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Review

Hydrogen and Other Bioenergy Fuels for Australia's Net-Zero Strategy: A Critical Review

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Abstract: Hydrogen plays an important role in the implementation of Australia's Net-Zero Strategy. It competes with lithium-ion rechargeable batteries in the electrification of Australian land transportation sector, and can provide an alternative energy storage medium for the greening of the country's electrical grid system. This paper reviews the role hydrogen plays in the current government's Net-Zero strategy, and investigates the potential role of other bioenergy sources. It is found that hydrogen and batteries play essentially complementary roles in reducing transport emissions, and that the former energy source is more suited to the operation of long-distance commercial service vehicles than batteries. It is suggested that bioenergy fuels such as biomethane, second generation biofuels and HVO can provide suitable bridging alternatives in the event that Australia's EV strategy is unable to meet the 2030 target.

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1. Introduction

Climate change policy, in the form of the Paris Agreement, is driving a global change which is transforming the way we produce and use energy. The aim of this energy transition is to replace emissions-intensive fossil fuels with clean renewable energy sources in power generation and transportation systems to achieve global net – zero emissions by 2050.

Australia's efforts to tackle the challenge started with the former (coalition) government's net-zero strategy, which was centred around a Technology Investment Roadmap which delivered 40% of the emission reductions. The current (Albanese) Labour government's strategy has taken a bolder approach, with the 2030 reductions target increased to 43% and a concerted effort to phase out coal-fired power plants (the heaviest emitters) from Australia's grid system.

Hydrogen plays a significant role in the strategies of both of these two consecutive governments. Australia's National Hydrogen Strategy was established in 2019, with the aims of developing a hydrogen industry that benefited all Australians and made the country a major player in the global hydrogen industry by 2030.

To see how hydrogen can play an integral part in achieving the emissions reduction targets of Australia, it is first necessary to obtain a clear picture of the country's net-zero strategy. Other chemical and electro-chemical media such as biomethane and batteries are also instrumental in achieving the same goal, and it is instructive to compare the relative merits of these options.

This paper reviews the potential use of hydrogen and other bioenergy resources as clean energy options for power generation and transportation, and provides a critique of Australia's net-zero strategy and the role bioenergy can play in the successful achievement of the 2050 target. In particular, it suggests the potential use of conventional bioenergy sources such as biomethane to complement hydrogen in the achievement of the 2030 goal.

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The paper begins by introducing the important bioenergy fuels that are now available for power generation and transportation in Australia and on the global scale. It then outlines the former (Coalition) and the present (Albanese) government's net-zero strategies, paying particular attention to the roles of the (reformed) Safeguard Mechanism and the (new) National EV Strategy in meeting the 2030 and 2050 targets. The merits of hydrogen, biomethane and batteries are then compared. The paper ends by emphasizing the need for urgent action, and noting the possibility of the emergence of a technology gap in the absence of such action. It is pointed out that bioenergy fuels such as biomethane and second generation biofuels offer the opportunity to fill such a possible technology gap.

2. Hydrogen and Other Bioenergy Fuels for Power Sources

Australia's existing grid power systems depend largely on fossil fuel sources such as coal and gas for their dispatchable energy supply. To maintain grid stability during the greening process, these need to be replaced with renewable sources that are also dispatchable in nature.

Intermittent energy sources such as wind and solar can be transformed into dispatchable sources for the grid through the mechanism of energy storage. Such sources include energy storage systems consisting of rechargeable batteries utilizing intermittent wind and solar energy as their energy source, as well as pumped hydro. The possibility of adding regenerative hydrogen fuel cells to this list of new dispatchable energy sources will become real as this technology comes of age.

The list of current and emerging clean and green energy options (either available or in development) for Australia's power and transportation industries comprise:

- Intermittent renewable energy for power generation (wind, solar)
- Dispatchable clean energy for power generation (hydro, geothermal, ocean)
- Bioenergy fuels for thermal power generation (solid biomass, biogas, biomethane, pyrolysis oils, firstgeneration biofuels, biobutanol, HVO, syngas, hydrogen and ammonia) [1].
- Energy storage systems for grid-greening and stabilization (wind-solar powered rechargeable batteries, pumped hydro, regenerative (reversible) hydrogen fuel cells (RHFCs)).
- Rechargeable batteries for battery-powered EVs (BEVs), hydrogen fuel cells for fuel cell EVs (HFCEVs) (see [1], Ch. 7).

Most of these technologies are mature and market-ready. The latest additions are hydrogen and ammonia, which are in a near-market state of readiness. RHFCs which have a roundtrip efficiency of 30%, still lag behind the 75-90% efficiency range for Li-ion batteries [2]. However, these two energy sources have similar return on investment at storing overgeneration, particularly from wind energy.

A rechargeable battery that promises to be cheaper than Li-ion batteries is the sodium-ion battery. (See [1], Ch. 7.4 and [3]).

Like other bioenergy sources, hydrogen stores its energy in chemical form. Fuel cells typically use hydrogen as their fuel. This may be used in its pure form directly, or obtained from organic fuels such as natural gas and biogas through the process of external or internal reforming. The Direct Methanol Fuel Cell (DMFC) is able to use methanol as the fuel directly.

3. The Role of Hydrogen in Australia's Net-Zero Strategy

3.1. Australia's National Hydrogen Strategy (2019)

In December 2018, the Council of Australian Governments (COAG) established a working group, chaired by Chief Scientist Dr. Alan Finkel, to develop a strategy for "a hydrogen industry that benefits all Australians and is a major global player by 2030" [4].

The specific aim of this strategy was to "create, test and prove Australia's clean hydrogen supply chains, encourage global markets and develop cost-competitive production capabilities".

Hydrogen has many uses, ranging from the making of ammonia, which is used in the manufacture of fertilizers, explosives and plastics, to its better-known function in decarbonising energy systems. It is a zero-emission fuel for hydrogen fuel cell EVs (see [5], p.26) and storage systems

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such as regenerative (reversible) hydrogen fuel cells, and can be blended with natural gas for cooking and heating uses (see Ref [4], p.5).

A key feature of Australia's hydrogen strategy is the creation of hydrogen hubs, which are "regions where users of hydrogen are co-located – in metropolitan, regional and remote areas of Australia" (Ref [4], p.31).

The hydrogen strategy received a boost this year with the announcement by the government of a $2bn Hydrogen Headstart program to "make Australia a renewable energy superpower" by providing support for large-scale hydrogen projects [6].

3.2. Australia's Net-Zero Strategy

Called Australia's Long-Term Emissions Reduction Plan: A whole-of-economy plan to achieve net zero emissions by 2050, the key feature of the previous (Coalition) government's net-zero strategy was a Technology Investment Roadmap, which amounted to 40% of its total reductions, and sought to produce clean hydrogen, low-cost solar and energy storage as key technologies assisting the effort, as well as reducing emissions through producing low-emissions steel and aluminium and sequestering carbon through carbon capture and soil carbon ([7] and Ref [1] Table 13.6).

The current (Albanese) government's strategy is still evolving. It consists of a government act and a suite of policies sometimes referred by the collective name of the Powering Australia Plan. The strategy comprises:

- Climate Change Act 2022 [8], which is an umbrella legislation to implement Australia's net-zero commitments, and includes the reduction of net GHG emissions to 43% below 2005 levels by 2030, and its reduction to net-zero by 2050, implemented by
- a raft of strategies known collectively as the Powering Australia Plan [9].

The key elements of the Powering Australia Plan consist of:

- The Safeguard Mechanism – reducing the emission baselines of the 215 heavy-emitters on a broad trajectory to net zero by 2050.
- National Electric Vehicle Strategy – improving the uptake, affordability and choice of electric vehicles by expanding the Australian EV market.
- Rewiring the Nation – a $20 billion commitment to rebuild and modernize the grid to enable greater penetration of renewable energy.
- Powering the regions fund – supporting industry to decarbonise and develop new clean industries, support workforce development and purchase carbon credit units (ACCUs) on behalf of the Commonwealth.
- National Reconstruction Fund - $15 billion to diversify and transform Australia's economy and industry.

3.3. The Safeguard Mechanism [10,11]

The Safeguard mechanism is aimed at ensuring that the emissions from Australia's 215 largest emitters (from the mining, manufacturing, transportation, oil, gas and waste sectors) reduce their (real) emissions in line with the government's 2050 plan. Under the Abbot government, this scheme required the 215 facilities to hold their emissions below a 100,000 tonnes of CO_2 eq. per annum ceiling. Excess emissions were allowed to be reduced through the purchase of Australian Carbon Credit Units (ACCUs).

The amended Act, called the Safeguard Mechanism (crediting) /Amendment Act 2023 was passed on 31 March 2023 [12].

Under the reformed scheme, the emission baselines are gradually reduced (by 4.9% annually) over time till they are on a path to the 43% reductions by 2030 and net zero emissions by 2050 trajectories. A "hard cap" has been imposed on 116 of the emitters for the fraction of reductions that can be replaced by carbon credits. The reductions are monitored by the Clean Energy Regulator.

Whether Australia is able to achieve its goal of 43% reductions by 2030 will depend critically on the efficacy of this reformed mechanism to reduce the baseline emissions from the power sector in keeping with the 2050 trajectory.

3.4. The National EV Strategy [13],[5]

Australia's current EV sales stands at 3.8% of the total annual vehicles sales. This is dismally low compared to the 9% of global sales, 15% for the UK and 17% for the EU.

The National Electric Vehicle Strategy (NEVS) was just introduced on 18th April this year [13]. It aims to improve the EV uptake rate by increasing the supply of affordable EVs and establishing the required supporting systems and infrastructure for EV uptake and maintenance. This national EV strategy (NEVS) largely supplements and plays a supporting role to the state and territory EV strategies that have existed since well before the enactment of this national strategy.

Note that hydrogen plays roles in both the Safeguard Mechanism (in Reversible Hydrogen Fuel Cells for energy storage) and the National EV Strategy (in the supply of fuel for fuel cell EVs (HFCEVs) for long distance commercial vehicle operations [4].

Prior to the announcement of the NEVS, it was not clear whether Australia could achieve the complete electrification of its transportation sector by the 2030 target. The NEVS has helped in allaying some of this uncertainty, but it is still not clear if it will be able to do enough

4. Hydrogen, Biomethane and Batteries

4.1. Hydrogen as a Net-Zero Fuel-Production, Distribution, and Use

Most of the global production of hydrogen is from natural gas via the processes of steam-methane reforming and partial oxidation [14]. However, hydrogen produced in this way is not clean and must be coupled with carbon capture and storage (CSS) to reduce the associated emission. Hydrogen is classified into the categories of green, grey, blue, brown and black hydrogen, with associated emissions increasing from green (zero emissions) to black (the highest emissions) (Ref [1] Chapter 11). Green hydrogen is made through the electrolysis of water using renewable energy sources.

To utilize this new green fuel, methods must be developed to store, distribute and deliver it to the users. Many of these methods have been in use in the US for some time. Storage methods that have been investigated in the US include physical based methods (compressed gas, cold/cryo compressed, Liquid hydrogen) and materials-based methods (Adsorbent, interstitial hydride, chemical hydrogen – e.g., NH3BH3) [15].

Hydrogen can be delivered to the user in various forms and by different means: as gaseous hydrogen through gaseous compression, pipelines and tube trailers; as liquid hydrogen, as novel hydrogen carriers, and stored on-site and in bulk storage [16]. It can be distributed by road via pressurized tubes and cryogenic trucks/trailers, and by pipelines in several forms [17].

Rather than establishing new pipelines for hydrogen delivery, an easier option is blending with natural gas in established natural gas pipeline networks.

This method of delivery presents several issues, including potential embrittlement of pipeline steel and welds, the control of hydrogen leaks and permeation, and the need for a reliable hydrogen compression technology.

These issues have been enumerated and reviewed by Singh [1] and Melaina et al. [18]. respectively.

The key findings by the latter are that:

- hydrogen can be blended with natural gas in low concentrations (5-15%(v/v))
- maximum blends not requiring modifications for end users of piped hydrogen lies in the (5-20%) range
- there are no major concerns for hydrogen-induced failures in steel and PVC pipes at normal pressures and stress levels in the natural gas distribution systems.

4.2. Biogas and Biomethane as Fuels for the Energy Transition

Two well-known gaseous energy sources in mainstream energy application today are biogas and biomethane (also sometimes known as renewable natural gas – RNG).

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Biogas consists of a mixture of methane and carbon dioxide, with biomethane comprising 40-75% of the mix. It is produced from agricultural, industry and municipal wastes through the process of anaerobic digestion and methane fermentation (Ref [1] Ch 4, 10).

The current biogas production utilizes only 1.6 – 2.2% of its global production potential [19]. In 2018, 61.1% of the total biogas production was used for power generation or Combined Heat and Power (CHP) plants, 27.3% for heating and cooking, and 8.6% for upgrade to biomethane.

Biomethane is produced from biogas via the processes of pressure swing adsorption (PSA), solvent scrubbing or water scrubbing of the carbon dioxide content.

How does hydrogen compare with other clean fuels? A case study is provided in Table I by comparing its performance with that of biomethane.

Table 1. Comparison of Hydrogen and Biomethane as Fuels for the Implementation of the Energy Transition**.**

Fuel Property	**Hydrogen gas**	**Biomethane gas**	**Comment**
Calorific value (MJ kg $^{-1}$)	141	55	Hydrogen has a higher calorific value than methane.
Density (kg m $^{-3}$)	0.09	0.716	But hydrogen has a much lower density – the need to compress hydrogen to obtain same energy yield.
Production	Electrolysis of water; steam-methane reforming + CCS	Anaerobic digestion + CO_2 removal	Biomethane production technology is well-known and more mature than that of hydrogen.
Transportation of fuel	Hydrogen pipelines, pressurised gas tubes and cryogenic tankers by road.	Pipeline or RNG tankers in liquid form.	Hydrogen blends cam be transported using existing natural gas pipelines. Biomethane easily transported using natural gas infrastructure.
Technology for use	Hydrogen fuel cells for energy storage and EVs.	Combustion engines, hydrogen fuel cells with external reformers.	Hydrogen fuel cells and regenerative hydrogen fuel cells mature/developing tech for road transport and grid storage respectively.

It is clear that while hydrogen is well suited as a clean fuel for the transition, biomethane is also able to provide most of the functionalities of hydrogen. It therefore provides an alternative fuel, particularly during the remaining lifetime of exisitng combution engine vehicles.

4.3. Hydrogen v Batteries

Hydrogen and batteries provide alternative means of energy storage. How do they compare?

As pointed out by Saul Griffith [20], hydrogen has a lower efficiency than batteries for energy storage and for powering EVs. However, a comparison of the roundtrip efficiencies of Reversible Hydrogen Fuel Cell (RHFC) (30%) and Li-ion battery (75-90%) shows that this disadvantage is offset by the similar return on investment (ROI) for the two technologies for storing overgeneration, in at least the case of wind energy [2]. As the roundtrip efficiencies of RHFCs improve through research and development, it is quite conceivable that these hydrogen-fueled energy sources will begin to compete favourably with Li-ion batteries in the foreseeable future.

One clear advantage of fuel cell-powered vehicles over BEVs is that the former do not need long recharging times, enabling long-distance vehicles to complete their routine operations with fewer

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refueling stops. Table II compares the strengths and weaknesses of the two technologies for grid and transportation applications.

Table 2. Hydrogen and Batteries: Strengths and Weaknesses**.**

Property/Sector	**Strengths and Weaknesses**
Energy Storage	Rechargeable batteries (Li-ion) provide scalable technology. They have good storage capacity, cycle life and calendar life for both grid storage and transportation applications. Hydrogen fuel cells have better energy densities than batteries.
Grid Application	Large-scale (200MW/400MWh) batteries are now available. Reversible Hydrogen Fuel Cells (RHFCs) for grid storage are still under development.
Transportation	BEVs (Li-ion) are the norm in EV transportation. But charging times are long (Shortest charging times of ~ 20 mins). - Need to establish charging networks nationally Hydrogen Fuel Cell EVs (HFCEVs) are suitable for long distance commercial vehicles (refuelling times ~ 5 mins). Higher energy densities of hydrogen fuel cells allow longer driving range and heavier payloads than for BEVs.

It is obvious that overall, hydrogen plays a complementary role to that of batteries in Australia's strategy to reduce emissions by 43% by 2030. With further development in technology, it is quite possible that the advantage that batteries have over hydrogen fuel cells may reduce even further.

5. The Race to Net–Zero

5.1. The Need for Urgent Action

Soon after the enactment of the Paris agreement, it became clear that global warming was not going to be contained within the required limits by the help of the existing NDCs at the time, and that more ambitious pledges had to be made by all Parties if the goals of the Paris Agreement were to be realised. The warnings emanated from several reports, two of which were the IPCC Special Report on 1.5 oC [21], and the Emissions Gap Report 2021 [22].

The IPCC Special Report on 1.5 oC was produced on 8 October 2018, and the key outcomes of the report has been summarised by the SDG Knowledge Hub [23] as:

'to be consistent with global emission pathways with no or limited overshoot of the 1.5°C goal, global net anthropogenic CO2 emissions need to decline by about 45 percent from the 2010 level by 2030, reaching net zero around 2050.'

This report was received with much concern at COP24 (Katowice, Poland), and was one of the first indications that the existing NDC pledges by the Parties of the UNFCCC were insufficient in meeting the desired goals.

Each year since 2010, the United Nations Environment Program (UNEP) produces a Gap Report relating to global emissions. This report estimates the gap between the future GHG emissions if all countries implemented their mitigation pledges (via their NDCs) and what the pledges should be to avoid the worst impacts of climate change.

The 2021 report, titled Emissions Gap Report 2021. The heat is on: a world of climate promises not yet delivered, [22] was published on 26 October 2021. Its ten findings are a cause of both concern and alarm. They show that the NDC pledges of the Parties fall far short of achieving the near-term (2030) target, and if business was allowed to proceed as usual, it would lead to a temperature rise of as much as 2.7 °C by 2050.

Evidence of the gap between the NDC pledges of the Parties and the actual emissions is abundantly clear when one considers the actual trend in global emissions over the last twelve years. This is shown in Figure 1.

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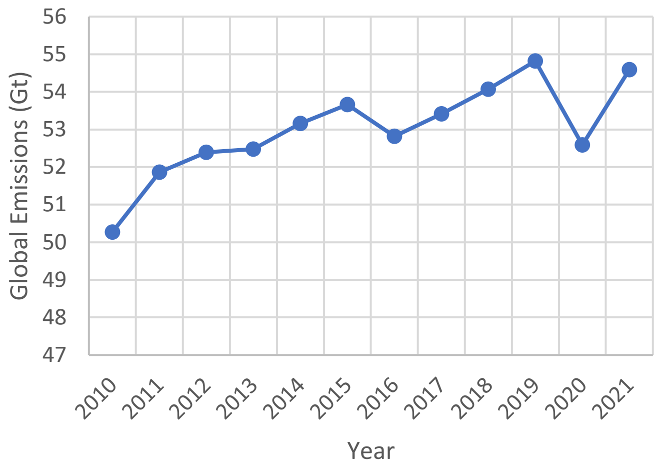

Figure 1. Global emissions (Gigatonnes) for selected years [24].

Apart from the small dip in 2020, the trend in global emissions has generally been upwards over recent years. The small decline in 2020 was caused by the economic impacts of COVID19, and is an anomalous exception

5.2. Technology Readiness for the Energy Transition

Will the EV strategies be able to meet the 2030 deadline?

For emissions from transportation to meet the 2030 target, all states must meet their EV targets on or before 2030. An overview of the deadlines adopted by the states indicates that this may not be achieved.

This creates the possibility of a technology gap, where combustion engine vehicles are phased out before electric vehicles are ready to replace them, leading to the non-achievement of the net-zero emissions by 2050 goal. As the Figure above indicates, emissions have not peaked yet (i.e. they are still rising), and we must wait for the peak before they begin declining towards net-zero.

Saul Griffith [20] demonstrates graphically (see his Figure 2.4) that the longer we wait for the peaking to occur, the sharper the required decline rate in the emissions will become for a 2050 target. This will inevitably lead to the need for drastic measures to achieve the required rates.

The consequences can be dire. The emissions reductions will mostly likely occur through reduced use of fossil fuels, leading to an unprecedented fuel supply shortage. As economies depend on fuel supply as a vital resource, this is likely to result in a global economic crisis that is more severe than ever before.

Bioenergy-powered combustion engines can act as a stop-gap measure to fill the technology gap under such circumstances. Renewable Natural Gas (RNG) is a “drop in” replacement for Liquid Natural Gas (LNG), and second-generation biodiesel together with Hydro-treated Vegetable Oil (HVO) are clean replacements for petroleum diesel. These fuels will be able to act as alternatives for gas and liquid fuel-driven combustion engines till EVs become fully market-ready.

6. Conclusions

Hydrogen has an important role in the implementation of Australia’s Net-Zero Strategy. This role has been actively promoted by Australia’s National Hydrogen Strategy, and through the recent $2 billion boost it received in the form of the Hydrogen Headstart Program.

Hydrogen plays a complementary role to batteries in road transportation and provides a viable solution to the impact of the (relatively) long battery charging times issue on the operation of long-distance commercial service vehicles.

Other bioenergy fuels such as biomethane, second generation bidiesel and HVO can also contribute strategically to the success of the energy transition. They may provide the needed temporary solution in the event that Australia is unable to meet its EV commitments by 2030.

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