduce upfront capital costs and benefit from technological advancements.

For these reasons, the modelling assumes PEM electrolysers are used for hydrogen production in both the Current and Proposed Models.

STEP 2: OPTIONS FOR SUSTAINABLE WATER INPUTS

Most hydrogen research to date has paid little to no attention to the role of water in the production process, assuming access to a reliable supply of drinking water. However, the use of this resource to produce hydrogen at scale in Australia would be subject to limited social license given supply shortages and growing concerns about the scarcity of freshwater sources. Alternative water sources for hydrogen production must be considered.

‘Social license to operate’ (SLO)

We only need to look at recent history to see that gaining social approval or acceptance for projects that use significant amounts of drinking water is a major challenge. For example, during the Millennium Drought, concerns over the use of drinking water to top up Lake Wendouree in Ballarat, Victoria, resulted in an alternative more sustainable and socially acceptable approach which utilised harvested stormwater, groundwater and recycled water.

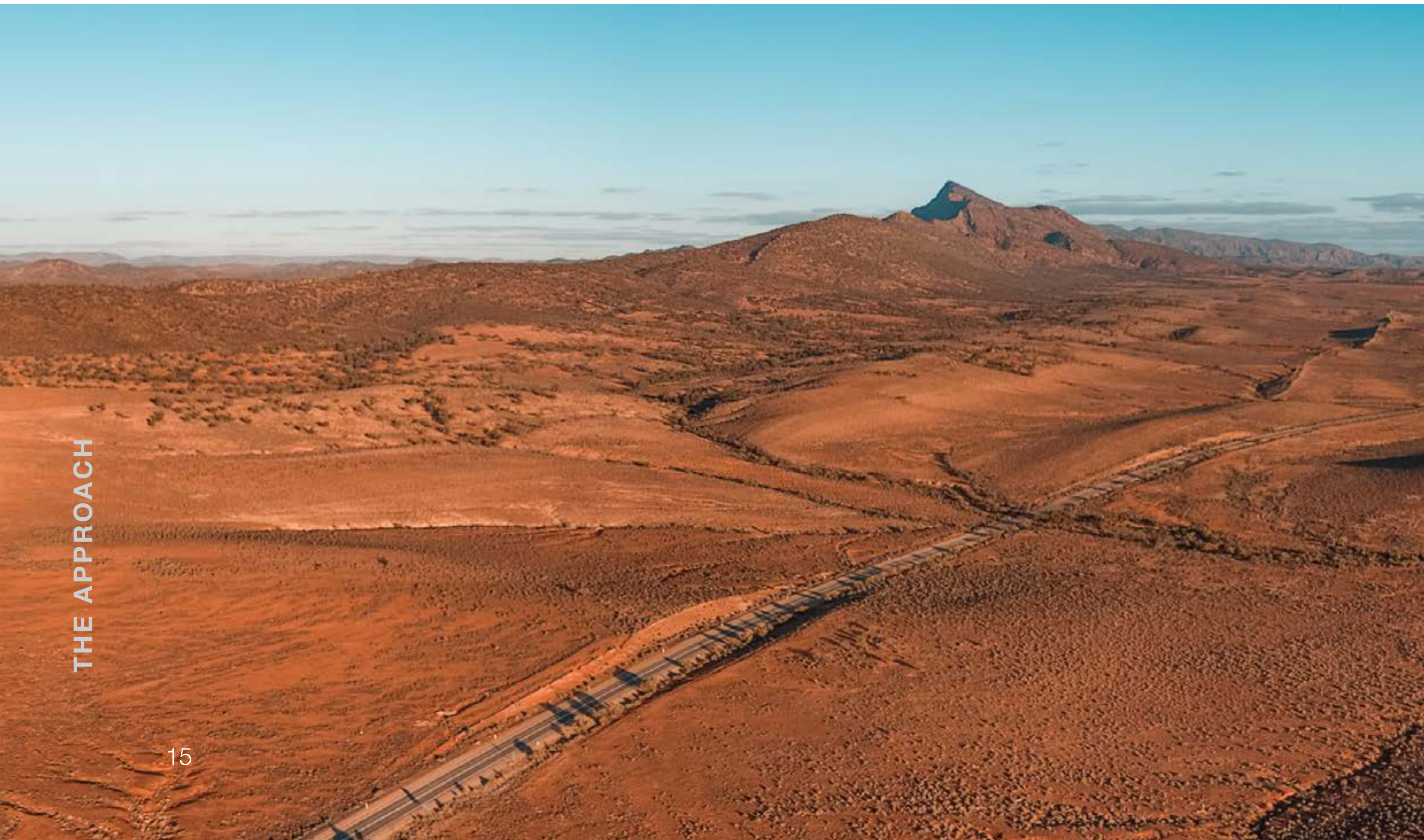
Water sourced from desalination plants is one option. Although this is a sustainable way to source water, it is also an expensive one. The cost to source desalinated water from the existing Victorian Desalination Plant (VDP) is approximately $5/kL[11], compared to the cost of sourcing fresh drinking water estimated at approximately $2.75/kL[12]. Further, the production capacity of existing desalination infrastructure is insufficient to meet the water demands of a large-scale hydrogen economy; new desalination plants would need to be built. The costs of materials, construction of core and supporting infrastructure and the additional energy required to operate these plants could increase the cost to $10/kL[13].

A second option is to use recycled water sourced from wastewater treatment plants. This water is in abundant supply and volume is consistent throughout the year. Wastewater treatment facilities servicing major urban centres and even medium-sized towns produce millions of litres of recycled water each year. Despite being treated to a very high standard, this water is mostly discharged to the environment due to the political, legislative and cost barriers that limit its use for a broad range of potential applications (see Table 1).

The use of recycled water for hydrogen production is unlikely to encounter these challenges. It could also reduce the impact of wastewater treatment facilities on local ecosystems which can be highly sensitive to changes in water chemistry and flow patterns. From a cost perspective, recycled water for hydrogen production could also be less expensive than both desalination water and drinking water at approximately $0.70/kL[14]. Recycled water is therefore used as a sustainable alternative to primary-use drinking water sources in the Proposed Model.

Table 1: Positives and negatives of recycled water in potential applications

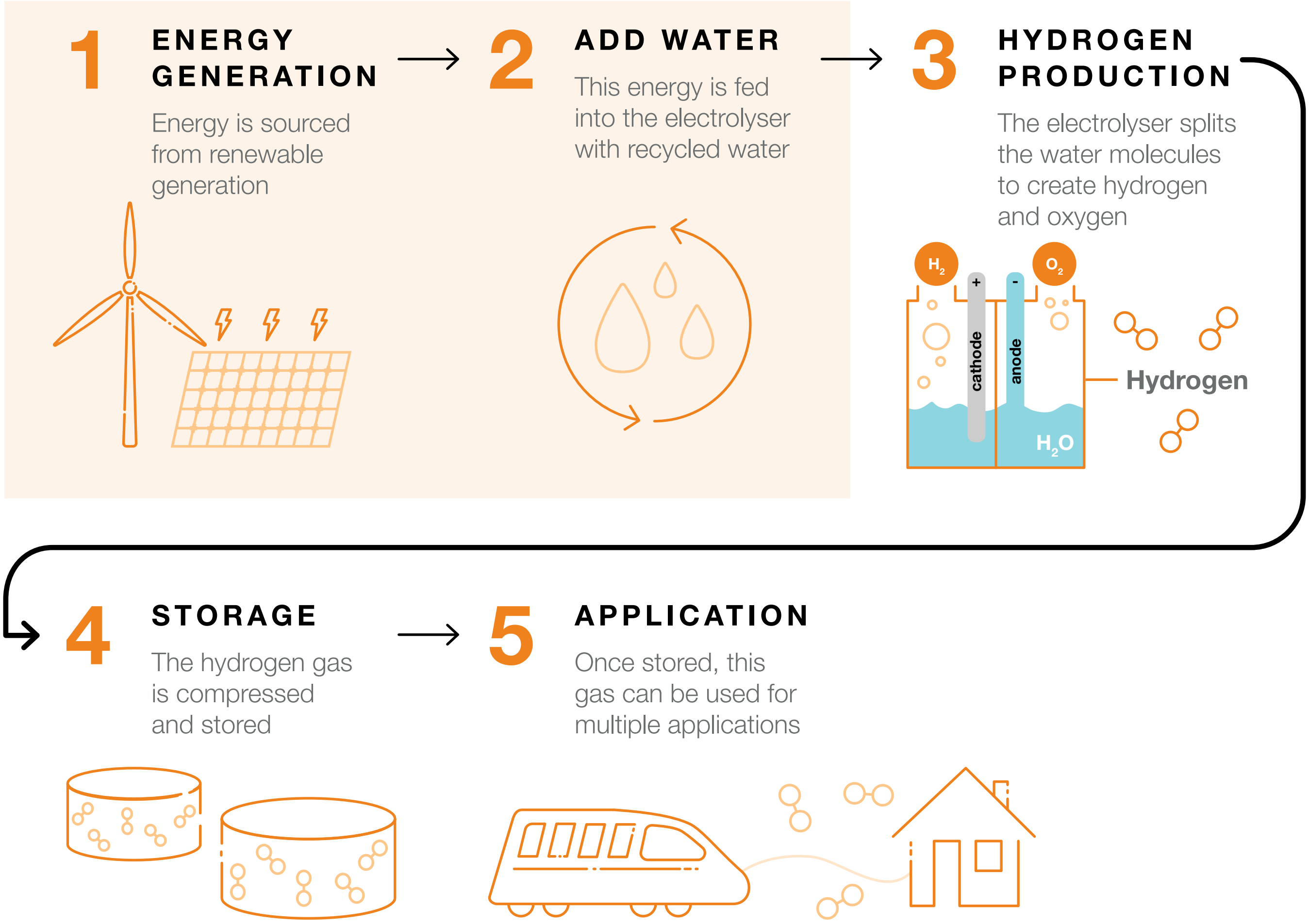
Potential Application	Positives	Negatives
Irrigation	Potentially large volumes of water used Can substitute drinking water in urban areas	Water is only required part of the year Can be used for low value uses
Dual pipe (urban development)	Possible in greenfield developments	Expensive to retrofit in existing developments
Residential/ commercial drinking	A constant supply of water is required throughout the year	No political appetite Legislative barriers
Industrial	Can substitute for drinking water	The volume required is limited
Environmental flows	Potentially replace drinking water during prolong dry periods and provide minimum flows	Legislative barriers Need to be able to store wastewater to supply water at specific times Risk of water quality impacts on waterways that may outweigh benefits
Hydrogen production	A constant supply of water is required throughout the year Minimal need for expensive storage	May require additional treatment and higher purity compared to other applications.



The Proposed Model

A sustainable hydrogen supply chain model using recycled water and renewable energy is proposed in Figure 5. The economic viability of this model relative to the Current Model is evaluated via a Cost-Benefit Analysis (CBA), the details of which are outlined later in this section. •

Figure 5: Proposed sustainable hydrogen supply chain model which uses renewable energy and recycled water



1 ENERGY GENERATION

Energy is sourced from renewable generation

2 ADD WATER

This energy is fed into the electrolyser with recycled water

3 HYDROGEN PRODUCTION

The electrolyser splits the water molecules to create hydrogen and oxygen

4 STORAGE

The hydrogen gas is compressed and stored

5 APPLICATION

Once stored, this gas can be used for multiple applications

Test application: the use of rail freight

Why rail?

Hydrogen has strong potential for use in medium to large-scale transport vehicles due to its light weight, long travel range per kilogram, fast refuelling times, and ability for fuel cells to operate continuously and at full capacity without reducing their lifespan. Despite these advantages, the implementation of hydrogen solutions for transport applications faces certain challenges. One of the main barriers to adoption stems from the lack of existing hydrogen production and refuelling infrastructure, along with the difficulty of estimating where and to what extent this infrastructure would be required.

These challenges are more easily overcome in the rail sector in general and rail freight in particular for the following reasons:

- **More space for hydrogen gas**

  Hydrogen gas is energy dense but takes up larger amounts of space than other fuels. Rail freight has more fuel storage capacity than other modes of transport.

- **Reduced infrastructure requirements**

  Australia's lack of hydrogen production, distribution and re-fuelling infrastructure is one of the major barriers to hydrogen-fuelled vehicles in this country. However, locomotives are typically serviced and refuelled at the end of their journey, eliminating the need to develop an extensive hydrogen refuelling network along the transport routes.

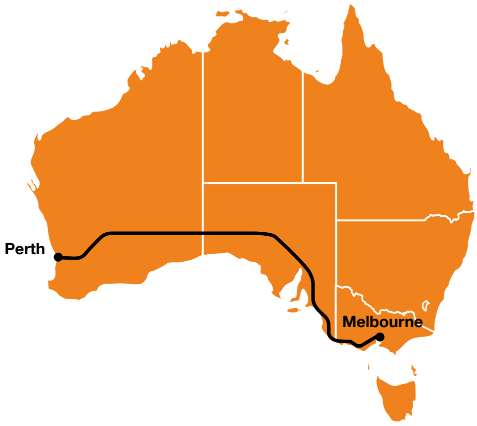
- **Predictable routes and journey distances**

  Rail freight operations are more predictable than other modes of transport and journey distances are fixed. As a result, the amount of hydrogen required to support operations and the size of hydrogen production equipment, storage tanks and dispensing equipment needed can be estimated more accurately, thereby reducing capital and operating costs by limiting potential overbuild.

For these reasons, rail freight represents a potential early adopter of hydrogen technology and is an ideal real-world scenario to compare the viability of different hydrogen supply chain models.

The existing diesel-powered East-West Rail Corridor from Melbourne to Perth was selected for our test application because:

- It is the longest freight route in Australia and would require a relatively large volume of hydrogen. This allows the hydrogen supply chain models to be tested at scale.
- The locomotives are currently powered by imported diesel fuel and options to improve energy security for large diesel importers should be considered.
- The Victorian Labor Government has recently legislated the Victorian Renewable Energy Target (VRET) and the State is projected to see a large increase in renewable energy uptake by 2025. This is particularly true of regions such as North-West Victoria which is near to the planned intermodal Western Interstate Freight Terminal (WIFT) in Ballarat.
- Both the Victorian and Western Australian Governments are currently developing hydrogen strategies and allocating funding to develop hydrogen-fuelled transport opportunities. Creating large-scale sustainable hydrogen production facilities at central transport terminals in each State could support their strategies. •



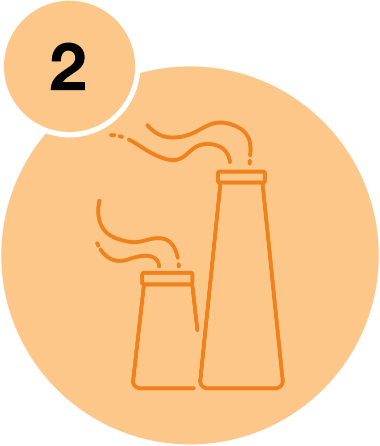
Assessing the relative economic viability and sustainability of the Proposed Model

Relative economic viability

The economic viability of the Proposed Model and the Current Model relative to a Business-as-Usual case was assessed via a Cost-Benefit Analysis (CBA) on converting the East-West Rail Corridor freight route to hydrogen fuel. The CBA identifies and expresses all the incremental costs and benefits created to calculate the Net Present Value (NPV)[15] of adopting each Model. This is a well-established methodology that is widely employed in project evaluation. The costs include initial capital investment, ongoing fuel consumption costs, replacement costs and routine maintenance costs. The included monetised benefits of the options are outlined below.

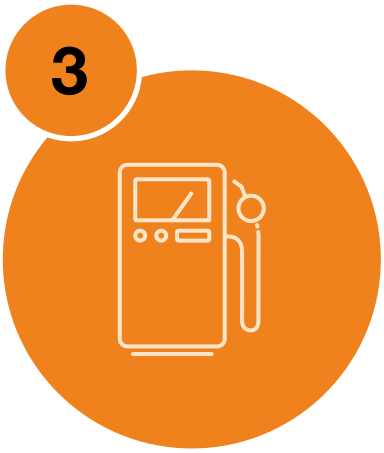
Local environmental externalities

Avoided noise, air pollution, upstream/downstream costs of switching to hydrogen powered trains.



Avoided Greenhouse Gas Emissions

Avoided cost of greenhouse gas emissions from using renewable energy to produce hydrogen. This benefit is only received if a shadow value on greenhouse gas emissions (dollars per tonne of $CO_{2\text{-}e}$) is applied.



Fuel cost savings

Reduced fuel costs brought about by using hydrogen which is more energy dense per unit than diesel.

Relative sustainability

The environmental sustainability of each Model is measured by the amount of greenhouse gas emissions created in the hydrogen production process and whether the water required would put additional strain on existing drinking water resources. •

Test scenarios

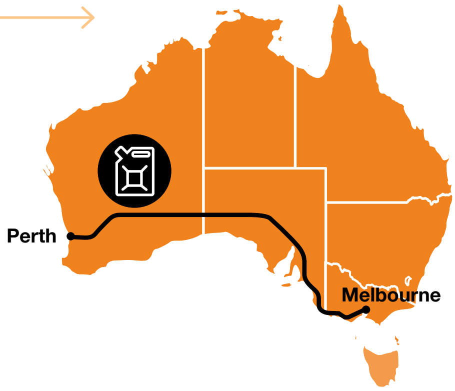
The NPV of the Current and Proposed Models is calculated by using a 'Business-as-Usual' (BAU) scenario as a baseline which assumes no transition to hydrogen fuel for the freight route. The hydrogen scenarios assume an operational start-date in Financial Year (FY) 2025[16] and all scenarios are assessed over a 40-year project lifecycle.

The details of each scenario are summarised below and outlined in greater detail in Table 2. Key modelling assumptions, including capital and operating costs, energy prices, and technology learning rates, are provided in Appendix A.

Scenario 1

BUSINESS-AS-USUAL (BAU)

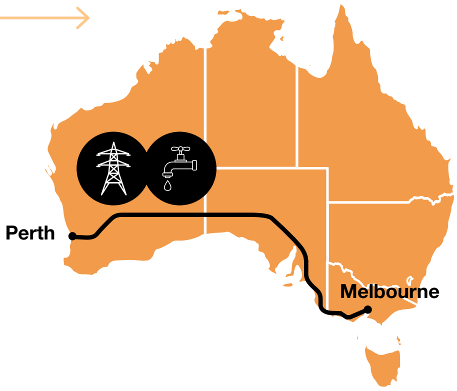
Operations continue as they are today, with locomotives powered by diesel fuel.



Scenario 2

CURRENT HYDROGEN SUPPLY CHAIN MODEL

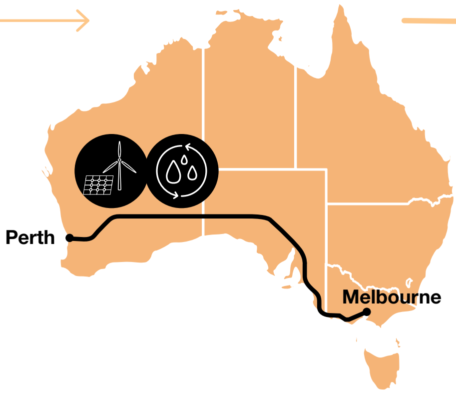
Locomotives transition to hydrogen fuel by FY2025. Hydrogen is produced using grid-purchased electricity and drinking water.



Scenario 3

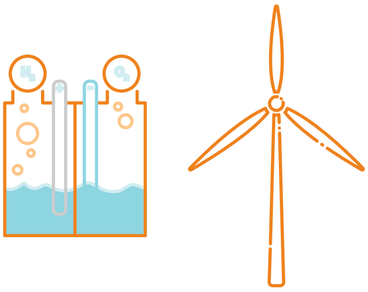
PROPOSED SUSTAINABLE HYDROGEN SUPPLY CHAIN MODEL

Locomotives transition to hydrogen fuel by FY2025. Hydrogen is produced using renewable electricity and recycled water and is therefore zero emissions.



Sensitivities for the three different sources of renewable energy - previously discussed on page 13 - are also tested within Scenario 3:

3A DEDICATED RENEWABLES

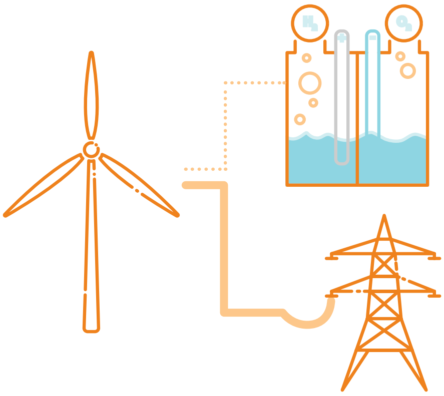


Wind and/or solar PV plants are built 'behind-the-meter' of the hydrogen production facilities. Because these plants are not connected to the electricity grid, market fees are avoided. Plants receive only enough compensation to recover their costs.

3B RENEWABLE POWER PURCHASE AGREEMENT

Emissions created by electricity purchased from the grid are offset by entering a contract to pay a fixed price for renewable electricity.

3C CURTAILED RENEWABLES



Wind and/or solar PV plants are built with the primary purpose of supplying energy to the electricity grid but are also connected to hydrogen production facilities. This allows any energy that is not able to be sent to the grid to be diverted to hydrogen production. •

Key assumptions

Project Assumptions	Technology Assumptions	Electricity Market Assumptions
First year of operations: 2025 Operations appraisal period: 40 years	Full Capital costs ($/kW): • Wind: $1,600/kW in 2040 • Solar: $1,240/kW in 2040 • Electrolyser: $750/kW in 2040	Emissions reduction policy: The Australian electricity market achieves a 26% emissions reduction on 2005 levels by 2030 via an Emissions Intensity Scheme, reaching zero emissions in 2070.

Note: *See Appendix A for further details on modelling inputs and assumptions.*

Table 2: Details of each scenario tested

Parameter	Scenario 1: Business As Usual	Scenario 2: Current Hydrogen Supply Chain Model	Scenario 3: Proposed Sustainable Hydrogen Supply Chain Model
Scenario Description	Assumes no change from current operations and fuels. Freight operators continue to use diesel powered trains and must replace locomotives as they approach their end of life.	Assumes that all diesel-fuelled rail vehicles are replaced with hydrogen rail vehicles by 2025. The hydrogen is produced using grid-purchased electricity and purified drinking water. For simplicity, diesel locomotives are de-commissioned once hydrogen fuel cell locomotives become available.	Assumes that all diesel-fuelled rail vehicles are replaced with hydrogen rail vehicles by 2025. The hydrogen is produced using renewable energy and recycled water to improve supply chain sustainability. For simplicity, diesel locomotives are de-commissioned once hydrogen fuel cell locomotives become available.
Fuel	Diesel	Hydrogen (emissions dependent on grid emissions intensity factor)	Zero-emissions Hydrogen
Energy Input	N/A	Grid electricity	Renewable Energy: 3a. Dedicated Renewables; 3b. Renewable PPA; 3c. Curtailed Renewables.
Water Input	N/A	Drinking water	Recycled water
Production Facility Location	N/A	As close to existing rail terminals as possible to minimize infrastructure costs.	Most suitable wastewater treatment plant(s). Suitability based on water quality, volume available and proximity to rail terminals.
Electricity Price Projections	N/A	Jacobs' Energy Markets Team April 2019 'Base Case'. The Base Case assumes an Emissions Intensity Scheme (EIS) is applied to the National Electricity Market (NEM) and Western Electricity Market (WEM) from 2021 to achieve Australia's Paris Agreement commitment, with a target of zero grid emissions by 2070.	

3

Results & discussion

The purpose of this paper was to propose a more sustainable hydrogen supply chain model for a large-scale hydrogen economy in Australia and to evaluate whether this model could be adopted without sacrificing economic viability when compared to the current approach. Both the Current and Proposed models were applied to convert the East-West Rail Corridor to hydrogen to ensure our cost-benefit analysis was grounded in a real-world application.

Overview of findings

Figure 6 displays the greenhouse gas emissions produced in each Scenario and Figure 7 presents findings on the economic viability of the Current Model (Scenario 2) and the Proposed Model (Scenario 3) relative to Business-As-Usual (Scenario 1).

While the Proposed Model's sensitivities – 3a. Dedicated Renewables, 3b. Renewable PPA, and 3c. Curtailed Renewables – were all zero-emissions, none of them proved more economically viable than the Current Model.

Figure 6: Total emissions produced from 2025 to 2065 in each Scenario

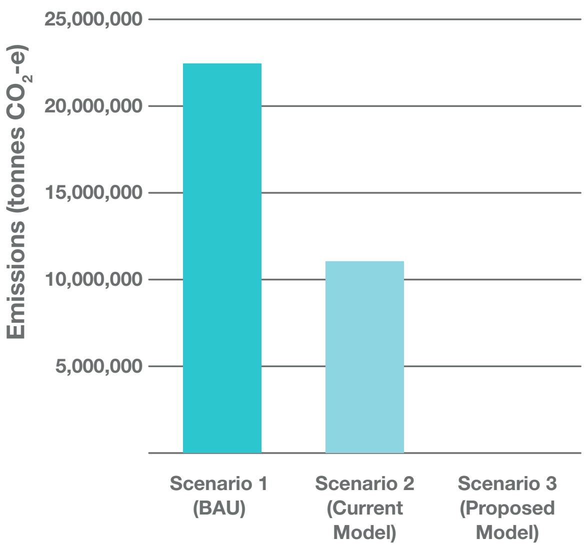
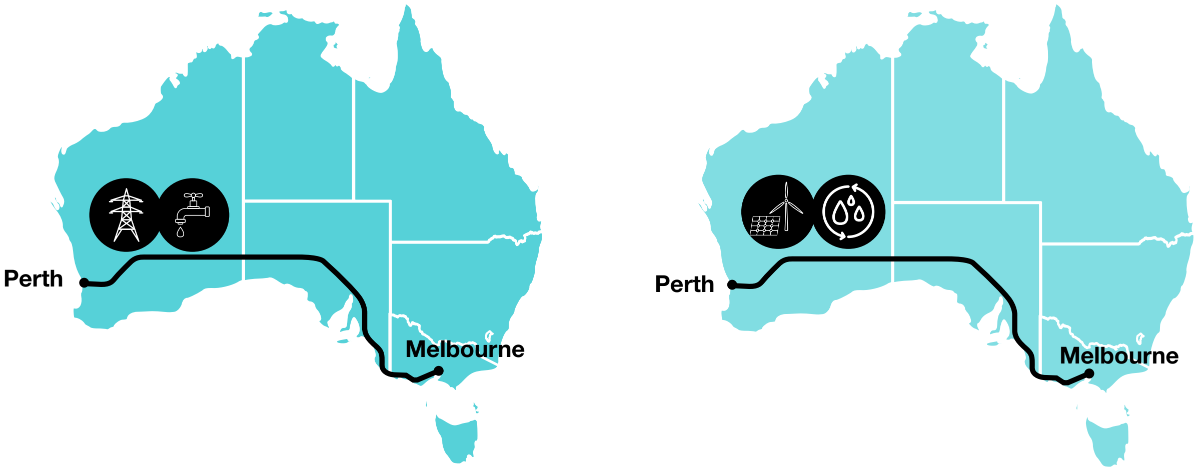


Figure 7: Economic viability of Scenarios 2 and 3 relative to Scenario 1 (BAU)



SCENARIO 2: CURRENT MODEL

Cost viability: Yes (relative to Scenario 3)

- **NPV:** -$270 million

SCENARIO 3: PROPOSED MODEL

Cost viability: No (relative to Scenario 2)

- **3a NPV:** -$2,000 million
- **3b NPV:** -$1,060 million
- **3c NPV: -**$6,250 million

Note: These figures assume no shadow value on greenhouse gas emissions is applied beyond the electricity market.

Electrolyser usage rate as a key cost driver

Although we determined that recycled water was less expensive than drinking water earlier in this paper, when the costs of hydrogen production are viewed holistically, water prices were not a substantial cost driver in the overall economics. Rather, the intermittent nature of renewable energy had a much larger influence on cost as it meant that electrolysers could not run as frequently (see Figure 8). Therefore, larger capacity electrolysers were needed in the Proposed Model scenarios to produce the same amount of hydrogen as the Current Model. The reason for the lower usage rates under the Proposed Model scenarios (40-50% for Scenario 3a and 3b, and 11% for Scenario 3C) is that hydrogen production could only occur when renewable energy was available to avoid creating emissions. Conversely, the Current Model drew on a consistent supply of grid-purchased power (which enabled a usage rate of 85-95%). This allowed the use of lower capacity electrolysers while producing the same amount of hydrogen.

The need for larger electrolysers in the Proposed Model scenarios and the resulting increase in capital and operating costs is evident when comparing the levelised cost[17] of hydrogen by Scenario (see Figure 9). The declining costs over time are primarily due to the decreasing cost of energy required for hydrogen production and increasing efficiency of the electrolyser from technological advancements. •

Figure 8: Average annual electrolyser usage rate in each Scenario

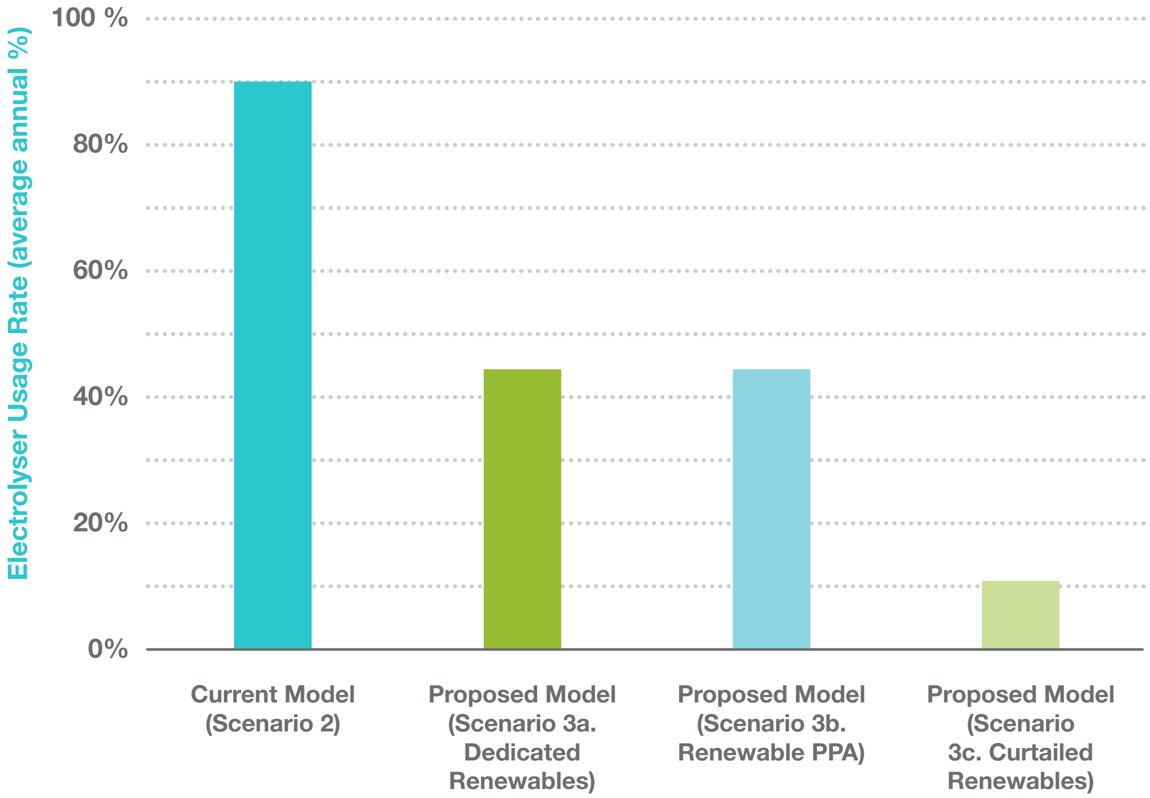
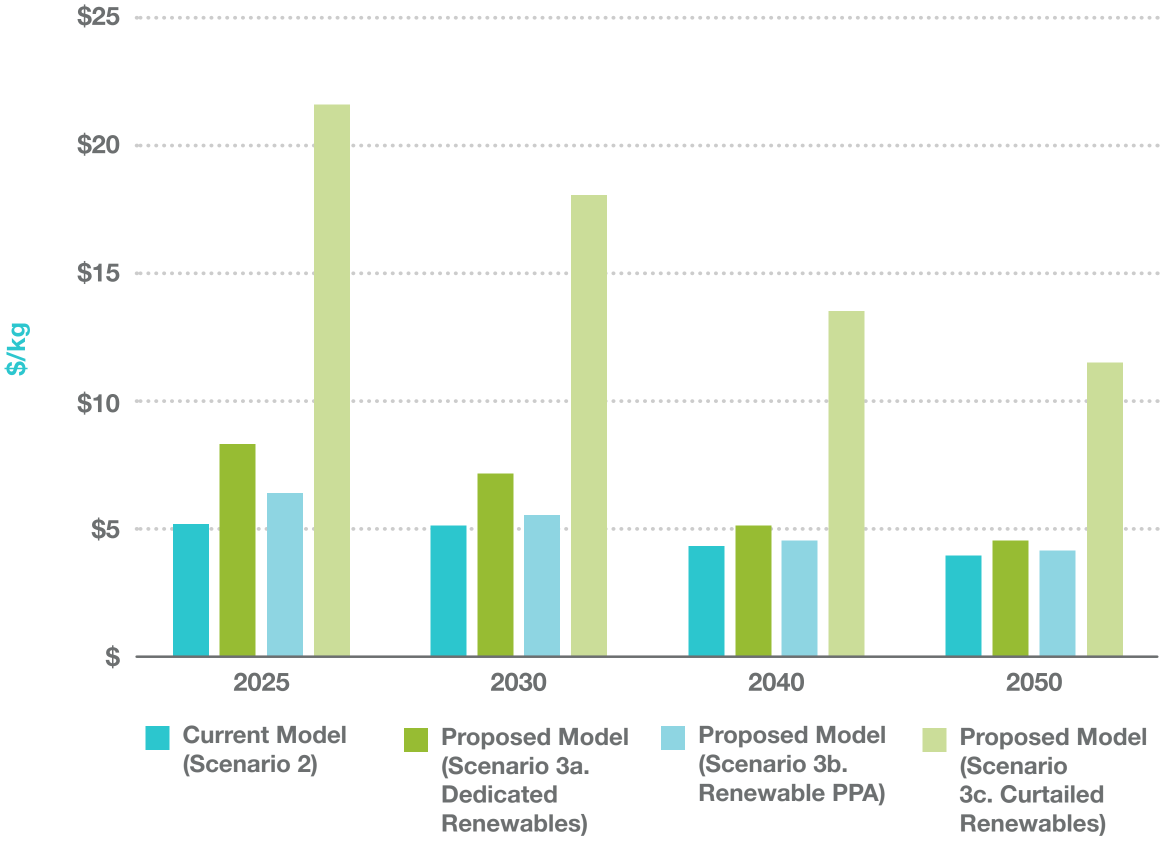


Figure 9: Levelised cost of hydrogen ($/kg) by Scenario and year



Improving economic viability

A ACHIEVING HIGHER ELECTROLYSER USAGE RATES

Given that the usage rate of the electrolyser represented the most significant cost driver of the Proposed Model, we suggest three potential solutions that might increase this rate and improve economic viability:

1. Source the electricity from a high capacity factor renewable energy source. Existing options in Australia are either hydropower or waste-to-energy plants.
2. Government could assign a hydrogen-specific emissions reduction target or continuous improvement policy.
3. Incentivise grid emissions reductions by adopting more ambitious emissions reduction targets or State and federal subsidy schemes to support renewable energy development.

Each option is explored in more detail in Table 3.

Table 3: Evaluation of solutions for increasing electrolyser usage rate and cost viability

	1 **High capacity factor renewables** Source the electricity from a high capacity factor renewable energy source. Existing options in Australia are either hydropower or waste-to-energy plants.		2 **Hydrogen Emissions Policy**	3 **Lower Emissions Grid**
	1a. Hydropower plants	**1b. Waste-to-energy**		
Description	Hydropower plants release water stored in a dam to spin turbines and thereby generate electricity.	The process of generating energy in the form of electricity and/or heat from the primary treatment of waste.	Government could assign a hydrogen-specific emissions reduction target or continuous improvement policy.	Grid emissions reductions could be incentivised by adopting more ambitious emissions reduction targets or State and federal subsidy schemes to support renewable energy development.
Rationale	Hydropower plants alone would not provide high enough usage rates but could be combined with wind and/or solar to allow the electrolyser to run more frequently.	As many of Australia's landfills close to large metropolitan centres begin to reach capacity, interest in waste-to-energy plants has grown. Waste-to-energy plants typically generate at high capacity as long as there is a consistent supply of waste materials.	Policies could mandate that hydrogen production becomes increasingly less emission intensive, presumably at a faster rate than the grid itself.	If the emissions intensity of the grid declines faster than projected, hydrogen production could run more often without creating emissions.
Benefits	The energy is available at times when wind or solar isn't and is zero emissions.	Reduces the residual waste going to landfill and contributes to a more circular economy[18].	Lower capacity electrolysers that run more frequently could be installed earlier, while sourcing an increasing proportion of renewable energy from PPAs over time.	Electrolysers would be able to run in an optimised way at the highest utilisation rates. A less emissions intensive grid would also reduce emissions across all electricity-using sectors.
Downsides	New projects may be required as the capacity of existing hydropower plants becomes stretched. Developing new hydropower plants can result in local environmental impacts. The output of hydropower is dependent on rainfall levels.	The supply chain of waste material is still evolving and only about 50% of electricity generation can currently be classified as renewable. This is because waste streams usually have some non-renewable content. The waste-to-energy industry in Australia is emerging and will take time to mature, which may also create logistical difficulties in the ease of sourcing and transporting the waste. Further, waste-to-energy projects typically have longer development times due to the need to engage local communities and mitigate the environmental impacts of projects during construction and operation.	Policy and/or regulatory arrangements need to be developed and are reliant on State and/or federal government decisions. Due to their progressive nature, these target-based schemes would create low emissions hydrogen rather than zero-emissions hydrogen in their early years. This may be acceptable if it enables net emissions-savings in the end-use application for the hydrogen.	Transmission infrastructure upgrades and increased energy storage investment are likely to be required to support higher volumes of renewable energy uptake. The lack of these measures could result in much higher energy losses, increasing energy costs and potentially delaying renewable energy investment. This trend is becoming apparent in the current electricity market, with many projects facing delays or increased transmission losses.

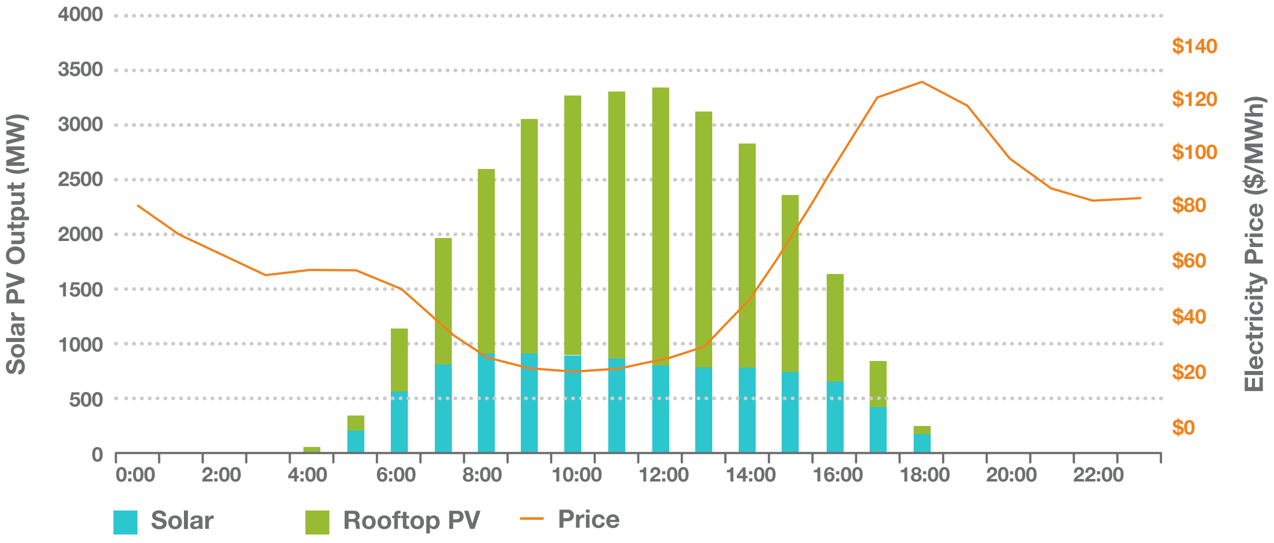
All three of the solutions in Table 3 could, hypothetically, be implemented to improve the economic viability of the Proposed Model, each with their own advantages.

- Least emissions intensive: Solution 1 (sourcing high capacity factor renewable energy) would allow hydrogen to be completely zero-emissions, while the other options would still create some emissions in the short to medium-term. It is also less influenced by the political landscape than the other two solutions.
- Most cost efficient: Although Solution 1 (sourcing high capacity factor renewable energy) is the least emissions intensive, Solution 2 (Hydrogen Emissions Policy) and Solution 3 (Lower Emissions Grid) may be more efficient overall as they would allow the most economic renewable energy projects to be built, thus reducing overall electricity costs.

Creating some emissions from hydrogen production may be acceptable if net emissions from the end-use application are reduced. This is likely to be the case in many transport-related applications if the emissions intensity of the electricity grid declines at a rapid enough rate. The projected decline in grid emissions intensity in the modelling assumed a national emissions reduction policy is implemented. No such policy is currently in place and emissions from hydrogen could therefore remain substantially higher than projected if the emissions intensity of the electricity grid declines slower than projected.

Hydrogen production may itself support increased solar PV investment and thereby reduce grid emissions by scheduling production to occur at the times solar is operating. One of the concerns around the projected increase in large-scale and residential solar PV is the imbalance between energy production and demand across a 24-hour period, which would greatly reduce their revenue and potentially limit their uptake (shown in Figure 10). While investment in battery storage and pumped hydro energy storage (PHES) can help store some of this energy until periods of high demand (such as the evening peak period), hydrogen facilities producing in the afternoon could also improve the economics of solar and enable greater uptake. While electrolysers would still need to be run at a high utilisation rate overall, it is likely that as afternoon prices decrease solar will be increasingly incorporated into hydrogen production arrangements. •

Figure 10: The 'Duck-Curve' - impact of projected solar generation on Victorian electricity prices (Summer 2030). The dip in mid-day prices reflects the imbalance between energy supply and demand.



Source: Analysis from Jacobs' Energy Markets Insights Group 2019

B METHODS FOR SOURCING RENEWABLE ENERGY

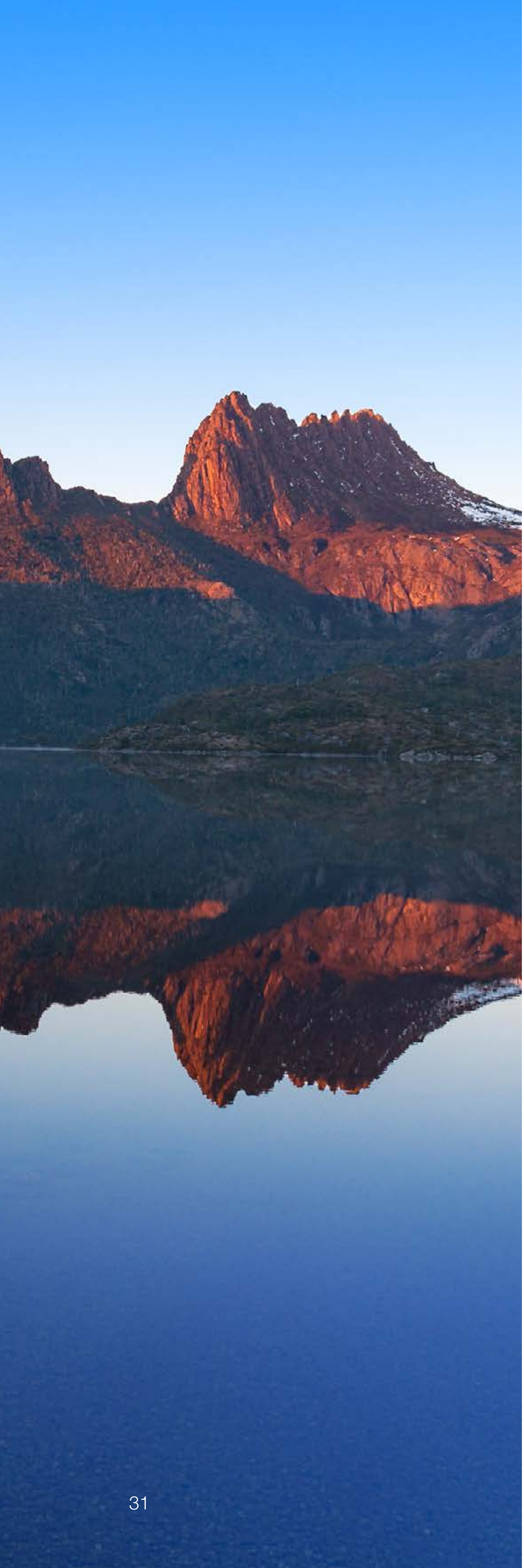
In the context of the three potential solutions outlined in Table 3, it is also important to consider the most cost-effective means of sourcing the renewable energy. Sensitivities for three potential sourcing methods were tested: 3a. Dedicated Renewables, 3b. Renewable PPA and 3c. Curtailed Renewables.

According to the outputs of our model, smaller-scale demonstration and pilot projects could benefit from using behind-the-meter renewable energy generation (3a. Dedicated Renewables) by avoiding market fees and reducing losses. However, the purpose of this paper was to investigate possibilities for a large-scale hydrogen economy. Given it would provide the most flexibility in implementing the solutions in Table 3 on a larger scale, the PPA sensitivity (3b. Renewable PPA) is best suited to this context. If demand for hydrogen grew more than expected, the amount of renewable energy purchased could be increased more easily than attempting to build additional generation capacity to meet this demand. Similarly, an increasing proportion of electricity could be purchased outside of the PPA as the emissions intensity of the grid declines.

While using curtailed energy (3c. Curtailed Renewables) to produce hydrogen may seem an attractive concept, our findings indicate that it would have limited viability in practice where specific and consistent daily, monthly or annual volumes of hydrogen are required. Curtailment created by network constraints represents a flaw in the current energy market, not a characteristic inherent to it, and is likely to be resolved in the medium term. Conversely, the type of curtailment created by excess generation at given times of day is more likely to be an ongoing trait of a future energy market that is composed largely of renewable energy sources. Curtailed energy is therefore likely to help reduce the costs and emissions of hydrogen production but is too seasonally dependent and unpredictable to serve as a primary energy source. •

C SOURCING DIFFERENT TYPES OF RENEWABLE ENERGY

In general, sourcing a diverse mix of different types of renewable energy generation may help to increase usage rates of electrolysers by reducing the risk of lower than expected generation for any particular source. For example, although using wind resulted in the lowest hydrogen costs across all Scenario 3 sensitivities due to its superior generation output compared to solar PV, this assumed that wind farms generate energy 40-45% of the year. In reality, actual wind speeds and the resulting generation output can vary substantially from these averages. A mix of wind and solar would provide less risk as the two resources typically generate energy at different times and are not correlated. As noted above, adding high-capacity factor renewables (e.g. waste-to-energy) or other non-correlated generation (e.g. hydropower) to this mix would further reduce this risk and improve electrolyser usage rates. •



The use of recycled water has benefits beyond sustainability

Cost viability

Despite finding that the price of water did not substantially impact hydrogen costs, using recycled water instead of drinking water was still less expensive. Changing the source of water in Current Model from drinking water to recycled water without altering any other variables resulted in cost-savings of about AUD$29 million over the period evaluated. The economic outcomes would be further enhanced if the monetised benefits of reducing environmental discharges from wastewater treatment plants were included in the modelling.

Finally, industrial allocations for drinking water have previously been rescinded during times of drought, sometimes for years. From a continuity of supply perspective, using recycled water would eliminate any exposure to climate-related supply shortage risks.

These insights suggest there is no economic reason that would prevent the use of this unutilised resource and the potential commercial opportunities of using recycled water for hydrogen production should be considered.

Commercial opportunities

As population growth continues, so too does the volume of recycled water that is produced. This, together with the growing stringency of wastewater treatment requirements for environmental protection means that water utilities are increasingly searching for demands for this water. It is a relatively common misunderstanding that recycled water networks are built to provide an additional revenue stream for water utilities. Rather, they are often built for pollution control, that is, to avoid discharging treated wastewater to waterways and oceans. The most common commercial use for recycled water at present is irrigation and supply already outstrips demand, particularly in winter.

Using recycled water for hydrogen production presents several potential commercial opportunities for water businesses.

- **Sale of hydrogen as an off-regulated revenue stream.**

  Water utilities are regulated businesses and must take measures to ensure costs to consumers are reduced. Selling hydrogen produced from recycled water represents an off-regulated revenue stream that would not impact their current consumers. Given wastewater treatment plants tend to be located in close proximity to towns and cities, distribution costs could be minimised, potentially attracting a large number of different buyers for the hydrogen.

- **Avoided upgrade costs.**

  Diverting recycled water for hydrogen production may provide economic benefits via the avoided costs of upgrading wastewater treatment plants to comply with environmental discharge requirements in the future.

- **Pure oxygen as a by-product.**

  The pure oxygen created as a by-product of hydrogen production could be used to enhance the efficiency of the aerobic treatment systems within wastewater treatment facilities, a process which currently uses air (only about 20% oxygen). This increased efficiency would reduce capital and operating costs of tanks and pumps, while decreasing the energy required to operate the treatment systems. Any additional unused oxygen could be sold for use in ozone generation for advanced water treatment, industrial furnaces to improve combustion performance, or medical facilities for anesthesia, intensive care units and oxygen therapy.

- **Waste by-product from treatment as an energy source.**

  As noted previously, improving the usage rate of the electrolyser is critical to reducing the cost of hydrogen production. Bio-solids produced from the wastewater treatment process could be used to supply a waste-to-energy plant that would reduce the need to buy energy from the grid while still maintaining a high usage rate for the electrolyser. A number of water utilities are exploring or have already developed waste to energy plants, such as Yarra Valley Water in Victoria which built a commercial food waste to energy plant in May of 2017[19]. •

Benefits of hydrogen in transport applications and insights into economic viability of rail freight use

Although not a focus of this paper, our results provide insight into the present value of converting the East-West Rail Corridor to hydrogen in 2025.

Adopting hydrogen in transport applications serves several potential benefits, key among them being the decarbonisation of an emissions-intensive sector that produces 14% of total Australian emissions. In our rail freight case, converting diesel locomotives to hydrogen reduced emissions by an average of 232,000 tonnes per annum and 546,000 tonnes per annum under the Current and Proposed Models respectively, which is roughly equivalent to taking about 49,000 and 116,000 passenger cars off the road each year.

Further, the hydrogen supply chain offers greater certainty (and therefore greater efficiency) when compared to imported fossil fuel supply chains.

First, it avoids a number of key risks associated with the latter, including; fluctuations in global oil prices, exchange rates and international shipping rates, and political instability.

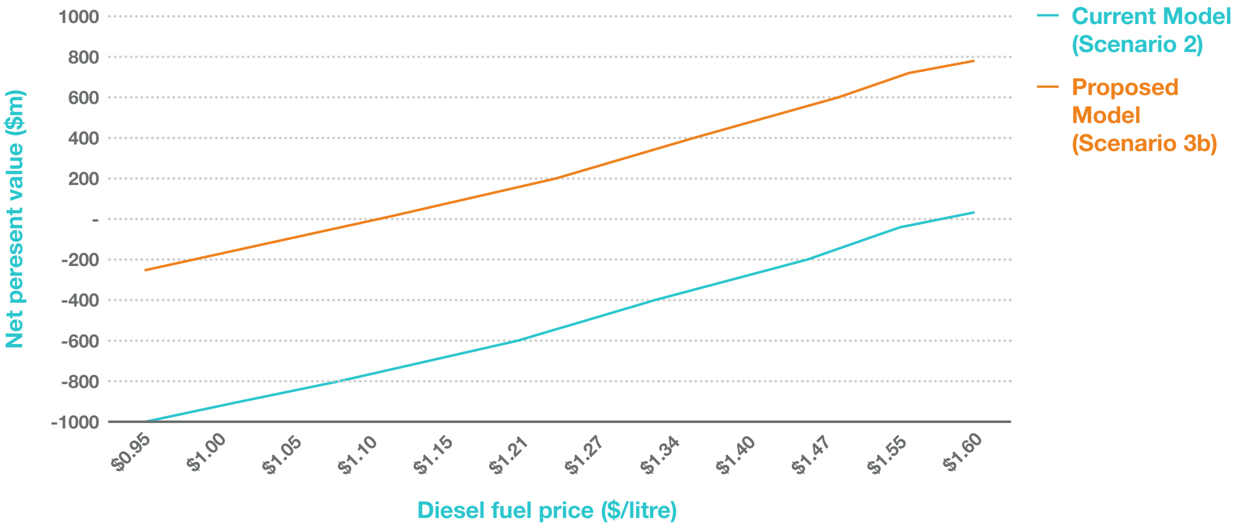
Second, in our Proposed Model, the efficiency of the hydrogen supply chain was improved by minimising distribution costs via siting production plants at wastewater facilities located as close as possible (within 5km) to existing or planned rail terminals.

Overall, hydrogen could reduce rail freight emissions under both the Current and Proposed Models. While neither model would be economically viable at present, our findings indicate that altering several key variables could influence this result in the future.

COST OF DIESEL FUEL

The current price of diesel represented a major determinant of the economic viability of transitioning to hydrogen fuel. Figure 11 displays the results of sensitivity analysis conducted on the assumed price of diesel fuel. Assuming no change to other modelling parameters, an 18% increase in diesel prices from AUD$0.95/litre to AUD$1.10/litre was required for the Current Model to ‘break-even’ with the BAU scenario. A 41% increase to AUD$1.62/litre was required under Scenario 3b in the Proposed Model.

Figure 11: Diesel fuel price ($/litre) versus NPV relative to BAU scenario ($m)



PRICE ON EMISSIONS

Applying a price penalty on emissions[20] (a 40-year average of AUD$24 per tonne CO2-e) improved the economic viability of all hydrogen scenarios, resulting in AUD$41 million and AUD$109 million in savings for the Current Model and all Proposed Model sensitivities respectively. However, these savings were still not enough to break even with the BAU case. Figure 12 displays the results of sensitivity analysis conducted on the dollar value per tonne of carbon equivalent emissions. The Current Model and Scenario 3b of the Proposed Model required an increase of about 450% and 820% to the emissions price series respectively to break even with the BAU case. This represented a 40-year average of AUD$146 per tonne $CO_{2\text{-}e}$ and AUD$221 per tonne $CO_{2\text{-}e}$ respectively. Increasing the emissions price is therefore unlikely to be a cost-effective measure to incentivise change in the transport sector, given the substantial increase required relative to other sectors such as energy.

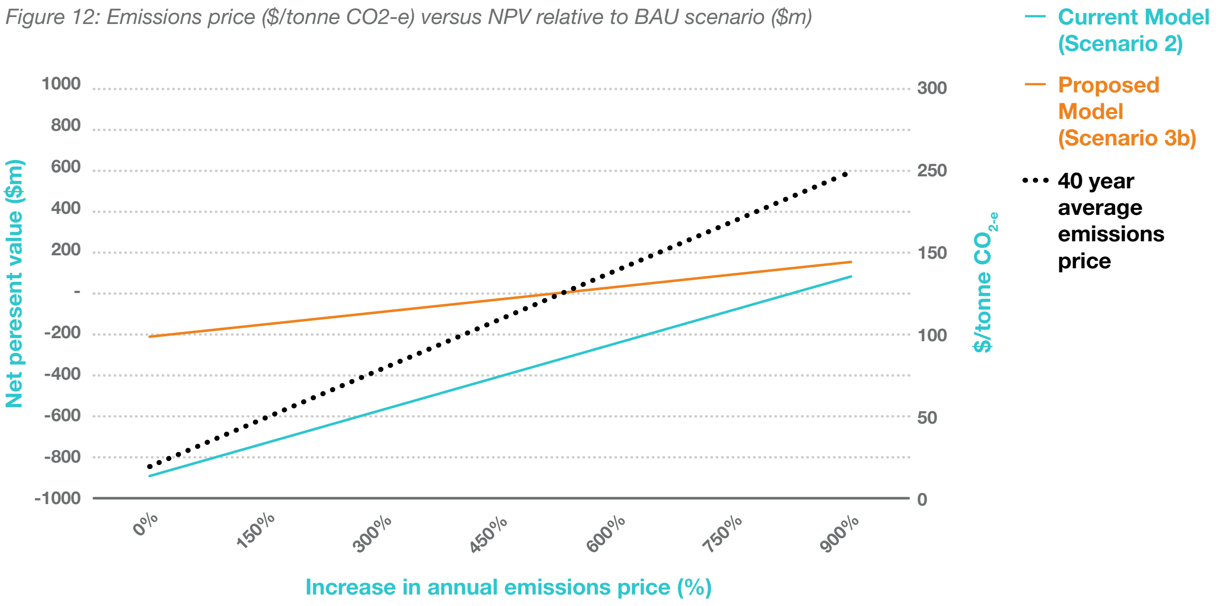
REDUCTION IN COST OF HYDROGEN VEHICLES

Ongoing research and development efforts and increasing economies of scale will help to reduce hydrogen-fuelled vehicle costs. Sensitivity analysis conducted on the estimated cost of hydrogen locomotives for the Current Model indicated that decreasing the cost per locomotive by 30% (from approximately AUD$9 million to approximately AUD$6.5 million) would result in a positive NPV. International initiatives such as the Hydrogen Council and national organisations such as Hydrogen Mobility Australia can help coordinate efforts and share learnings amongst vehicle manufacturers, while research bodies such as the CSIRO can contribute to technological advancements.

PROGRESSIVE VERSUS TOTAL REPLACEMENT COSTS

Our calculations assumed a total transition to hydrogen rail vehicles by 2025. In reality, ageing diesel locomotives are more likely to be progressively replaced or retro-fitted where possible, potentially lowering upfront capital costs. •

Figure 12: Emissions price ($/tonne CO2-e) versus NPV relative to BAU scenario ($m)



Results summary

This paper evaluated the economic viability of a proposed sustainable hydrogen supply chain model which uses zero-emissions energy and recycled water (the Proposed Model) against that of the current supply chain model which uses grid-purchased electricity and drinking water (the Current Model).

In terms of economic viability:

- Our results indicated that the Current Model was more economically viable than the Proposed Model, with the electrolyser usage rate representing the key cost driver.
- PPAs are the most viable means of producing zero-emissions hydrogen at large volumes. Reliance on dedicated behind-the-meter or curtailed renewable energy are unlikely to be viable as sole sources of energy for hydrogen production at the scale required to create a functioning large scale hydrogen economy.
- While the source of water did not have a large impact on NPV, using recycled water for hydrogen production could be beneficial due to its availability throughout the year, thus eliminating drinking water supply shortage risks and creating additional commercial opportunities for water businesses.

In terms of environmental sustainability:

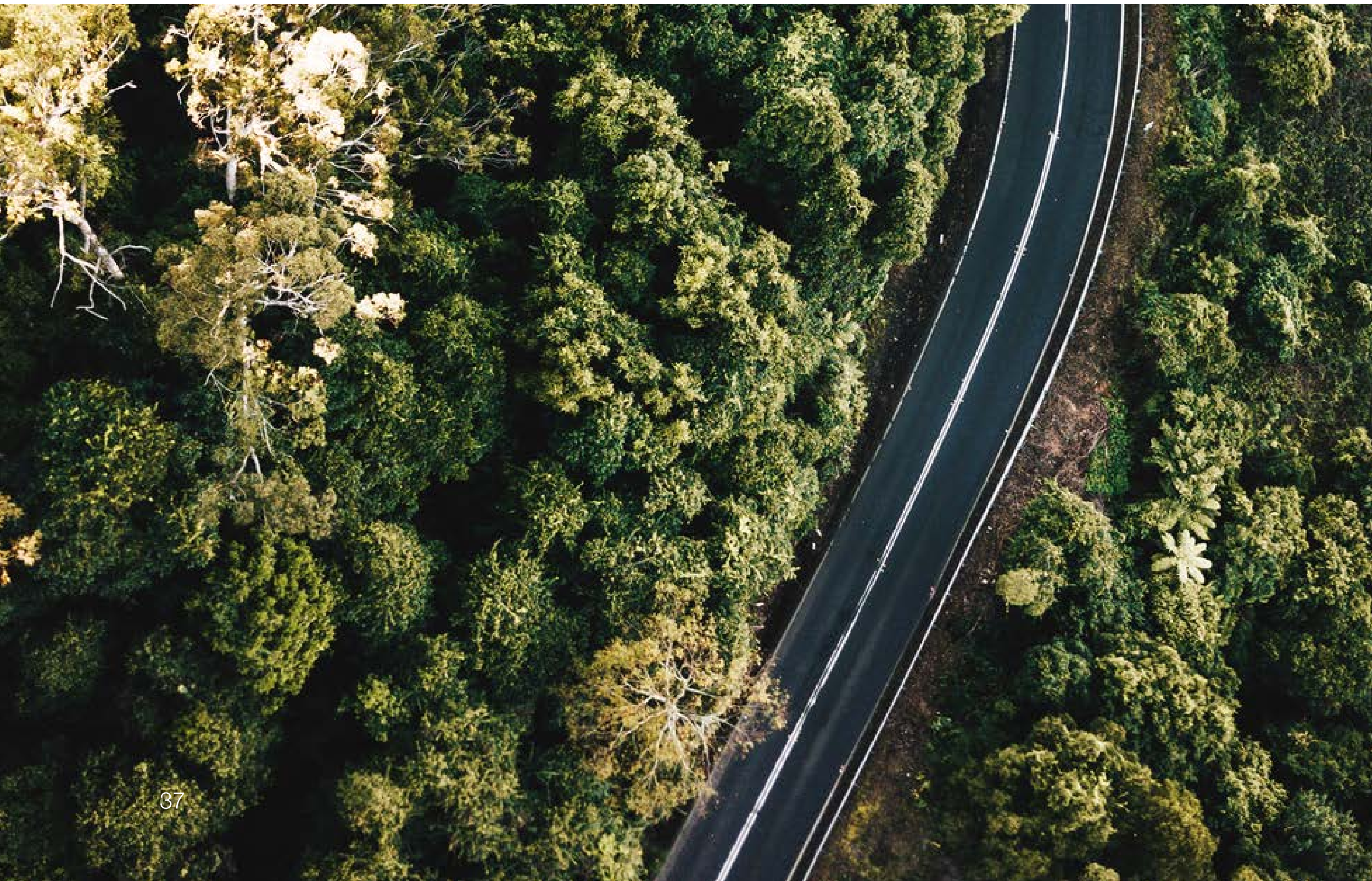
- Although the Current Model was not zero-emissions, replacing diesel rail vehicles with hydrogen rail vehicles still resulted in net emissions savings by an average of about 232,000 tonnes per annum. However, it is important to note that while the modelling assumed a national emissions reduction policy with targets that would ensure Australia meets its Paris Commitment targets in 2030 and reaches zero emissions by 2070, no such policy is currently in place. Achieving these targets is equivalent to a decline in the emissions intensity of the electricity grid at an average rate of 5% per annum from 2025 to 2065. Emissions created from the Current Model could be substantially higher if this decline is slower than projected.
- Even if no policy is implemented, hydrogen production could effectively reduce its emissions over time by procuring an increasing proportion of energy via PPAs and during periods where there is an oversupply of renewable energy.
- The use of recycled water in the supply chain model would have no adverse impact on Australia's drinking water supply.

In terms of rail freight:

- Sensitivity tests indicated that the price of diesel and cost of hydrogen rail vehicles were major influencing factors on economic viability.
- Though the analysis is high-level and could vary substantially based on project and site-specific factors, an increase in diesel prices of approximately 18% or a reduction in the cost of hydrogen rail vehicles of approximately 30% resulted in a positive NPV.
- Adopting the Current Model to convert the East-West Rail Corridor to hydrogen would result in emissions savings equivalent to taking 49,000 passenger cars off the road every year. •

4

Recommendations & next steps



Energy recommendations

The current discourse on hydrogen in Australia focuses on its zero-emissions benefits. However, our results indicate that if hydrogen production is scaled up to meet its large range of potential applications, sourcing the electricity required from only zero-emissions energy sources would negatively impact its economic viability.

The following actions should be considered:

1

TAKE A 'STAGED' APPROACH TO ZERO-EMISSIONS HYDROGEN

While producing hydrogen from Australian grid-purchased electricity would create emissions in the short to medium-term, this may be acceptable if the hydrogen produced is able to create more significant emissions reductions in its end-use application. Taking a progressive or 'staged' approach to making hydrogen zero-emissions could therefore still create net benefits from an emissions reduction perspective and enable earlier adoption of hydrogen by making the production process more economically viable. As outlined in Chapter 3, such approaches could take the form of a hydrogen-specific emissions reduction target or enacting policy measures to reduce grid emissions faster than currently projected.

2

EXPLORE FLEXIBLE ENERGY SOURCING OPTIONS TO AVOID LOCK-IN

Most zero-emissions hydrogen projects to date have been small-scale pilots or demonstrations that made effective use of behind-the-meter wind or solar generation. Our findings indicated that this approach is cost prohibitive for large-scale production facilities, locking-in their source of energy at a high cost. There are a number of other downsides to this approach. First, not all locations that are suitable for hydrogen production are likely to have strong renewable energy resources. Second, even where resources are available, it may not be possible to develop renewable energy plants large enough to meet hydrogen demand due to the trade-off between proximity to urban centres and planning restrictions/land availability.

Finally, building dedicated renewable energy plants increases capital and operating costs and may make scaling production difficult and time-intensive given the lead times for building additional generation. Instead, more flexible interim solutions should be considered, such as grid-purchased electricity with emissions offset by renewable PPAs. •

Water recommendations

The role of water in hydrogen production must be recognised and become a component of current and future conversations about the development of a large-scale hydrogen economy. As such, the following actions should be considered:

1

WATER BUSINESSES SHOULD EVALUATE THE POTENTIAL BENEFITS OF HYDROGEN PRODUCTION

Water businesses should evaluate the feasibility of producing hydrogen and consider the potential revenue stream, cost-savings and efficiency gains this would entail for their organisation. It is envisaged that water utilities would find this an attractive prospect, given the current challenge of finding a demand for recycled water that does not result in increased costs for customers.

2

DEVELOP HYDROGEN PRODUCTION FACILITIES THAT USE RECYCLED WATER

Using recycled water to produce hydrogen would eliminate the need to use drinking water resources. The prevalence of wastewater facilities across Australia and their proximity to urban centres would offer flexible siting options. Ideally, hydrogen production facilities should be located in areas with the largest number of potential end-users to reduce distribution costs to these users and create economies of scale. Increasing demand for recycled water would also reduce the water quality impacts of discharging recycled water to waterways and oceans, delivering an additional environmental benefit.

3

ADD SUSTAINABLE HYDROGEN AS AN OPTION IN ENERGY STRATEGIES

Cities and towns with medium to large wastewater facilities should incorporate hydrogen production as a potential option into their economic growth and energy strategies. Business cases will be further supported if these locations are adjacent to existing or planned transport hubs and other large potential end-users such as industrial business parks.

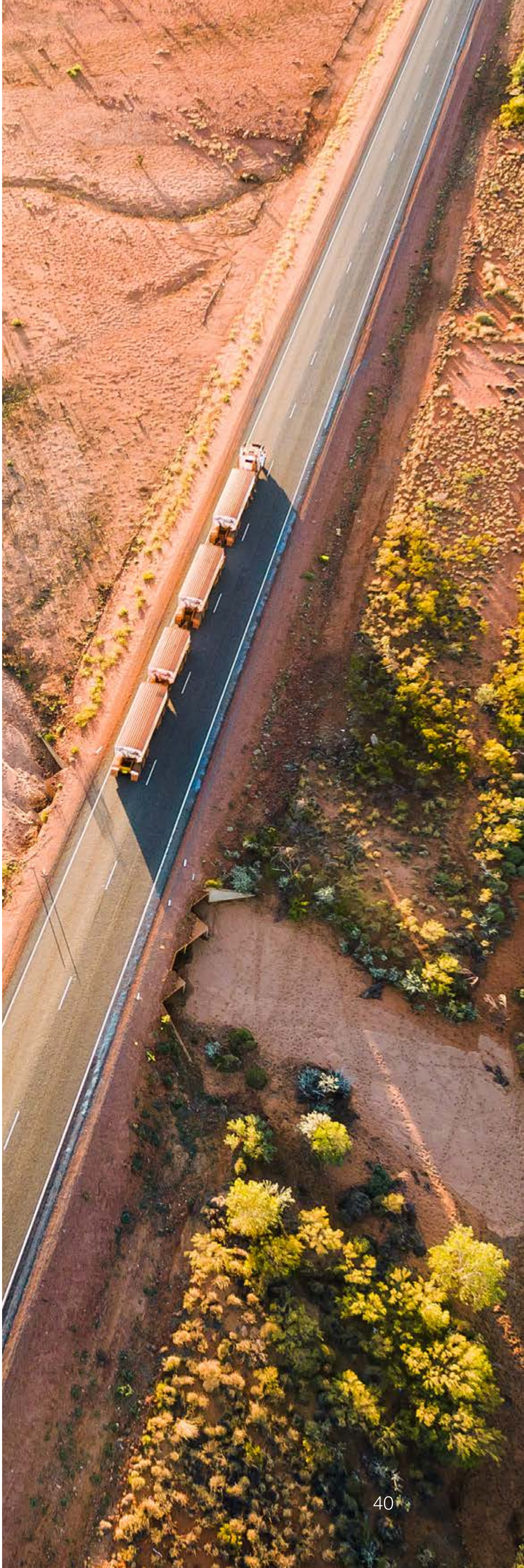
4

GOVERNMENT SHOULD ENCOURAGE MORE SUSTAINABLE PRODUCTION METHODS

Government has a role to play in establishing measures that encourage the adoption of hydrogen in a way that supports responsible consumption of scarce resources and in allocating funds to projects that advance this objective. •

Developing a large-scale sustainable hydrogen project

Australian hydrogen projects to date have comprised small-scale pilot studies. To attract hydrogen equipment suppliers and benefit from economies of scale on the supply-side, larger projects would need to be developed. If Australia intends to become a global leader in hydrogen production, early planning that addresses the sustainability implications highlighted in this paper is critical as project lifetimes can span multiple decades. A large-scale hydrogen project using recycled water could serve as a test case for a more sustainable model that reduces potential resource scarcity and climate risks, while providing additional economic benefits. •



5

Conclusion

Hydrogen could play a key role in decarbonising Australian industries if production is scaled up to meet the opportunities outlined in recent publications. However, we must ensure that broader sustainability challenges are not exacerbated by our pursuit of a large-scale hydrogen economy.

Our findings indicated that while hydrogen produced from grid-electricity may be acceptable if it creates lower net emissions for the end-use application, reliance on drinking water could prove problematic as the nation's hydrogen economy grows. While the volume of water required may seem small in comparison to highly water-intensive industries such as agriculture, Australian drinking water resources are already becoming strained. A large-scale hydrogen economy would create an entirely new water-reliant industry that scales with population growth and would be exposed to supply shortage risks as the frequency and severity of droughts increase. The use of drinking water for hydrogen production therefore presents supply concerns and is unlikely to gain social license in Australia. Instead, recycled water from wastewater facilities could represent a sustainable, low-cost and reliable alternative supply of water. The significance of this finding should be emphasised; it is unusual to find sustainable solutions with no major economic downside that would prevent their use.

This paper highlights the need for a cross-sector approach to effectively leverage any future benefits of a large-scale hydrogen economy. Decisions related to hydrogen will require government and industry to engage collaboratively with professionals and academics across multiple disciplines. Promoting a greater diversity of perspectives in strategic forums such as the Council of Australian Governments (COAG) Energy Council's Hydrogen Working Group will support this aim and encourage the development of innovative solutions that drive sustainable growth in the Australian market. As with any emerging technology nearing commercial deployment, it is vital that a holistic view is applied in early phases of development to identify risks and maximise potential. Overall, taking a wider view that considers the broader implications of rapidly changing technological, environmental and social trends supports the development of integrated solutions that create a more connected, sustainable world. •

Appendix A.

Parameters	Description
Project Assumptions	
Discount rate	7%
Dollar value	AUD real 2019 (Dec 2018)
First year of investment	2023
Operations appraisal period	40 years
Appraisal end year	2065
Freight demand growth	3% p.a.
Replacement rate of diesel locomotives under BAU scenario	2% p.a. plus any new locomotives required to meet ongoing demand
Technology Assumptions	
Capital costs ($/kW) & learning rates (%) by technology	Onshore Wind: $2,090/kW in 2020 declining to $1,600/kW in 2040 and $1,420/kW in 2060. Average learning rate of 1% p.a.
	Solar PV: $1,600/kW in 2020 declining to $1,240/kW in 2040 and $970/kW in 2060. Average learning rate of 1% p.a.
	Electrolyser (PEM): $1,400/kW in 2020 declining to $750/kW in 2040 and $600/kW in 2060. Average learning rate of 2% p.a.
Operating Costs by technology	Onshore Wind: Fixed O&M of $37/kW/year, Variable O&M of $3/MWh
	Solar PV: $18/kW/year
	Electrolyser: 5% of capex
Capital cost per Hydrogen Rail Vehicle cost ($m)	$9.2
Energy required for hydrogen (kWh/kg)	55 kWh/kg in 2025, declining to 45 kWh/kg by 2041.

Cost of energy ($/MWh)	Scenario 2 – Average of $74/MWh over 40 years	Tracks the time-weighted price and includes AEMO market fees for the National Electricity Market (NEM) and Western Electricity Market (WEM), and Network Use of System (NUOS) costs for High Voltage consumers.
	Scenario 3a – Average of $42/MWh over 40 years	Based on the levelised cost of energy of the renewable energy plant providing the energy.
	Scenario 3b – Average of $65/MWh over 40 years	Based on a fixed 15-year Power Purchase Agreement (PPA) set by the dispatch-weighted price required for the renewable energy generator to achieve profitability. Electricity market and NUOS fees are included. The PPA is re-contracted every 15 years.
	Scenario 3c – Average of $3/MWh over 40 years	Based on co-location with a renewable energy plant, producing hydrogen only when the plant is curtailed. Prices are therefore 95% lower than the dispatch-weighted price.
Water required for hydrogen (litres/kg)	11 litres	
Cost of water ($/kL)	Drinking water: $2.75/kL	Includes dual membrane treatment (UF & RO) and ion exchange treatment to get the very low salinity need by the hydrogen electrolysers.
	Recycled water: $0.70/kL	
Electricity Market Assumptions		
Emissions reduction policy	Australia meets its Paris Commitment of 26 per cent emission reduction policy by 2030 on 2005 levels achieved through an Emission Intensity Scheme. Emission target decreases linearly from 2030 to zero in 2070. The scheme places a dollar value on greenhouse gas emissions and rewards or penalises generators based on their emissions intensity relative to a declining threshold. This is only applied to the energy sector.	
Demand Growth	Australian Electricity Market Operator's (AEMO's) '2018 Electricity Statement of Opportunities' neutral demand scenario	
National and state-based renewable energy policies	Large-Scale Renewable Energy Target (LRET) continues operation in current form. 1st stage of Victorian Renewable Energy Target (VRET) included 1st stage of Queensland Renewable Energy Target (QRET) included 2nd stage of VRET, 40% renewables by 2025 included 2nd stage of QRET not included	
Treatment of coal fired power stations	All power stations retire when they can no longer recover their non-avoidable costs. Liddell retires in 2022. Yallourn to retire progressively from 2031 as its fuel supply is exhausted .	
Renewable generation inclusion	All committed renewable generation in the NEM and WEM (based on documented evidence that projects have reached financial close).	
Interconnectors	Group 1 and Group 2 upgrades under the AEMO 2019 Integrated System Plan to proceed, with further interconnector upgrades determined by the market model.	
Snowy Hydro	The Snowy Hydro Expansion is not included.	
Zero-price periods	5% on average by 2040. Only grid-connected electrolysers are able to take advantage of zero-price periods.	

References & notes

1 Net Present Value (NPV) is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present.

2 These emissions reductions are dependent on an ongoing decline in the emissions intensity of the electricity grid such that Australia meets its Paris Commitment targets and reaches zero emissions by 2070.

3 IPCC 2018, Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland. https://www.ipcc.ch/sr15/.

4 Australian Government - Department of the Environment and Energy 2018, Australia's emissions projections 2018, http://www.environment.gov.au/system/files/resources/128ae060-ac07-4874-857e-dced2ca22347/files/australias-emissions-projections-2018.pdf

5 Hydrogen Council 2017, How Hydrogen Empowers the Energy Transition, www.hydrogencouncil.com

6 Commonwealth of Australia 2018, Hydrogen for Australia's future: A briefing paper for the COAG Energy Council, https://www.chiefscientist.gov.au/wp-content/uploads/HydrogenCOAGWhitePaper_WEB.pdf

7 These include: The $2 million Victorian Hydrogen Investment Program, the Queensland Government's Hydrogen Strategy, the South Australian Government's Hydrogen Roadmap and $17 million co-investment in four green hydrogen projects, Jemena and ARENA's $15 million H2GO hydrogen gas network trial in New South Wales, and the formation of the Western Australia Hydrogen Council.

8 Whitehead, Jake & Smit, Robin & Washington, Simon 2018, Where are we heading with electric vehicles?. Journal of Air Quality & Climate Change (52), 18-27. https://www.researchgate.net/publication/328782184_Where_are_we_heading_with_electric_vehicles

9, 10 Commonwealth Scientific and Industrial Research Organisation (2018), National Hydrogen Roadmap: Pathways to an economically sustainable hydrogen industry in Australia, https://www.csiro.au/en/Do-business/Futures/Reports/Hydrogen-Roadmap

11 Melbourne prices for water from the Victorian Desalination Plant (VDP), Jacobs 2019.

12 This cost includes treatment to meet the quality required for hydrogen production. Estimated cost of drinking water will vary by consumer category and region, but is unlikely to cost less than treated recycled water.

13 Based on recent analysis conducted by Jacobs. Note that costs could vary substantially based on location, the price of energy, and distribution requirements.

14 Based on recent work conducted by with advanced wastewater treatment facilities. This cost includes treatment to meet water quality requirements of electrolysers.

15 Net Present Value (NPV) is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present.

16 The Australian financial year begins on the 1 July and ends on the 31 June (e.g. FY2025 is the period from 1 July 2024 to 31 June 2025).

17 'Levelised cost' refers to the Levelised Cost of Hydrogen (LCOH). The LCOH can be defined as the upfront capital cost amortised over the assumed economic life of the system (25 years) to determine an annual repayment. The annual repayment amount is added to other annual costs (including energy, water, and maintenance) and then divided by the amount of hydrogen produced per year.

18 'Residual waste' is the waste left-over after recyclables have been removed.

19 Yarra Valley Water 2019, Waste to Energy, https://www.yvw.com.au/waste-energy

20 Price determined by applying the $/tCO2-e emissions intensity price from Jacobs' Energy Markets 'Base Case' projections.

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