Flexibility of Hydrogen Electrolysers

Opportunities in the Australian National Electricity Market

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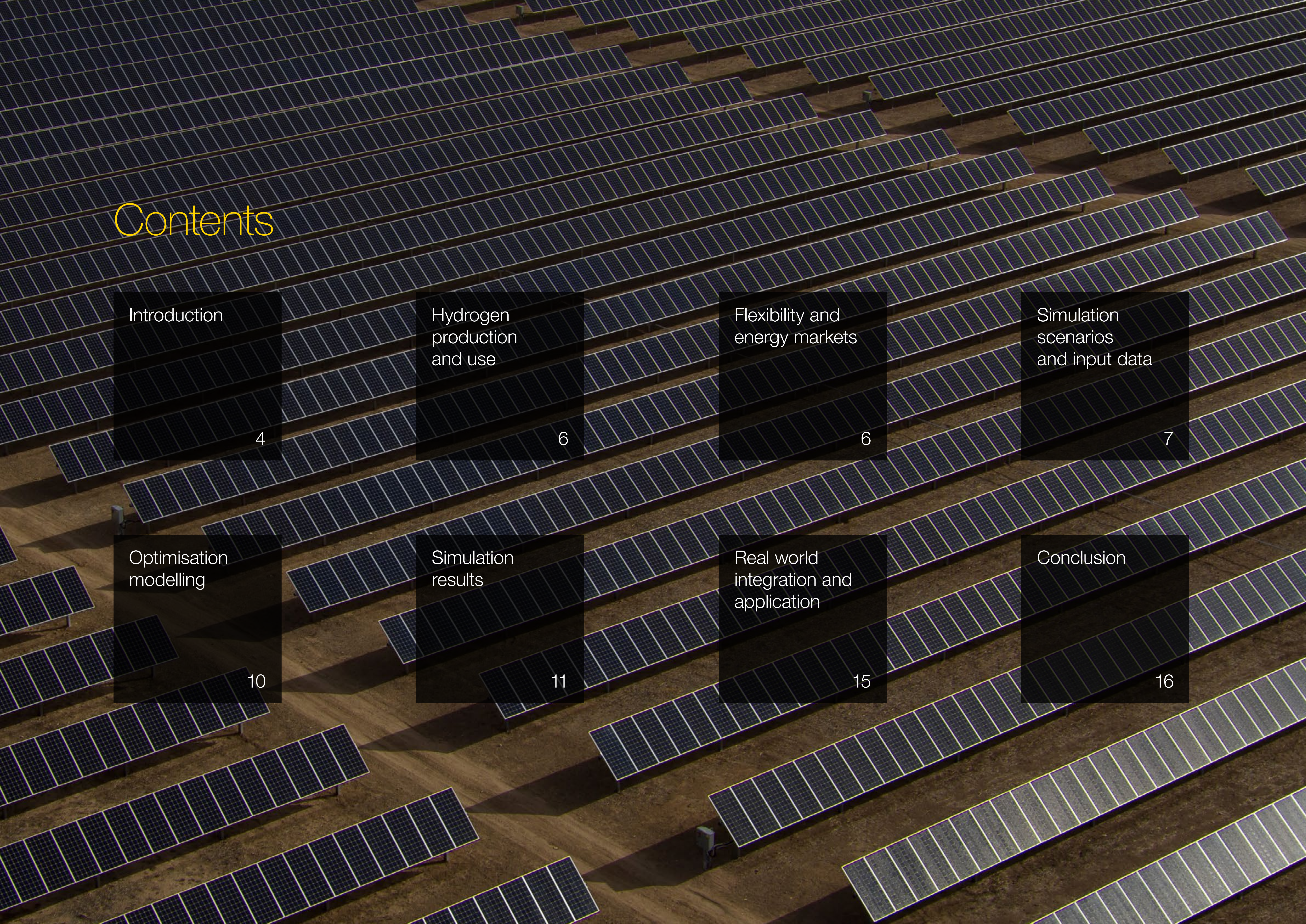

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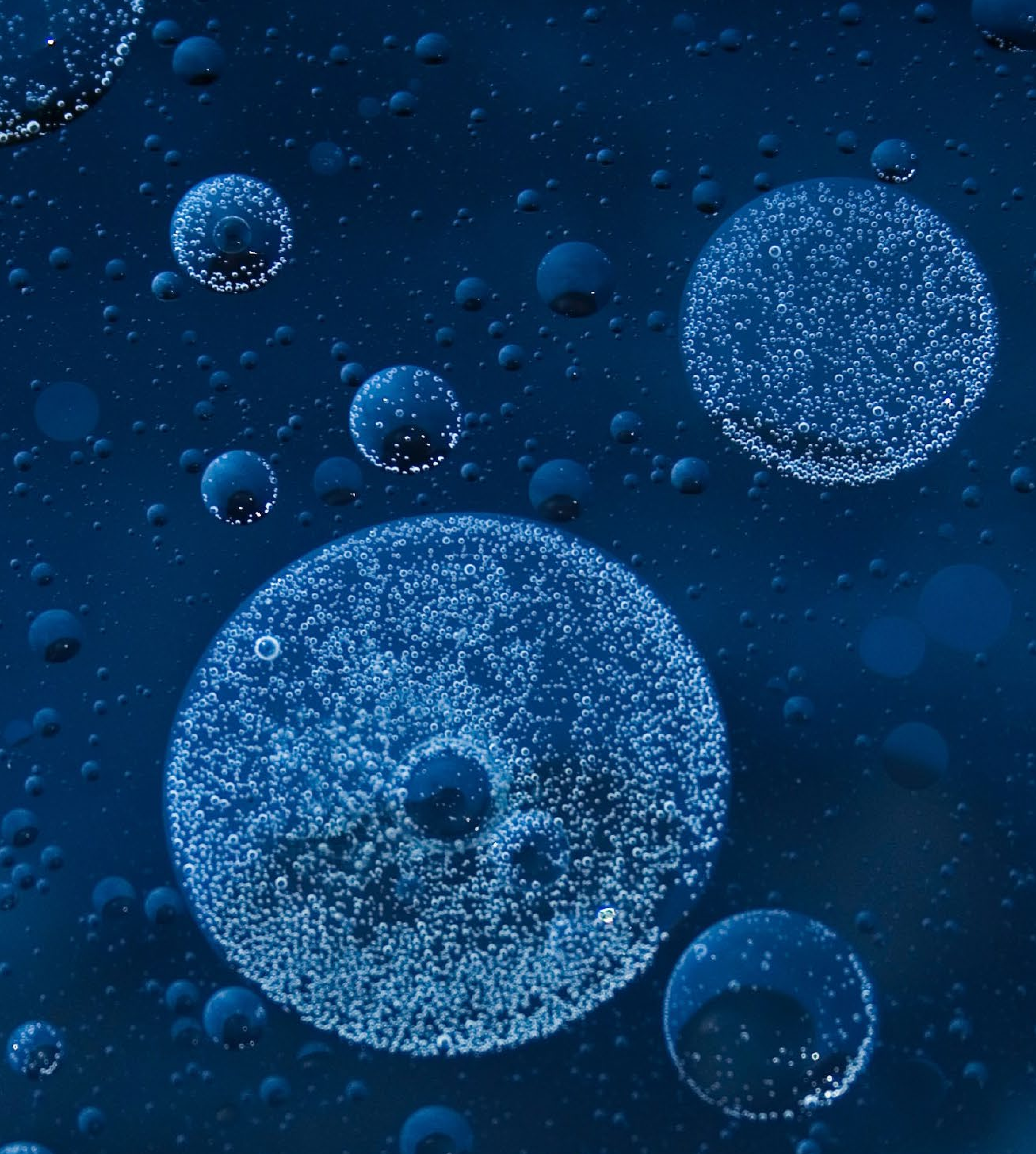
Introduction

Global hydrogen demand currently totals around 70 million tonnes per year[1], most of which is attributed to the petroleum and ammonia industries. Presently, fossil fuels are the dominant production source of hydrogen, resulting in approximately 830 million equivalent tonnes of carbon dioxide emissions per year[1]. However, with the increasing prominence of electricity derived from renewable energy, hydrogen electrolysers offer a pathway to decarbonise the production of hydrogen that will become competitive with tradition production method as costs continue to fall.

This article explores the net electricity costs of hydrogen production from electrolysis within the Australian National Electricity Market (NEM) with a key focus on operation of an electrolyser as a scheduled load participating in the wholesale energy and Frequency Control Ancillary Services (FCAS) markets.



1 The Future of Hydrogen (IEA report)

Hydrogen production and use

The traditional method of hydrogen production is via steam-methane: a process by which steam is mixed with methane at high pressure and temperature to produce hydrogen and carbon monoxide as a by-product. The carbon monoxide is then treated with water which produces carbon dioxide and additional hydrogen via the water-gas shift reaction. The advantages of using electrolysers to produce hydrogen over this and other fossil-fuel-based methods are two-fold. Firstly, this process inherently produces carbon dioxide and other greenhouse gases, whereas electrolysers offer an emissions-free production process when paired with a renewable source of electricity. Secondly, an electrolyser is a flexible load (a load which can rapidly increase or decrease the consumption of electricity, referred to as "ramping") which, when connected to an electricity grid, is highly useful in providing frequency balancing services. This is particularly important given the intermittent nature of most renewable energy sources; flexible generation and controllable load assets are crucial to enabling further renewable uptake around the world.

Hydrogen is primarily used within the industrial sector, the most common applications being petroleum refining, and for ammonia and methanol production. With regard to the development of a green hydrogen industry, the expectation is that diesel replacement in heavy and high utilisation mobility will be an early mover due to the economics which are comparable to the fossil fuel equivalent today. As hydrogen production costs fall, future use cases in areas that are otherwise difficult to decarbonise are likely to include industry and heat.

Flexibility and energy markets

As the transition of the energy generation mix continues towards intermittent renewable sources (i.e. wind and solar) and away from thermal technologies, particular energy system dynamics, listed below, consistently arise. The Australian NEM, (and specifically a state like South Australia) serves as a robust bellwether for changes that other similarly weakly interconnected and islanded markets around the world can expect.

Key energy system and deregulated energy market dynamics that have been observed in a state such as South Australia, as a result of high renewable uptake are:

- Increasing ramping requirements of thermal assets
- Higher energy spot price volatility
- Less grid inertia and stability
- Greater costs associated with frequency balancing services (FCAS in the NEM) and lower resilience to large unit trips or network issues
- Higher rate and intensity of negative price events and a pronounced 'duck curve' across multiple seasons.

As the above list compounds with ever-increasing renewable energy generation and retirement of ageing synchronous generation fleets, energy systems characterised by a high degree of flexibility increase in value: both from the perspective of the management and stability of the electricity grid, and for the economics of the energy system. Battery storage or fast start gas turbines combined with batteries are the systems currently typically thought of when discussing flexibility, but hydrogen electrolysers also fall under this class as a flexible load. Hydrogen electrolysers owe their capability to ramp quickly in response to control signals to their basis in power electronics. This means they can offer services such as balancing or FCAS and respond to rapid changes in renewables output and market conditions.

Simulation scenarios and input data

The following simulations are based on a case study of a fictitious, utility-scale electrolyser participating in the NEM as a scheduled market load. The electrolyser is assumed to be directly connected to the transmission network and have full access to the wholesale energy and FCAS markets. Importantly, unlike the distribution network, network and retail tariffs don't apply to the transmission network, and for the purposes of this study, the Transmission Use Of System (TUOS) charges are assumed inapplicable. The quantity of hydrogen the electrolyser is required to produce each day is assumed to be 10 tonnes, and final pressure of the hydrogen after compression is assumed to be 900 bar. This high pressure has been selected as the associated energy requirement for the compressor will provide conservative results for the electricity costs for a wide variety of use cases.

Four scenarios are considered in order to investigate the impact of two key factors on reducing electrolyser electricity costs: storage capacity and FCAS participation. In scenarios with storage capacity, the operators of the electrolyser can choose to produce more hydrogen than required to meet current demand and store the excess, which can be advantageous in avoiding periods of high energy costs. Stored hydrogen can then be used to meet demand at a later point in time. **Note:** the ability to store hydrogen for later use is approximately equivalent to dynamically modifying the hydrogen demand profile (i.e. refuelling trucks or buses at opportune times), therefore, any conclusions drawn about the advantages of storage also apply to scenarios in which hydrogen demand is flexible.

Scenario	Daily hydrogen demand (tonnes)	Storage capacity	FCAS participation
1	10	No	No
2	10	Yes	No
3	10	No	Yes
4	10	Yes	Yes

Table 1 - Scenarios

These scenarios are simulated in all regions of the NEM (NSW, QLD, SA, TAS, and VIC) to illustrate the different electricity costs in each NEM-connected state, and, to demonstrate the effect of electrolyser size relative to a fixed hydrogen production requirement: each scenario is also simulated over a range of electrolyser sizes (25, 50, 75 and 100 MW).

The simulation models have been built using readily available NEM data, specifications from electrolyser OEMs, and market assumptions based on the experience of the authors.

ITEM	VALUE	UNIT	COMMENT
Electrolyser specifications			
Technology type	Polymer electrolyte membrane (PEM)		The flexibility of PEM electrolysers enables a high level of FCAS registration
Min load	-	% of nameplate capacity	
Max load	100	% of nameplate capacity	
Ramp rate	10	% of nameplate capacity per second	
Hydrogen production efficiency	19.25	kg/MWh	Including compression
FCAS registrations			
Raise/lower 6s	60	%	Capped at 50 MW. Only scenarios 3 and 4 participate in the FCAS markets
Raise/lower 60s	100	%	Capped at 50 MW. Only scenarios 3 and 4 participate in the FCAS markets
Raise/lower 5mins	100	%	Capped at 50 MW. Only scenarios 3 and 4 participate in the FCAS markets
Regulation raise/lower	40	%	Capped at 50 MW. Only scenarios 3 and 4 participate in the FCAS markets
Hydrogen production, compression, and storage			
Production requirement	10	t/day	Demand is pro-rated linearly across the day
Pre-compression	3	Bar	Stack pressure
Post-compression	900	Bar	Storage pressure
Storage capacity	100	T	Equivalent to 10 days of demand. Only scenarios 2 and 4 have storage capability

Table 2 – Input parameters

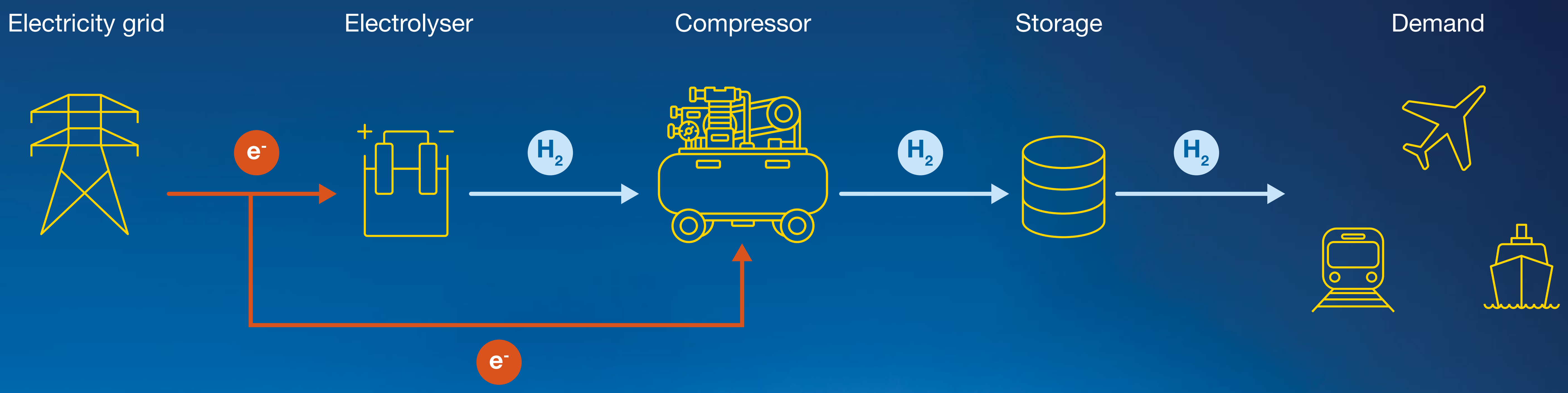


Figure 1 – System Schematic

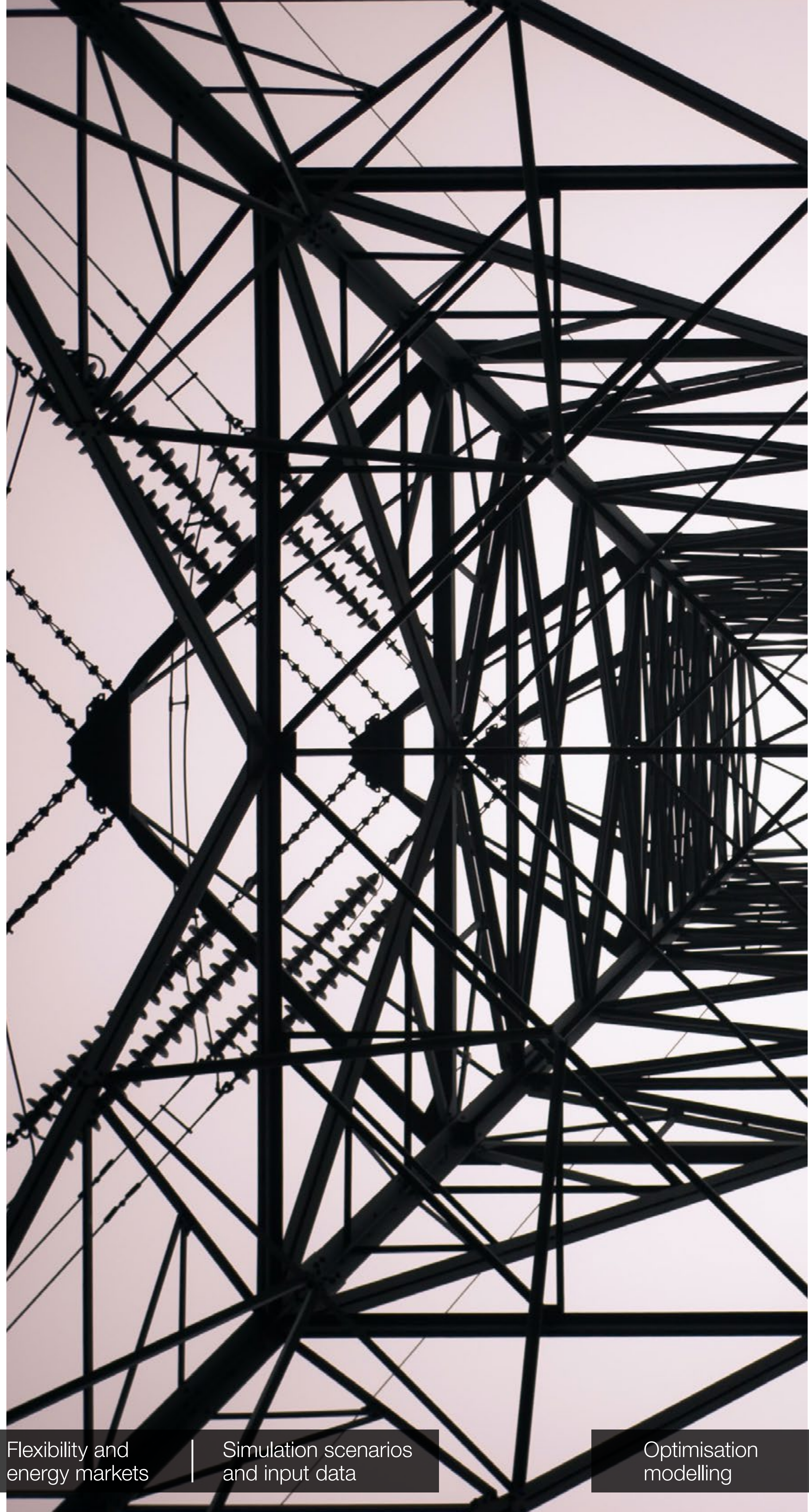
Optimisation modelling

To minimise electrolyser electricity costs, it is expected that electrolyser operators will make use of autonomous bidding software similar to what is currently used by many utility-scale batteries around the world.

The simulations presented here are based on optimisation methods used in such software, with a key difference being that the simulations have 'perfect market foresight', that is, the electrolyser operators have a full view of all market pricing for the entire year in advance. Of course, in practice, electrolyser operators will not have perfect market foresight. Furthermore, the nuances of bidding a load into the market and price elasticity are not accounted for in the simulation. It is assumed by the authors that autonomous bidding software will capture the decisions made in a perfect market foresight simulation with approximately 70% accuracy.

With this in mind, the objective of each optimisation is simply to minimise electricity costs for the entire year, electricity costs being the cost of any wholesale energy purchased less the revenue generated through the FCAS markets, whilst obeying the physical operating constraints on the electrolyser. The main constraints are the nameplate power capacity and hydrogen demand. The simulations are performed on a 5-minute time scale, the same timescale over which the National Electricity Market Dispatch Engine (NEMDE) operates the energy and FCAS markets, and the daily hydrogen demand is pro-rated throughout the day on this timescale. Numerically, there is a 34.72 kg hydrogen demand every 5 minutes that must be met by a combination of direct production from the electrolyser and stored hydrogen.

Finally, to reach the assumed storage pressure, a compressor has been included in the model, the energy requirement of which has been accounted for in the *hydrogen production efficiency* value (see Table 2). Note that this analysis only investigates the cost of electricity, the CAPEX and OPEX of these scenarios are not considered here.



Simulation results

The following charts display the net electricity costs for each scenario across a range of electrolyser sizes.

Historical CY 2019 market prices for wholesale energy and FCAS markets for New South Wales and Victoria. New South Wales and Victoria was chosen for deeper analysis as it was felt that these states offered a middle ground overview of the results as opposed to a state such as South Australia with its significant historical FCAS pricing. For completeness, the remaining states of Queensland, South Australia and Tasmania results are summarised in the appendix and offer interesting insight into the operating costs of hydrogen production on a state by state basis. It is important to note that neither the value of the hydrogen produced, nor any maintenance costs are included in the net cost: these results are purely based on net electricity costs from participation in the NEM.

New South Wales – Hydrogen Electrolyser Net Electricity Costs

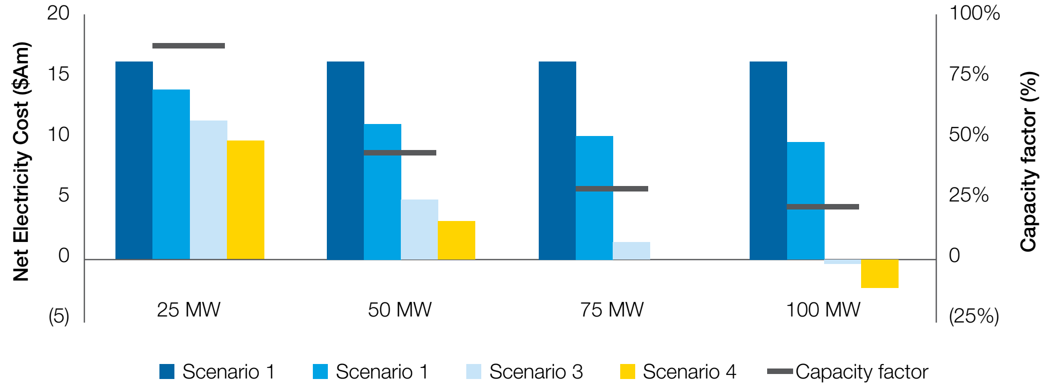


Figure 2 – NSW results – Scenario 1 (no FCAS participation, no storage), Scenario 2 (no FCAS participation, with storage), Scenario 3 (FCAS participation, no storage) and Scenario 4 (FCAS participation, with storage)

In Figure 2, it is observed that without FCAS participation or storage/demand flexibility (Scenario 1), the net electricity cost to operate the electrolyser is constant. This is because without any storage or demand flexibility, any electrolyser, regardless of size, needs to be operated constantly to meet the modelled constant demand profile. The addition of storage (Scenario 2), or equivalently flexibility in demand, allows the electrolyser to operate at more opportune times when electricity prices are lower. This result is more pronounced with larger electrolysers for the assumed demand profile of 10t per day, or synonymously, electrolysers of lower capacity factors. Generalising this result, electrolysers with lower capacity factors, and some flexibility in demand or storage, are better placed to capture advantageous electricity prices and reduce overall electricity costs. Allowing the electrolyser to participate in the FCAS markets (Scenario 3) significantly offsets electricity costs, even without storage or demand flexibility. This result is accentuated as capacity factor increases, as more of the electrolyser capacity can participate in these markets. The addition of storage or demand

Simulation results (continued)

flexibility to FCAS participation (Scenario 4) adds a further level of freedom to more fully participate in these lucrative markets whilst flexibly producing more hydrogen during periods of low electricity price. Interestingly, these results show that for the given assumptions, an electrolyser with a capacity factor of 22%, FCAS participation and storage/demand flexibility actually generates a net electricity revenue, rather than a cost. (**Note:** as mentioned earlier analysis does not take into account the CAPEX/OPEX of the plant which when included will alter the conclusion that has been obtained here).

Table 2 shows a summary of results from the New South Wales simulations as a function of scenarios and electrolyser power/capacity factor. All results are normalised to Scenario 1, 25MW.

	25 MW / 87%	50 MW / 43%	75 MW / 29%	100 MW / 22%
Scenario 1	100%	100%	100%	100%
Scenario 2	86%	69%	63%	60%
Scenario 3	70%	30%	9%	(2%)
Scenario 4	60%	20%	(1%)	(14%)

Table 2 – NSW net cost results summary

Figure 3 is an example of a typical day for the New South Wales and high power (100MW) case. For Scenario 2 (no FCAS participation with storage) and Scenario 4 (FCAS participation with storage) it can be seen how the electrolyser reacts differently to the same price signals. Without FCAS participation (Scenario 2), the electrolyser reacts to lower energy prices by ramping to full capacity, while the enablement of FCAS participation (Scenario 4) incentivises the electrolyser to vary the load in such a way as to optimise revenue from the FCAS markets. This can sometimes lead to unintuitive behaviour, where below it is observed that the electrolyser is not running at full capacity during periods of low electricity prices and is running to some extent during periods of higher electricity prices (this is to allow for greater participation in particular FCAS markets by offering to raise or lower the load of the electrolyser).

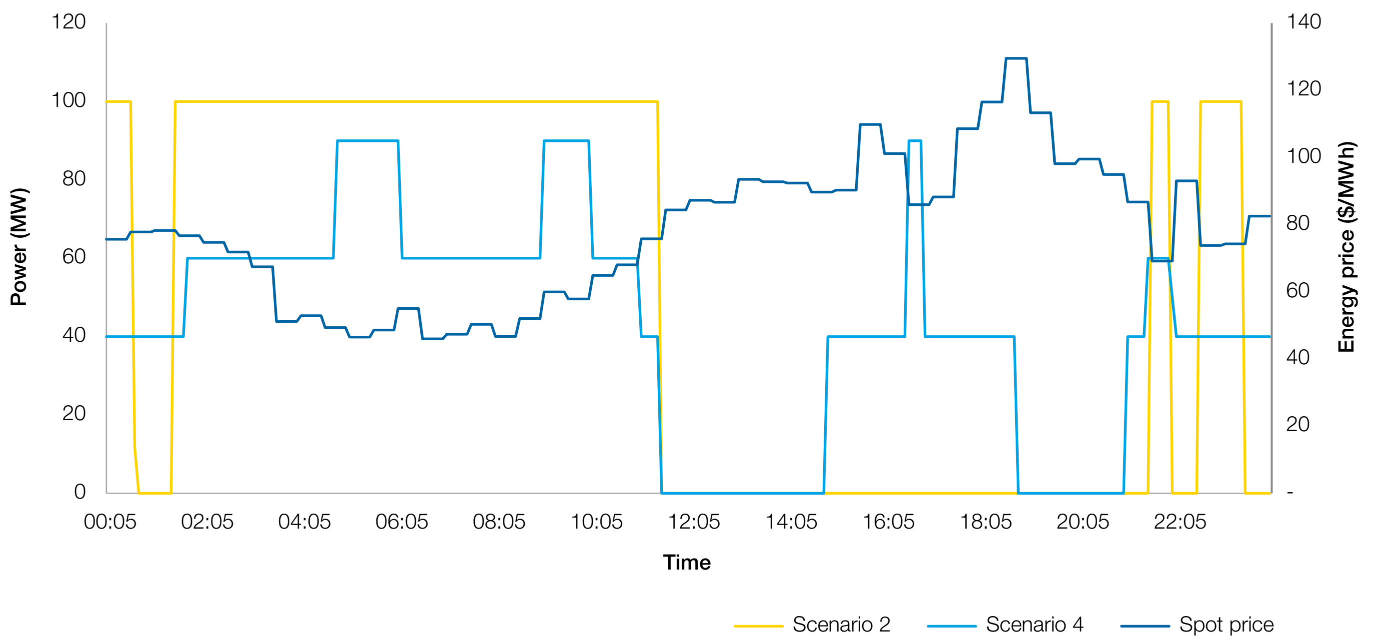


Figure 3 – Power consumption of a 100 MW electrolyser over a day in NSW

Victoria – Hydrogen Electrolyser Net Electricity Costs

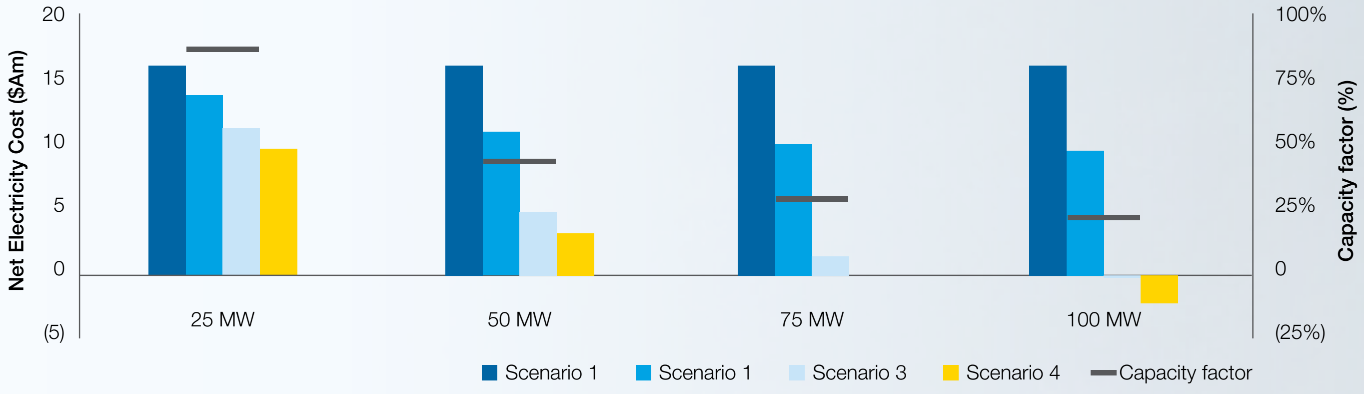


Figure 4 – VIC results – Scenario 1 (no FCAS participation, no storage), Scenario 2 (no FCAS participation, with storage), Scenario 3 (FCAS participation, no storage) and Scenario 4 (FCAS participation, with storage)

Figure 4 shows that Victoria is qualitatively similar to New South Wales. Quantitative differences arise from the differing electricity grid dynamics of the two states. Victoria experienced a more volatile 2019 than NSW; hence electricity costs are greater overall. Again, we see that FCAS participation, storage/demand flexibility and a capacity factor of 22% produce a net electricity revenue.

From the VIC and NSW simulations, we can conclude that the flexibility of electrolysers can come in several forms, each with their own degree of benefit:

- Increased freedom in decision making and responding to market price signals, facilitated by on-site hydrogen storage or flexibility in demand
- Participation in balancing or FCAS markets to produce revenue that offsets the cost of electricity
- Increasing the size of the electrolyser relative to the demand (i.e. reducing the capacity factor) allows more hydrogen to be produced during periods of low energy prices.

	25 MW / 87%	50 MW / 43%	75 MW / 29%	100 MW / 22%
Scenario 1	100%	100%	100%	100%
Scenario 2	76%	57%	48%	42%
Scenario 3	77%	46%	30%	22%
Scenario 4	57%	22%	5%	(6%)

Table 3: VIC net cost results summary

Real world integration and application

It is important to mention how a flexible hydrogen production system such as this can practically participate in electricity and FCAS markets. In this Australian NEM example, this would be analogous to large-scale storage market participation via market bidding software as offered by several well-known software providers. Although the authors are currently not aware of any such software providers having yet adapted this type of software for electrolyser market participation, it is anticipated that, given its similarity to battery energy storage, the development effort is within reason. Market bidding software is becoming more common and well understood by both investors and developers, as well as market operators and market participants.

As mentioned previously, the hydrogen electrolyser facility would be registered as a market load and would need to submit bids to the Australian Energy Market Operator (AEMO) to receive market awards for products such as energy and FCAS. It is the view of the authors that this is a reasonable assumption for a hydrogen electrolyser of a large enough size (>5MW) based on preliminary discussions with electrolyser OEMs regarding system capability, and current AEMO requirements. Ongoing investigation and discussions with electrolyser OEMs and AEMO are necessary to determine the viability of the market participation assumptions.

Conclusion

It is clear that all variables considered in this analysis, such as region, electrolyser size/capacity factor, storage capability/demand flexibility, and FCAS participation can have a material impact on the net electricity costs of hydrogen production from electrolysis, with FCAS participation, in particular, unlocking the value of the physical flexibility of an electrolyser.

The value of shifting demand, either via storage or literal demand shifting, and reducing the electrolyser capacity factor is also significant: a facility with these attributes will have much more operational flexibility, and this allows for a larger volume of hydrogen to be produced using low cost energy and greater FCAS market participation.

Those looking to develop and invest in hydrogen production facilities should consider the market participation applications, network benefits and challenges that a flexible load such as an electrolyser can offer. Careful selection and design of storage size, demand-shifting and electrolyser size/type and market participation software, as well as the associated cost implications, should be considered for any new hydrogen electrolyser development.

Commercial considerations

This paper is based on modelling completed by the Macquarie Energy Technology and Solutions team. Additional considerations that may impact its practical application to a project include the:

1. Inclusion of CAPEX/OPEX associated with the different hydrogen plant when analysing operating costs. For example:
   - With electrolyser pricing at circa $A1m/MW, a high capacity factor may be required to generate the required return on investment; and
   - The costs of storage and compression may be a limiting factor. A project's ability to move load around via demand shaping can be particularly valuable in this context.

The faster the industry is scaled, the quicker electrolyser costs are expected to fall. Lower electrolyser costs provide more opportunity to run the plant with a lower utilisation / capacity factor. A lower capacity factor may lead to lower energy costs as outlined in this paper.

2. The bankability of future revenue streams associated with providing ancillary services may be limited. Investors in a project may not be prepared to provide value to future revenue streams from FCAS due to the uncertainty associated with these revenue streams that may come from future changes:
   - In regulation impacting the market construct; and
   - In the balance of demand and supply given the expected increase in providers of ancillary services.

Changes in regulation that improved the bankability of ancillary services would increase the likelihood of hydrogen projects being funded as investors would ascribe value to the different FCAS revenue streams.

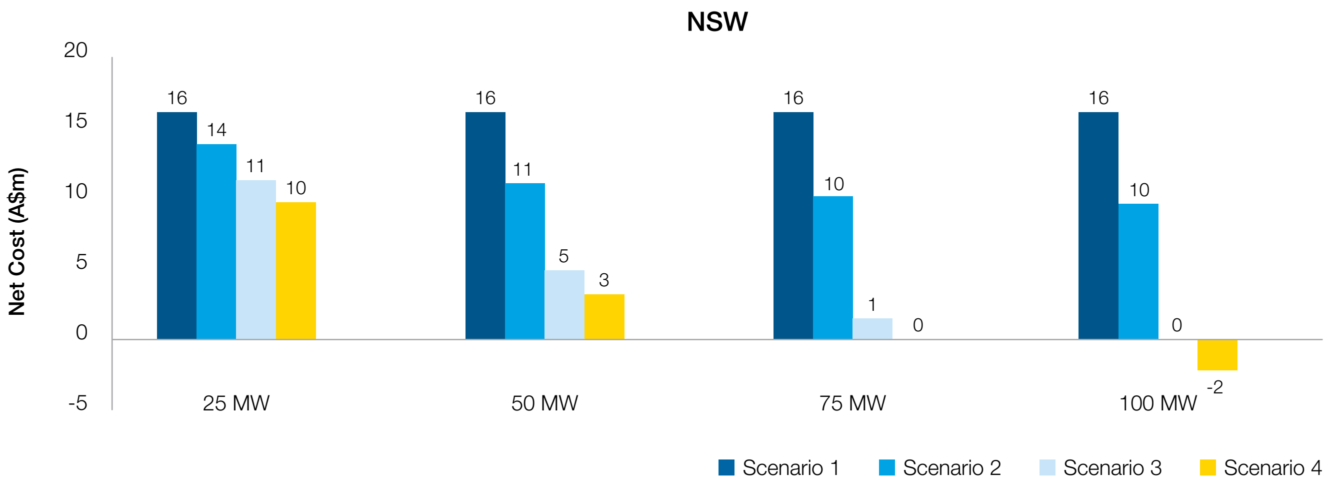
3. The modelling constraints of 10t/day and 34.75kg/5min interval may not reflect the practical constraints of a project. In practise a successful project will often involve re-shaping the demand to better match the generation profile of an optimised electrolyser. Optimisation of the energy solution, electrolyser operation, storage configuration and H2 demand timing is a key driver of value in these projects

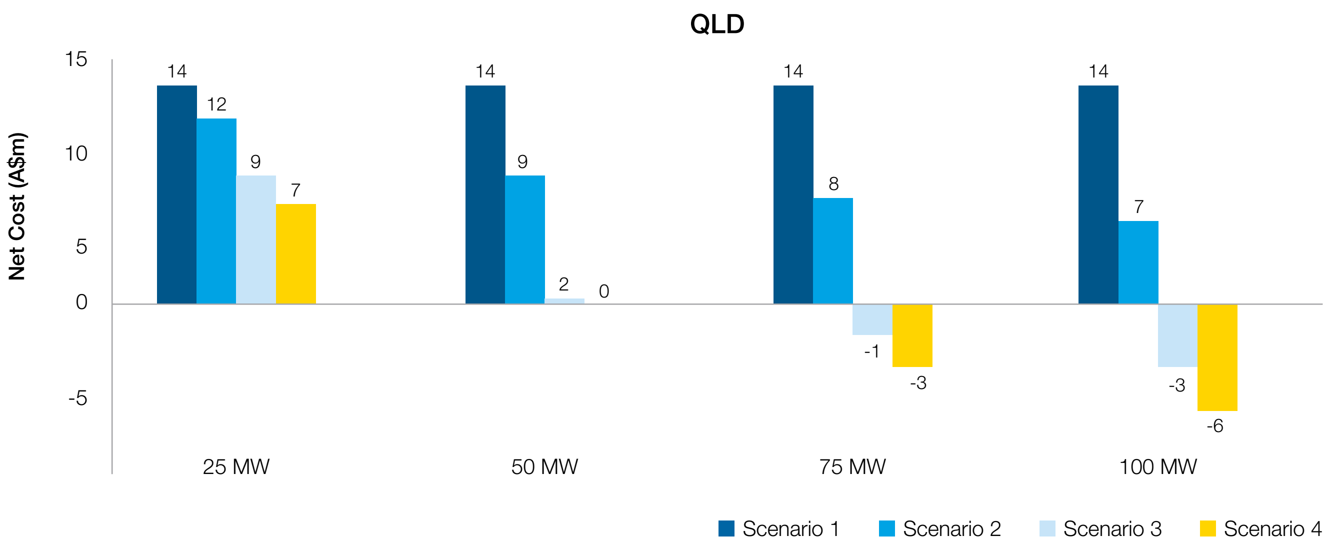
Further work

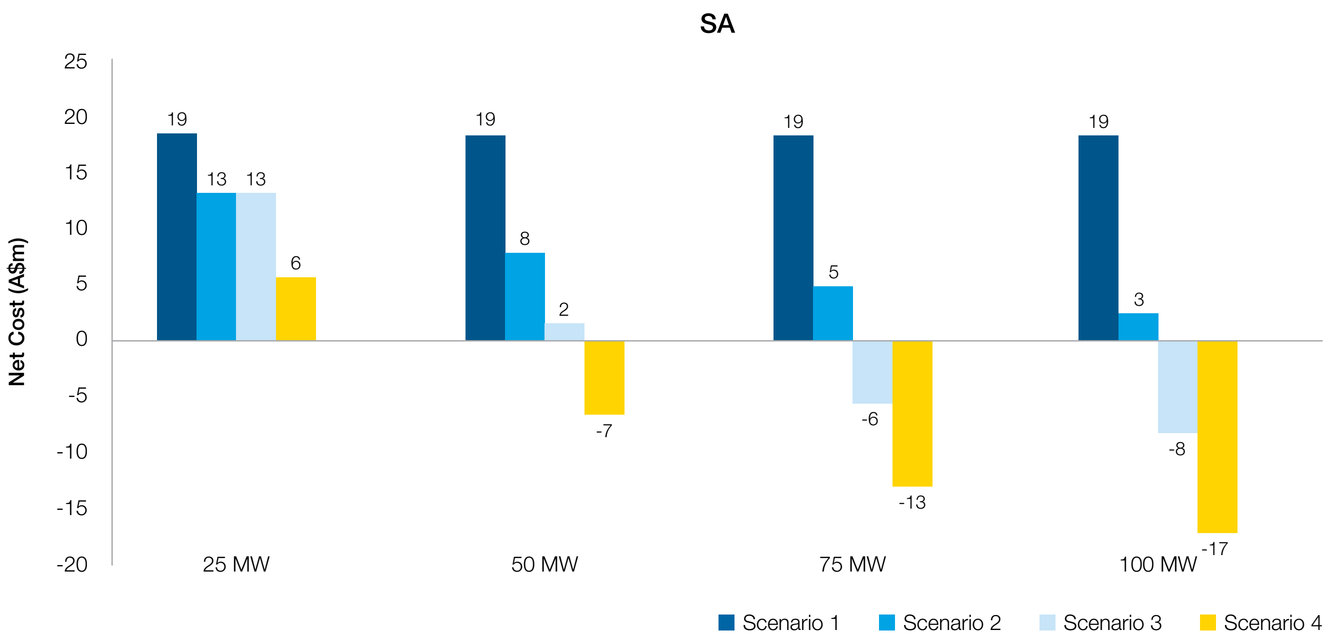
There are several interesting avenues that could be explored as a further study:

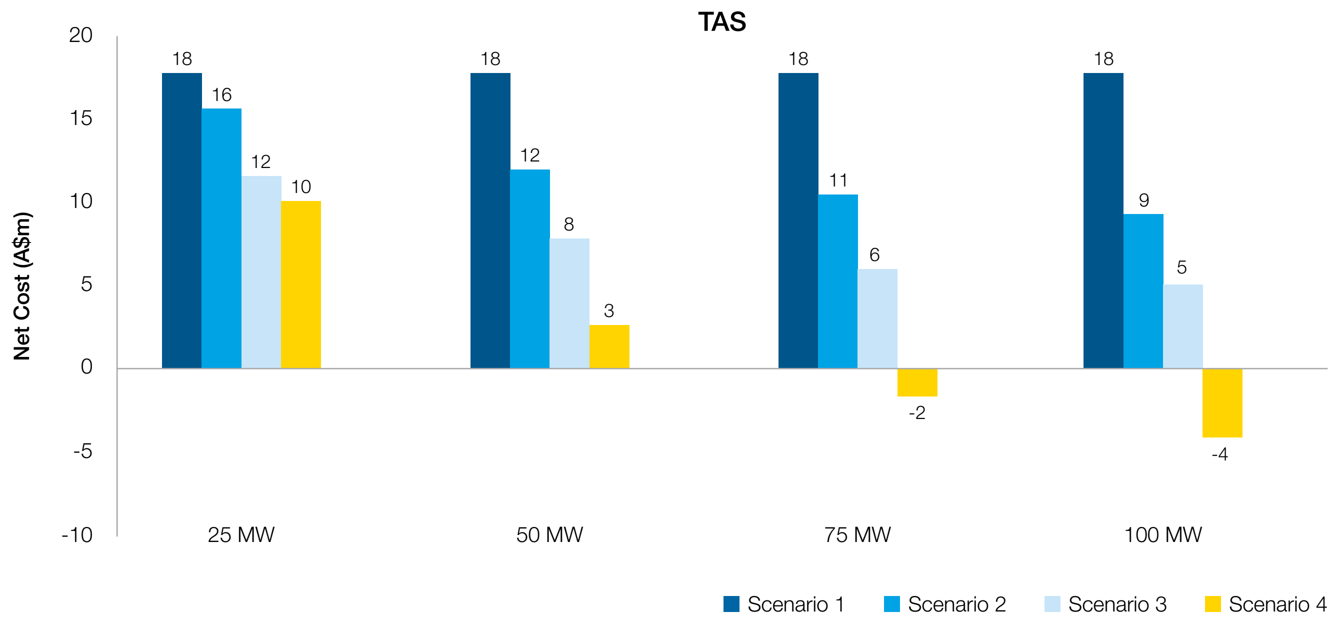
- Analysing the efficiency of an electrolyser to operate successfully with an actual intermittent behind the meter solar profile
- Modelling the optimal operating profile for an electrolyser given an assumed efficiency curve
- Including assumptions for CAPEX/OPEX in the plant to understand how this might impact results
- A full techno-economic analysis of all variables and their associated costs
- Use-case specific hydrogen demand profiles (i.e. pipeline injection, vehicle refuelling)
- Addition of a generation-following green PPA
- Addition of a carbon price.

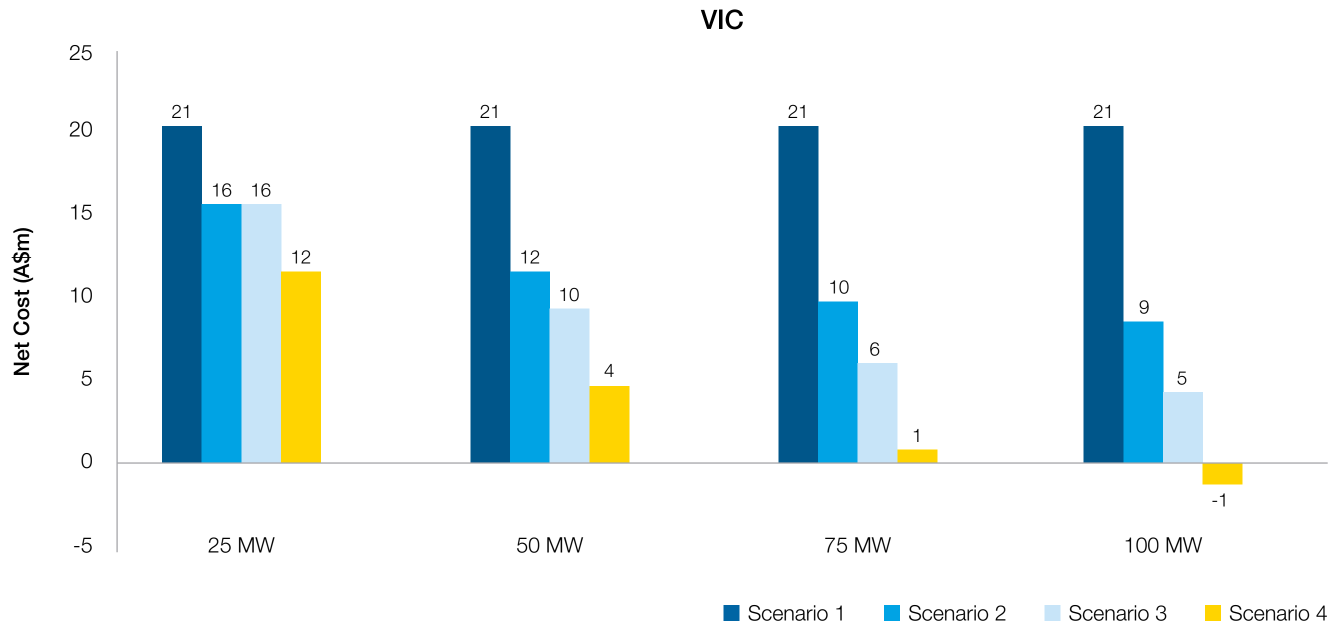
Appendix


NSW
Net Cost (A$m)
20
15
10
5
0
-5
16
14
11
10
16
11
5
3
16
10
1
0
16
10
0
-2
25 MW
50 MW
75 MW
100 MW
Scenario 1
Scenario 2
Scenario 3
Scenario 4


QLD
Net Cost (A$m)
15
10
5
0
-5
14
12
9
7
14
9
2
0
14
8
-1
-3
14
7
-3
-6
25 MW
50 MW
75 MW
100 MW
Scenario 1
Scenario 2
Scenario 3
Scenario 4


SA
Net Cost (A$m)
25
20
15
10
5
0
-5
-10
-15
-20
19
13
13
6
19
8
2
-7
19
5
-6
-13
19
3
-8
-17
25 MW
50 MW
75 MW
100 MW
Scenario 1
Scenario 2
Scenario 3
Scenario 4


TAS
Net Cost (A$m)
20
15
10
5
0
-5
-10
18
16
12
10
18
12
8
3
18
11
6
-2
18
9
5
-4
25 MW
50 MW
75 MW
100 MW
Scenario 1
Scenario 2
Scenario 3
Scenario 4


VIC
Net Cost (A$m)
25
20
15
10
5
0
-5
21
16
16
12
21
12
10
4
21
10
6
1
21
9
5
-1
25 MW
50 MW
75 MW
100 MW
Scenario 1
Scenario 2
Scenario 3
Scenario 4

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The Macquarie Capital Energy Technology and Solution team are a combination of engineers and scientists with significant expertise in energy technology, energy markets, battery storage and electric and fuel cell vehicles.

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