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Clean energy futures: An Australian based foresight study

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ABSTRACT

Political decarbonisation commitments and outcompeting renewable electricity costs are disrupting energy systems. This foresight study prepares stakeholders for this dynamic, reactive change by examining visions that constitute a probable, plausible and possible component of future energy systems. Visions were extrapolated through an expert review of energy technologies and Australian case studies. 'Probable–Abundant' envisages a high penetration of solar and wind with increased value of balancing services: batteries, pumped hydro and transmission. This vision is exemplified by the South Australian grid, where variable and distributed sources lead generation. 'Plausible–Traded' envisages power and power fuel exports given hydrogen and high-voltage direct-current transmission advances, reflected by public and private sector plans to leverage rich natural resources for national and intercontinental exchanges. 'Possible–Zero' envisages the application of carbon removal and nuclear technologies in response to the escalating challenge of deep decarbonisation. The Australian critical minerals strategy signals adaptations of high-emission industries to shifting energy resource values. These visions contribute a flexible, accessible framework for diverse stakeholders to discuss uncertain energy systems changes and consider issues from new perspectives. Appraisal of preferred futures allows stakeholders to recognise observed changes as positive or negative and may lead to new planning aspirations.

1. Introduction

Energy markets have been relatively stable since the oil crisis of 1973 but now face a fundamental change as the world shifts from fossil fuels to renewables. Political commitments and falling costs are driving the rapid uptake of solar and wind technologies. In 2020, renewables accounted for 82% of new capacity, 90% from solar and wind (Fig. 1AB) [1]. Net-zero targets already cover three-quarters of all emissions from countries representing half the world's gross domestic product (GDP) [2, 3]. Irrespective of this, further uptake of solar and wind will be propelled by exceedingly low levelised costs of electricity (LCOE) and virtuous market cycles (Fig. 1C) [4–7]. The variable and distributed generation, with nearly zero marginal costs, is disrupting energy systems. The lack of historical precedence creates forecasting challenges.

Numerous forecasting studies have modelled future energy systems, with at least 180 research articles on 100% renewable energy system design [11]. Forecasting studies often define expected future scenarios that enable precise, quantified modelling under certain assumptions. This approach serves many essential purposes, such as demonstrating technical and economic feasibility and outlining requirements to realise those scenarios [12–16]. However, simplifying assumptions may limit the scope and produce inflexible findings that diverge from reality over time. This divergence is pronounced for rapidly evolving energy systems that depend on economic, social, political and technical changes [17]. Foresight provides a novel planning approach for systems facing these uncertain changes, complementing the predominant forecasting approach in literature.

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Abbreviations

ACT	Australian Capital Territory
AC	Alternating current
DC	Direct current
FCAS	Frequency control ancillary services
GDP	Gross domestic product
HVAC	High voltage alternating current
HVDC	High voltage direct current
LCOE	Levelised cost of electricity
NSW	New South Wales
NT	Northern Territory
PV	Photovoltaics
QLD	Queensland
TAS	Tasmania
VIC	Victoria
VRB	Vanadium redox flow battery

The roots of foresight lie in the military, a profession that must build scenarios for even the most unlikely events given the reactive and dynamic environment and potentially dire consequences. Foresight gained broader recognition after successfully preparing Royal Dutch Shell for the dramatic oil price increases before the oil crisis of 1973. Design futures is now an active research field with many techniques, although application in technical fields is less common [18–20]. For this foresight study, the future cone concept (Fig. 2) helps define the scope and purpose of foresight compared to forecasting.

Forecast scenarios usually focus on futures judged as most likely (probable futures). They are often built on the assumption that the future will be an extension of the present with little significant change. Foresight visions expand the scope to include other reasonable extensions of current trends and understanding (plausible futures*)*. Foresight studies may also address other conceivable futures with uncertain likelihoods (possible futures).

The broader scope of foresight is possible as studies do not create numerical models for predicted scenarios. Instead, foresight futures are represented in an approachable and engaging form, such as a graphical rendering or descriptive narrative. This format is intentionally engaging and accessible, serving as a common platform for diverse stakeholders to discuss potential outcomes. When preparing for the future, the brain uses these future visions like real memories, which allows stakeholders to consider current issues from new perspectives [23]. Appraisal of preferred futures may also lead stakeholders to new aspirations when planning, and allow recognition of observed changes as positive or negative [24].

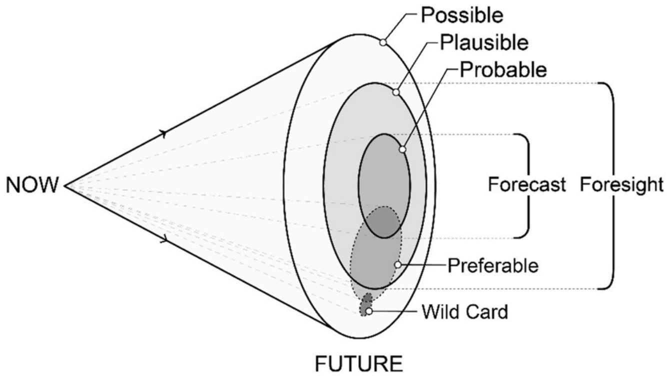

Fig. 2. The *future cone* defines: 1) *Possible* futures include anything we can imagine, such as science-fiction dreams, which may fail to seriously engage the audience, and *Wild Card* events like a global pandemic or outbreak of war. Systems should be flexible enough to adapt to these events. However, it is not feasible to prepare for all possible events with limited resources 2) *Plausible* futures are logical extensions of current trends and understandings 3) *Probable* futures are a subset of plausible futures, considered likely outcomes based on an appraisal of the current trends and understanding [21,22].

This foresight study aims to prepare stakeholders for uncertain changes to energy systems by examining broad future possibilities, derived from an expert-led review of clean energy technologies and Australian case studies. These futures enhance planning through a comprehensive analysis of trends, and by providing a framework for diverse audiences to openly discuss possible future outcomes rather than try to predict them.

2. Methodology

Subject matter experts reviewed clean energy technologies. Fossil fuel technologies were not reviewed. Given the broad scope and foresight purpose, these reviews focused on discerning high-level trends instead of providing an in-depth survey of individual studies. Other reviews which serve this purpose are referenced throughout. The characteristics of each technology are discussed, including drivers and barriers to future growth. Experts were drawn from complementary technological fields to provide a more balanced, interdisciplinary assessment [25–27].

Case studies were used to substantiate technological trends and consider the contexts in which they will be deployed. As grids become increasingly decentralised and flexible, these local contexts (commercial, political, social and technical) will become increasingly important [28,29]. Case studies were selected based on their level of advancement and potential impacts, as these leading cases may signal broader future change. Preference was also given to cases highlighting features unique to Australia and of interest to a global audience. Australia is an island nation in the Asia Pacific Region with rich natural resources, fossil fuels and renewables. Further context for the region is provided in Fig. 3 and throughout the study.

Futures were extrapolated from the clean energy technology and

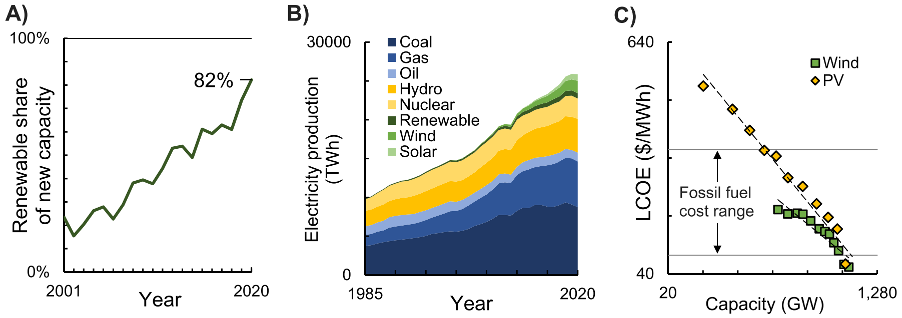

Fig. 1. A) Renewables share of new global energy capacity (261 GW - 2020) with solar contributing 127 GW and wind 111 GW. B) Global electricity production by source [8] C) LCOE learning rates for utility-scale solar PV and wind were 39% and 32% from 2010 to 2020 [9,10].

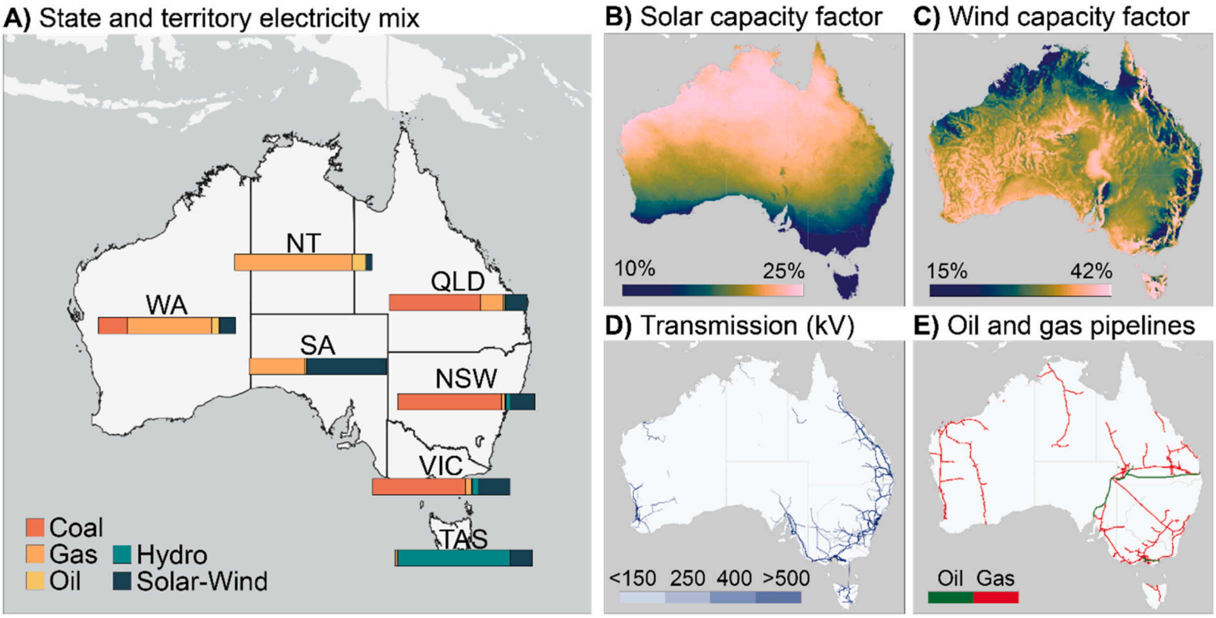

Fig. 3. Geospatial energy information for Australia. A) Electricity generation mix for Western Australia (WA), Northern Territory (NT), Queensland (QLD), South Australia (SA), New South Wales (NSW), Victoria (VIC) and Tasmania (TAS) [30]. The Australian Capital Territory (ACT) has been omitted but sources 100% of electricity from renewable generators, mainly secured via a reverse auction process [31] B–C) Capacity factors for solar and wind (150 m), noting climate limits application of district heating to niche location [32] D) Electricity transmission network (kV) [33] E) Gas and oil pipelines [34].

case study reviews, as categorisations of the current trends and expert understanding, the iterative process outlined in Fig. 4. The categorisation approach limited the risk of conjecture by grounding futures in existing evidence. Futures were not classified as preferred to avoid framing effects for the audience. The futures retained some inextricable relationships due to technology interdependencies. Therefore, presented futures should be considered a potential component of the future rather than a mutually exclusive outcome.

This paper is structured under three futures: Abundant, Traded and Zero. Technology reviews and case studies are then structured under these three futures, depending on which is most relevant. The sub-structuring of technology reviews and case studies aim to substantiate each future rather than provide a sub-component or further definition of that future. Additionally, technology reviews and case studies should not be considered exclusively to each future, as they may have relevance to other futures. Each future is judged as probable, plausible or possible, which applies only to the future and not the technology reviews and case studies structured under them. The futures presented by this study represent one valid solution to the described method; they do not encompass all possible solutions or all potential futures outcomes. The broad scope of this study limits the depth of certain technological discussion, such as smart energy systems.

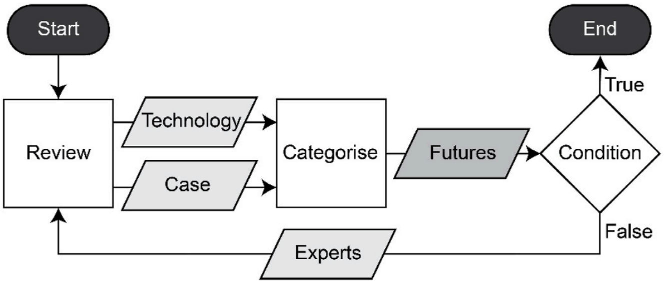

Fig. 4. A) Futures creation process where the feedback condition was whether the futures were clearly defined, realistic and encompassed significant trends and understanding identified in the technology reviews and case studies, as evaluated by the contributing experts.

3. Probable future component: *abundant*

The *Abundant* future envisages a high uptake of solar and wind, with balancing services being increasingly valued (Fig. 5). Given current commercial deployment and technological maturity, this vision is judged to constitute a *probable* component of future clean energy systems.

From 2010 to 2020, the LCOE of solar photovoltaics and on-shore wind has dropped by 85% and 68%, respectively [9]. Recent auction bids have hit record lows for both solar (0.011 €/kWh) and wind (0.020 €/kWh) [35,36]. Although renewables only accounted for 10% of global capacity in 2020, they accounted for 82% of new capacity expansion [1]. Virtuous cycles are expected to drive further cost reductions and

Fig. 5. A graphical representation of the *Abundant* future. A high mix of solar and wind with balancing services from hydro, gas, batteries, demand side management and transmission at utility and distributed scales.

deployment in markets. The growth potential of this positive feedback loop has been recognised in previous studies [5] and reports [37–39].

As the mix of solar and wind increases, so will the importance of low-emissions balancing technologies such as batteries and pumped hydro. Solar and wind provide the majority of generation in South Australia, often peaking above 100% for hourly periods [40–42]. The state demonstrates the feasibility of servicing a variable, distributed grid using gas generators, interstate transmission and batteries.

3.1. Technology: solar

Solar PV offers some of the lowest electricity costs in history, with high learning rates (40%) reducing the LCOE by 90% between 2010 and 2021 [4]. Virtuous cycles will drive further growth (lower costs make solar competitive in new markets, with increased deployment then reducing costs through economies of scale and learning effects [43]. As of 2020, solar PV contributes a small portion (3.2%) of global electricity generation [8]. However, newly installed capacity has doubled every two years, with solar accounting for 40% of new capacity in 2020 (127 GW). Continuation would result in high penetration of solar PV [5,44].

Current grid balancing services are strained by the penetration of intermittent solar PV, particularly in high latitude regions with lower solar insolation and higher interseasonal variation. Energy storage technologies may supplement or replace traditional fossil fuel, nuclear and hydroelectric generators for balancing [45,46]. Oversizing generation capacity, and hybridising with anti-correlated wind and demand management may also alleviate imbalances [47]. Also, the potential of these balancing services may be increased by expanding interregional transmission [48,49].

The distributed nature of solar PV presents opportunities and challenges. The modularity opens residential and commercial markets, which accounted for 31% of new solar capacity in 2021 [50]. Decreasing costs promote bottom-up solutions suited to local contexts and stakeholders [48]. Panels are also advantageous for electrifying off-grid communities in remote and developing regions [51].

Widespread uptake of solar PV creates scaling challenges. Waste from panels could reach 29 Mt by 2058 [52]. Significant demands may also be placed on raw materials, such as aluminium, copper and indium [35]. New cell technologies may counteract these issues [53,54]. Reskilling of labour forces is also required, although increased job opportunities provide a political incentive [55,56]. Space requirements may constrain deployment in some nations, with floating solar power and interregional transmission potential solutions. Many other financial, political and production systems will also need to scale [5,55,57]. Electrification of transport, building and industry sectors will be essential to foster long term growth of solar PV [58]. Despite scaling challenges, widespread deployment will be driven by falling costs and mounting global emissions targets.

3.2. Technology: wind

Falling costs and accumulating emissions targets are driving the deployment of wind farms. In 2020, wind accounted for 35% of new generation capacity after the LCOE fell by 39% between 2010 and 2019 [1,9]. Wind now accounts for a moderate share of global capacity (5.9%) [8]. Further growth depends on technological advances that reduce system costs and support integration of this variable and highly visible energy source.

Like solar, approaches for mitigating intermittent generation include dispatchable generators, energy storage, interregional transmission, oversized capacity, hybrid wind-solar and demand management. However, wind generation is not limited to daytime hours as solar.

Increased wind penetration requires improved forecasting to ensure grid reliability and resilience [59], with self-forecasts are already required for systems above 30 MW in Australia [60]. Better forecasts require an improved understanding of flow interactions between the atmospheric boundary layer and wind farm structures and terrain [61]. Flow understanding will also reduce system costs through design optimisations, including blade profiles and material choice [62].

The wind industry aims to reduce system costs via larger turbines (capacity, rotor diameter and hub height) and LCOE through more flexible structures that can reach a lifetime of 20 years or more [63]. Larger turbines create challenges, such as insufficient wind tunnel sizes and blades bending into support structures. The enormous structures also strain manufacturing supply chain capabilities.

Off-shore sites may reduce wind energy costs through superior resource quality; more consistent and faster wind speeds. Estimates put 90% of potential on-shore resources below a capacity factor of 30%, while 67% of potential offshores resources are above this [64]. Offshore turbine capacities also tend to be larger. Vestas released production plans for a 15 MW offshore turbine in 2024, with a rotor diameter of 236 m [65]. The size and resource quality mean the average capacity factor of offshore systems (43.6%) is higher than on-shore systems (35.6%). Although, average electricity costs are still more than twice as high for off-shore farms due to increased transmission, support structure and maintenance costs [66]. In any case, off-shore capacity growth of 11.8 GW is expected in 2021, from 31.9 GW installed at the end of 2020 [67].

Many emerging wind energy technologies have garnered interest, including turbine components, alternative support structures, active and passive smart rotors and modular generator concepts [62]. Floating offshore wind has potential, demonstrated by the Hywind farm in Scotland since 2017. Airborne systems with tethered kites eliminate support tower costs and access increased wind potential in the higher atmosphere [68]. Unlike floating offshore, airborne systems lack commercial trials.

Wind farms are extremely visible, and face social and ecological barriers. The criticality of these barriers depends on local contexts. However, common risks include the number and height of turbines and proximity to residents [69]. Turbines can disrupt wildlife, habitat and the physical landscape or communities through competing land use, noise, aesthetics and otherwise [70–72]. Social strategies can alleviate these risks, such as community ownership and engagement [73]. Technical solutions also exist, such as reducing blade noise or deterring bird flight paths [72]. Stakeholders should account for these risks during all stages of development for wind energy.

3.3. Technology: batteries

Falling costs are making batteries competitive for an increasing number of energy storage applications [45,74]. Lead-acid has established markets for automotive batteries ($25 billion) and industrial standby for critical services ($10 billion) [75]. However, lithium-ion has emerged as the leader for high-power large scale battery storage, representing 90% of installed capacity in 2019 [76].

Megawatt scale lithium-ion is becoming common. The world's largest lithium-ion battery (300 W/1200 MWh) was connected in California in late 2020 [77]. These utility-scale systems followed increased production from electric vehicle manufacturing, with learning rate cost reductions of 14–30% between 2010 and 2019 [78]. These utility-scale systems provide grid services such as peak displacement, frequency regulation and short duration energy arbitrage [76]. However, limited capacity means alternative storage technologies are preferred for periods beyond a threshold of around 4–6 h [45,76,79].

Battery modularity opens distributed energy storage markets. Behind-the-meter applications (residential, commercial and industrial) accounted for 48% of new capacity in 2019; with system services (10%), transmission and distribution (17%), arbitrage and peak support (21%) and other (3%) providing the rest [80]. Rooftop solar promotes behind-the-meter batteries, such as in Australia, where a quarter of homes have rooftop solar [81]. Battery deployment may also be driven by virtual power plants, which aggregate distributed energy resources [82].

Vanadium redox flow batteries (VRB) may enable longer-duration storage than lithium-ion [45]. VRB differs fundamentally from conventional batteries by decoupling capacity and power. VRB could enable longer lifetimes (25 years) given adequate maintenance such as electrolyte rebalancing to eliminate capacity fade [83,84]. VRBs are also more readily recyclable and avoid lithium-ion fire risks. However, scale is lacking with commercial systems (100 MW/500 MWh) planned following smaller-scale demonstrations (2 MW/8 MWh) [85,86]. Modular, easy to install VRB are also under development [85,86]. Given adequate development, VRB suits commercial projects with longer-duration and high-cycle rates across the full depth of charge [45]. Noting the diversity of service requirements suggest various energy storage technologies will find applications [79,87].

Battery uptake depends on technology cost reductions, integration and application improvements [78,88,89]. Goodenough, Whittingham and Yoshino were awarded the Nobel Prize in Chemistry for pioneering lithium-ion work and remain involved in organic compounds for electrolyte exploration [90] and electrode materials for intercalation research [91]. VRB research investigates electrolytes and hybrid systems and organic compounds for abundant, low-cost electrolytes [92]. Advances in material science and chemistry show the most promise for step-changes in technology, for higher power-densities, lower costs and longer lifetimes. Advancements may also reduce dependence on critical minerals; for example, the geographical concentration of lithium and cobalt present geopolitical risks [35,93].

3.4. *Technology: pumped hydro*

Pumped hydro is a mature long-duration energy storage solution that provides about 96% of global storage capacity [94]. Pumped hydro cannot respond as quickly as batteries ($<$10 s). Therefore, the technologies present complimentary solutions over long (hours to days) and short (sub-seconds to hours) timescales [45]. Pumped hydro has established daily storage uses (18 h), such as storing excess midday solar and overnight wind. Pumped hydro also supports grid security. For example, it may increase generation during a heatwave or provide black-start capabilities after a severe storm. Pumped hydro also has the potential to serve seasonal storage needs [95].

The feasibility of pumped hydro projects is geographically dependent. Most suitable on-river sites have been developed, with only 37% of the world's largest rivers ($>$1000 km) remaining free-flowing [96]. Projects must manage potential impacts from damming waterways, such as disrupting ecological processes and community/commercial services [97]. Off-river sites may circumvent these issues.

Potential off-river sites are abundant. A recent study identified 3000 sites in Australia, with a theoretical capacity of 163 TWh [98]. Off-river sites typically have increased head than on-river sites, increasing power and storage capacity at an equivalent size. Off-river sites often lie outside catchment areas which reduces flood protection infrastructure costs. However, the source, transport and maintenance of water increase cost and project complexity [99]. The transmission costs of each site must also be considered [100]. Given rigorous feasibility studies, off-river sites present expansion opportunities for pumped hydro energy storage.

Due to their scale, pumped hydro projects are capitally intensive and take several years to plan and construct, with project requirements often underestimated. For example, Snowy 2.0 in Australia is expected to take seven years to complete, with costs increasing from $4.5 billion to $5.1 billion [101]. These figures should be considered relative to the massive scale (2 GW/350 GWh gross). Long-lifetimes may also increase perceived investment risk (40–60 years) [79]. Governments may implement supporting policies, given unmatched storage capacity and the increasing mix of variable renewable generators [40,100].

3.5. *Case: south Australia leading uptake of solar and wind*

The rapid penetration of solar and wind in South Australia (SA) demonstrates the feasibility of broader uptake. SA transformed from 0% to 50% renewable generation in 10 years (2006–2016) [41,42], with solar and wind generating 61% of electricity demand (13.9 TWh) between July 2020–2021 (Fig. 6). SA is tracking towards 100% net renewable electricity generation by 2030, the market operator estimating it may achieve this five years earlier [40,102].

Solar and wind often exceed state demands for hourly periods (Fig. 6B) and have exceeded average daily demand December 6, 2020 (106.6%). Solar alone exceeded 100% of local demand from 12:30–1:30 p.m. on October 11, 2020, with 77% from rooftop systems [103]. During this period, gas-fired generators were still running to maintain grid stability. The bulk of excess power was not stored but exported to the neighbouring state VIC. This complimentary state demand may not always exist.

A few months later, interstate demand dropped to record lows due to a planned outage of the Heywood interconnector. Consequently, the market operator reduced around 12,000 solar customer's supply to increase net demand by 60 MW [104]. A few days earlier, several factors, including a fire near a switching yard, prompted the market operator to switch on additional gas power to avoid load shedding blackouts. Recently, time-of-use tariffs have been used to manage solar peaks [103]. Besides gas generators and interconnectors, batteries have also provided critical grid services in SA.

The Hornsdale Power Reserve (150 MW/194 MWh) recently lost the world's largest battery title. Nevertheless, analysts estimate construction costs ($96 million) were recouped in just over two years of operation [105], partly due to a separation event where SA batteries received some $50 million from frequency control ancillary services (FCAS) [106]. The success of this project laid the groundwork for a larger project in VIC (300 MW/450 MWh) and one in NSW (50 MW/75 MWh) [107,108], with SA planning a flow battery demonstration plant (2 MW/8 MWh) [109,110]. The commercial feasibility of batteries has been demonstrated in Australia's national electricity market, generating $12.8 million of revenue in the first quarter of 2021 through FCAS (78%) and energy arbitrage [111].

Policy in SA has driven renewable uptake. Early projects were established in Port Augusta, attracting federal funding with rich wind resources and a transmission line to Adelaide city. Later state policies supported wind farms distanced from residents, and government supply contracts often underwrote projects. Additionally, the state did not subsidise coal-fired plants as they became unprofitable but did provide grants for disrupted workers, such as the solar-greenhouse project, which employed around 220 people [112].

SA renewable energy policies have faced criticism from federal politicians and the public, often blamed for price increases and blackouts between 2014 and 2018. During this period, a consistent state government party helped renewable projects establish. This criticism has subsided, with the state government now having ambitions of up to 500% renewable generation by 2050, compared to current local demand [102]. The market operator is also preparing grids to run at 100% instantaneous penetration of renewable energy by 2025 [113]. The state government aims to become a national and international exporter of clean energy, projecting low renewable electricity costs, which attract power-hungry industries such as data centres or hydrogen producers [114–116]. Government policies have also promoted the bottom-up growth of distributed renewable resources.

Three-quarters of SA's solar comes from rooftop systems [117], with 3 GW of new rooftop installations in Australia in 2020 [118]. Residents with rooftop solar and batteries are taking increasingly active roles in the grid, with around 14 virtual power plant projects in Australia [119]. Tesla is expanding a project in SA to 4100 solar-battery homes, with visions of up to 50,000 [120]. Other residents take roles via new business models, such as cooperative ownership of neighbourhood batteries

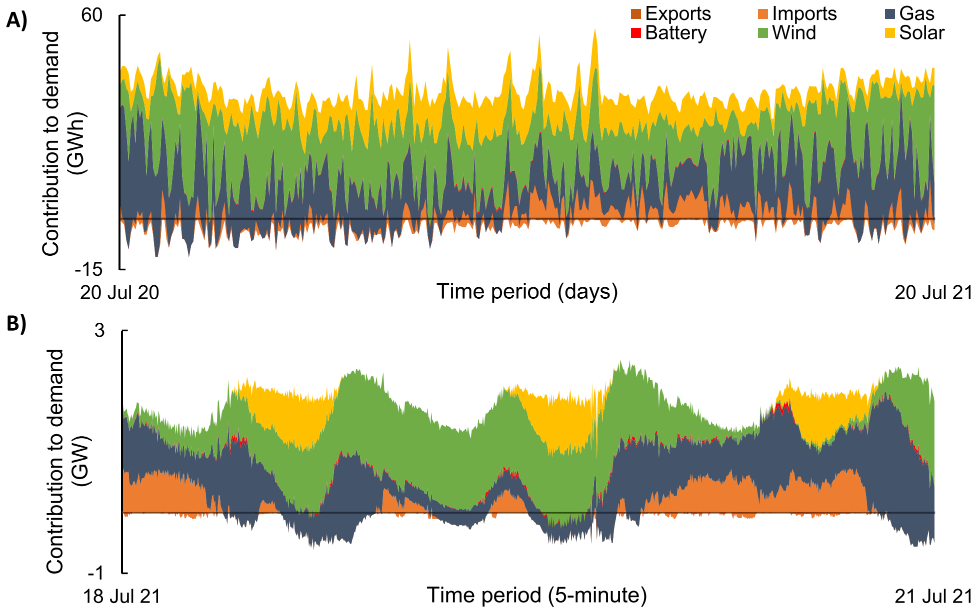

Fig. 6. A) SA yearly energy mix where solar and wind met 61.6% of state demand: rooftop solar 14.5%, utility solar 4.8%, wind 42.3%, gas 36.2%, battery discharging 0.6%, battery charging −0.8%, transmission imports 8.7% and transmission exports −7.2% [42]. B) SA energy mix of three days, solar pushing demand into evenings with gas and transmission balancing variability.

and solar farms [121,122]. Renewable cost reductions are also driving deployment in non-residential sectors, such as: hospitals [123,124], desalination plants [125], agriculture [126] and telecommunication sites [127].

There are other smart energy systems that may support grid stability [16,128–130], such as demand side management for mitigating impacts of distributed energy resources [131–133], noting a lack of policy support has seen limited uptake of electric vehicles in Australia compared to other nations [134].

4. Plausible future component: *traded*

The *Traded* future envisages the emergence of power and powerfuel export markets, with hydrogen and direct high-voltage current (HVDC) transmission as national and international energy carriers (Fig. 7). Given limited commercial deployment and technological maturity, this vision is judged to constitute a *plausible* component of future clean energy systems.

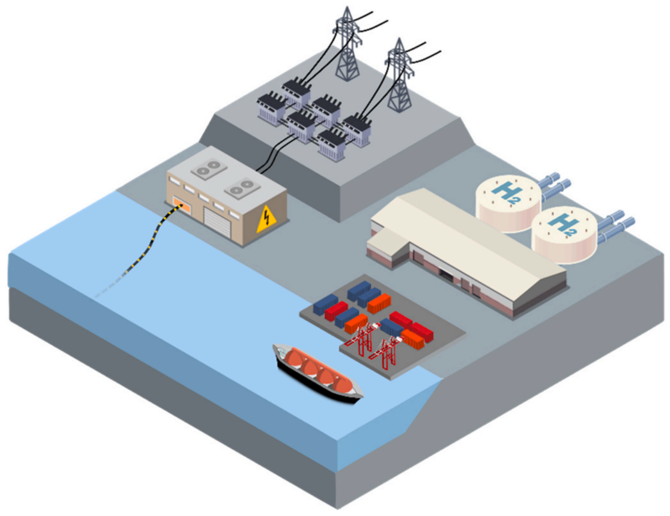

Fig. 7. A graphical representation of the *Traded* future with new power and powerfuel export opportunities as nations shift from fossil fuels to low emission alternatives, enabled by hydrogen, bioenergy and HVDC technologies.

Hydrogen is experiencing a surge of commercial and political interest as a clean energy carrier, with 30 national strategies, more than 228 announced projects and USD 70 billion in public funding [3]. A national strategy may establish Australia as a hydrogen economy, given rich renewable resources and Asian trade partnerships [135,136]. However, hydrogen faces significant challenges in storage, transport and production costs. HVDC may enable flexible, long-distance connections which transform power exchanges on national and perhaps intercontinental scales [100,137]. The Australian mainland has tapped into Tasmania's hydroelectric resources for years via a 370 km HVDC submarine cable, with planned and proposed network expansions to form a national supergrid, and perhaps connecting with east Asia.

4.1. *Technology: hydrogen*

Hydrogen is gaining political and commercial support as a low-emissions fuel alternative for hard to abate sectors. Long-haul transport, chemical processing and iron/steel production account for 18.3% of global emissions [138,139]. Over 30 countries have already developed hydrogen roadmaps, backed by $70 billion in public investments [3]. However, significant challenges remain in scaling production and distribution, and expanding applications.

Hydrogen has established markets: oil refining (33%), ammonia production (27%), methanol production (11%) and steel production (3%) [138]. Almost all this hydrogen is produced using fossil fuels [3]. Green hydrogen is produced by splitting water in an electrolyser using low-emissions electricity. Hydrogen may penetrate new markets (transport, building, power generation and industry) given advancements to storage and transport both regionally and internationally.

Compression and cryogenic storage may solve transport issues. However, these methods require complex infrastructure and incur significant energy losses: liquefication 40% and compression 10% [140]. Alternatively, hydrogen may be converted into commercially traded vectors such as ammonia, methanol or methane. These powerfuels have established infrastructure and are safer to transport over long durations and may be generated by combining hydrogen with nitrogen or waste carbon dioxide using mature conversion technologies.

Even with carbon prices, hydrogen costs must be reduced from $5.4/kg to less than $2.0/kg to compete with fossil fuels [3,141]. Electricity accounts for the largest share of hydrogen production costs, so the falling costs of renewables support production cost reductions [142]. Electrolysers account for the next highest share, and costs here also decrease as production ramps up due to economies of scale and learning effects. As a result, several projections put costs below $1.0/kg in favourable regions by 2050 [3,138,141,142]. However, significant research and development is required to achieve these long term estimates [143].

Emerging technologies include direct ammonia synthesis, high-temperature electrolysis, hydrogen peroxide production and hydrocarbon formation through electrolysis [144]. Further work is justified given hydrogen's unique advantages in substituting fossil fuels.

4.2. Technology: bioenergy

Humanity's use of bioenergy precedes recorded history [145]. Traditional biomass such as wood and dung is still burnt for cooking and heating in developing countries, with adverse health and environmental impacts. Modern biomass improves efficiency and safety and accounts for roughly one-tenth of global primary energy supply [146].

Key processes include biochemical conversion (composting and fermentation) and thermochemical routes for liquefaction and gasification (pyrolysis and combustion) [147]. Wood combustion and charcoal production are well-understood for high-temperature heat. Biogas (anaerobic digestion) and biomethane (methanation) provide an opportunity to utilise organic waste for carbon-neutral natural gas substitutes [148]. Likewise, liquid biofuels from crop waste deliver renewable methanol and ethanol for transport fuels through distillation and synthesis. Modern bioenergy overlaps with other forms of Power-to-X, both with output products such as powerfuels [149] and integrated processes which lower energy input for hydrogen production, such as biomass electrolysis [150,151].

The utilisation of waste products for fuel production presents an opportunity for bioenergy.Early adopters include Denmark for solid biomass and transport fuels [152–154], Brazil for biofuels [155] and China for energy-from-waste [156]. A national roadmap may help grow the small bioenergy market in Australia [157]. Concerns remain around biomass sources, which can compete with food production or result from unsustainable land and water use. Pollution from the process, including combustion, makes bioenergy's sustainability a more complex and controversial topic. Bioenergy is expected to play an essential role in the global energy mix with appropriate regulation and technological innovation [158].

4.3. Case: Australia's hydrogen export opportunity

Rich solar and wind resources make Australia a prospective hydrogen economy, as electricity represents the highest production cost for green hydrogen. Other countries also possess high renewable resources, such as Chile [3]. However, Australia may benefit from trade partnerships.

Australia has recently committed to early hydrogen trade agreements with Germany and Japan [159,160]. Countries in East Asia such as Japan, Korea and Singapore represent an export opportunity for Australia, which could import up to 42% of regional supply by 2040 [161]. This potential has been targeted by Australian government policies at state and federal levels.

Domestic scenario modelling suggests hydrogen could suggest hydrogen could contribute up to $11–26 billion to Australian GDP and create up to 8000–16,900 jobs [136,162]. The national hydrogen strategy has committed about $1.5 billion to hydrogen and supporting activities, targeting ambitious prices below $2/kg [163]. However, most projects remain small-scale. As of May 2021, 61 projects were in Australia. The largest of the five projects in operation is the Hydrogen Park in SA at 1.25 MW. However, larger projects have been awarded funding for ammonia production and natural gas blending by 2024 [163].

The government research agency has recognised the storage and transport advantages of ammonia [164]. Several industry groups are developing ammonia projects (Yara, QNIP Nitrates, Origin, BP, Fortescue) [165–168]. Other projects target ammonia exports (Western Green Energy Hub, Murchison Renewable Hydrogen Project and Eyre Peninsula Project) [169,170]. The government is also investing in hydrogen hubs, following IEA recommendations [138,171]. These hubs include industrial ports of Darwin NT and Newcastle NSW, attracting $345 million of public funding [172–174].

4.4. Technology: DC transmission

DC systems may enable longer, more flexible network connections [137,175,176]. DC systems typically require higher initial investment than alternating current (AC) systems due to substation costs. However, power line capacity and distance are not limited by reactive power consumption or the skin effect. Therefore, HVDC suits long distances, breaking even with HVAC around 300–800 km for overhead lines and 50–100 km for offshore and underground cables [175,177]. HVDC can also connect asynchronous zones, unlike HVAC, allowing regions with different grid frequencies to share resources [137]. HVDC flow control improves the management of intermittent, distributed generators. DC systems based on voltage source converters can provide grid support functions such as frequency support or black start. However, DC system complexity poses operational reliability challenges, especially as system power and size increase.

Technological advances are required to expand large-scale commercial applications of DC systems. Cables remain expensive and require optimisation for higher voltages; the highest-rated overhead HVDC lines are 1100 kV while cable ratings reach 640 kV. Semiconductor device research may expand power transfer capabilities while lowering overall losses [178]. Circuit breakers require further development for feasible large-scale adoption [178]. Conversion between DC voltages at higher power remains problematic; modular converters and modern materials may overcome these issues [179,180]. Multiterminal networks require cables and grid protection innovations, while management between multiple vendors presents logistical challenges [137,175]. Flexible medium and lower voltage DC systems may support the uptake of distributed energy resources, presenting solutions on peer-to-peer trading and local microgrids [181,182].

4.5. Case: Australia's prospective supergrid

Australia's longitudinal transmission network suits the integration of long-distance HVDC, with most major cities close to the coastline of the vast landmass (Fig. 8). Australia was an early adopter of HVDC, with Terranora in 2000 (63 km) and MurrayLink in 2002 (180 km). In 2016 Basslink (360 km) connected the island state of Tasmania (TAS) with the mainland via a submarine cable. This link allowed the national electricity market to benefit from abundant hydroelectric resources (Fig. 9).

The Battery of the Nation projects aims to establish TAS pumped-hydro sites as low-cost energy storage for the mainland [186,187]. The project includes a second HVDC line to the mainland (MarinusLink – 250 km) and a new pumped hydro site to bolster storage (Lake Cethana 0.6 GW/6.7 GWh) [183,188]. This transmission and storage infrastructure will enable exports from utility-scale wind farms from resource-rich regions of north-western TAS (Granville Harbour 112 MW) and provide other ancillary services. For example, the infrastructure mitigates the risk of events like the Basslink outage in 2016 [189], and provide balancing services through coordination of generation, storage and demand.Other network expansion could enable states, besides VIC, to benefit.

Planned network expansions from the national market operator aim

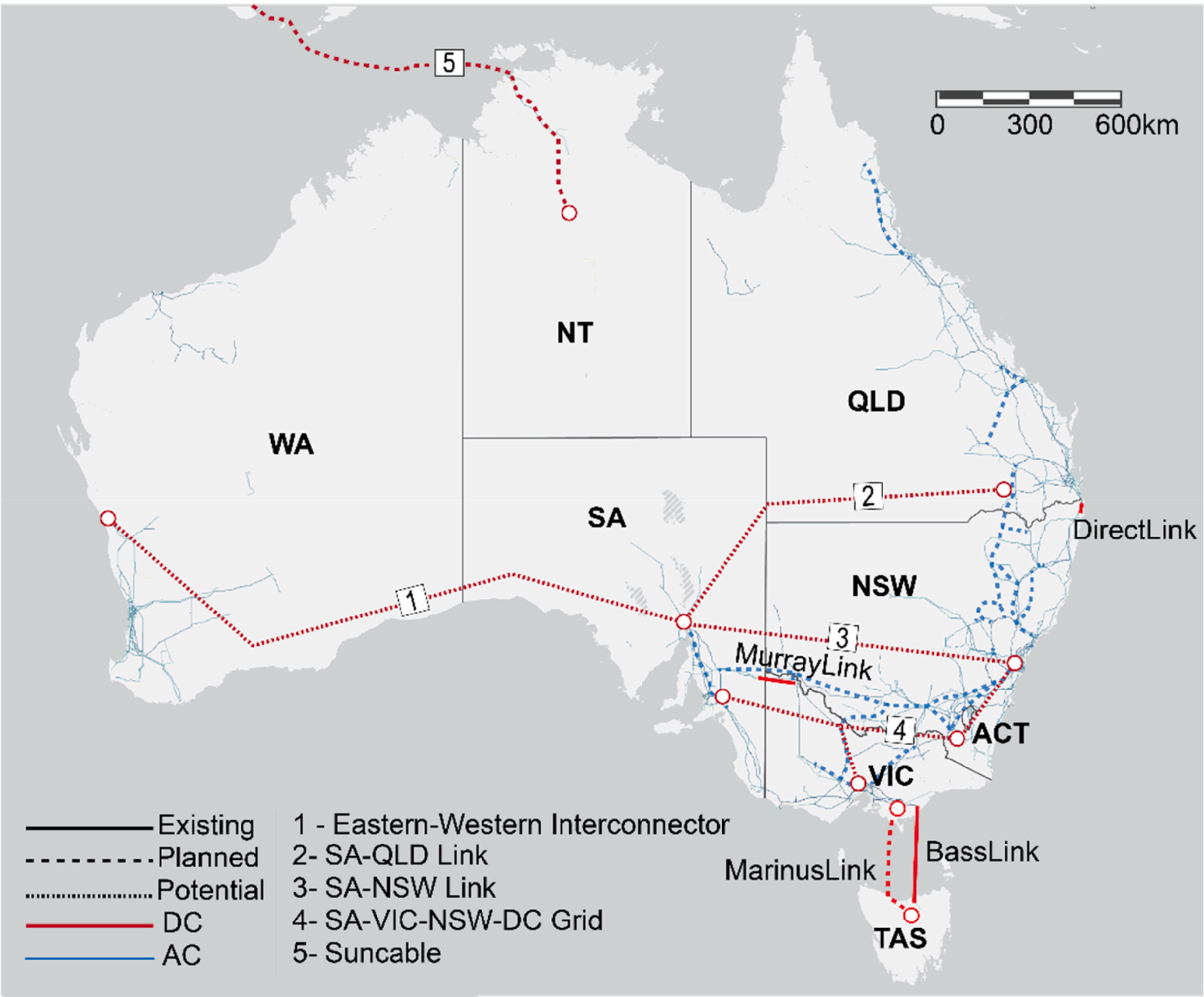

Fig. 8. Australian electricity network expansions from the market operator [183] and HVDC studies [100,184,185], with potential lines to offshore wind not shown.

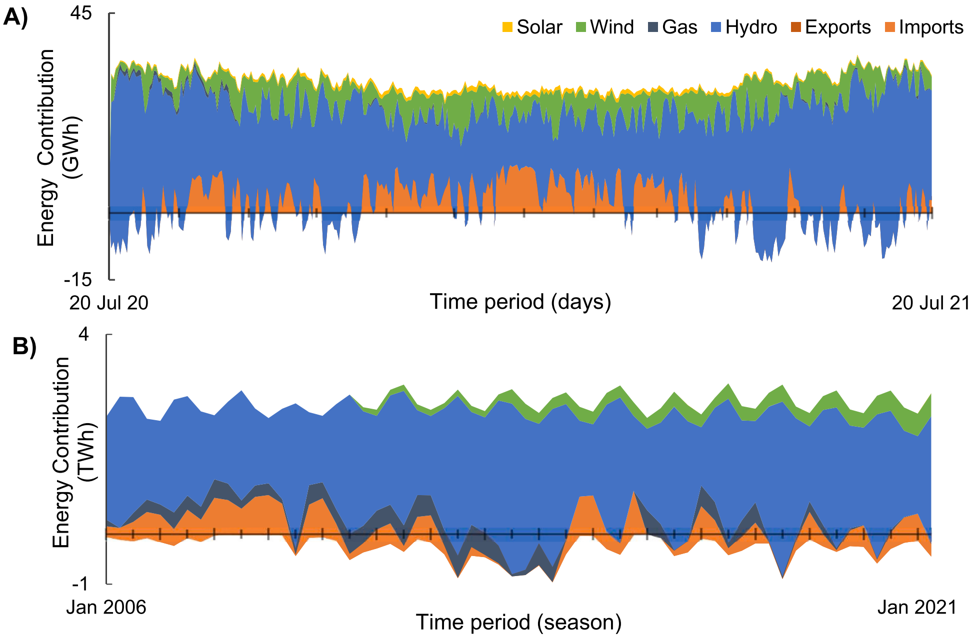

Fig. 9. A) TAS yearly energy mix with demand met by solar (2.0%), wind (16.3%), hydro (75.4%), gas (0.7%), exports (−9.6%) and imports (15.2%). For imports, renewables contributed about 29% of total generation in VIC and the national electricity market over the same period [42]. B) TAS seasonal energy mix.

to improve interstate connections and access to utility-scale renewable sites (Fig. 8) [183]. MarinusLink is the only HVDC project planned. However, other supergrid expansions have been proposed to leverage long-distance cost-effectiveness (Fig. 8) [175]. Previous studies have estimated that renewable storage requirements could be reduced by up to four times when modelling seven independent grids and one supergrid [100]. Besides national expansions, technological advances may enable intercontinental connections.

The Sun Cable project proposes an Australia-Singapore connection involving a 3750 km HVDC submarine cable and 750 km overhead transmission to export electricity from a solar (14 GW) and battery (3 GW/33 GWh) facility in Darwin [190]. These long-term, long-distance connections are technically complex and have uncertain costs due to political considerations of cross-border energy flows. For perspective, VikingLink is the longest cable currently under construction, spanning 770 km between the United Kingdom and Denmark [175]. HVDC could enable national or intercontinental sueprgrids. However, the feasibility of such proposals is strongly dependent on individual project conditions and future technological advances.

5. Possible future component: *zero*

The *Zero* future is built on the escalating challenge of deep decarbonisation, envisaging increased utility for nuclear and carbon removal technologies (Fig. 10). Given the physical and temporal scale of change of achieving net-zero, many futures are possible. Therefore, this vision is judged to constitute a *possible* component of future clean energy systems.

Fossil fuels supply 83% of primary global energy consumption [8]. Replacing the majority of global energy systems over the next few decades is a massive task. Hard to abate sectors will increase the challenge of eliminating emissions as net-zero targets are approached. The physical (463 EJ) and temporal (30+ years) scale mean many futures are possible, and many issues will remain unknown for some time. As an emissions superpower, the challenges of deep decarbonisation are pronounced in Australia [191]. Mining is the largest industry in Australia by GDP and must adapt to shifting mineral resource values. Carbon removal methods may also help abate emissions in the most challenging sectors. Although prohibited in Australia, nuclear energy may find unique value as a low-emissions, low-resource electricity generator.

Fig. 10. A graphical representation of the *Zero* future, built on the many uncertain challenges of deep decarbonisation. Nuclear and carbon removal technologies may find new value, while industries incumbent on fossil fuels must adapt, such as mining.

5.1. Technology: nuclear

Since 1938, nuclear technology has been among the most disruptive, divisive innovations to have shaped the twentieth century. Now, nuclear reactors may find new value for firming the increasing mix of variable generation with low-emissions and low-resource use [192]. However, the use of nuclear power remains strongly dependent on its relationship with societies and governments.

Nuclear power is prohibited in Australia, although recent government enquiries suggest it remains a considered option [193]. Concerns include high upfront costs, waste management and negative perceptions. The looming challenge of deep decarbonisation may eventually outweigh these concerns, and there is precedence for nations using nuclear power as a substitute for fossil sources.

The Messmer Plan saw 56 reactors deployed in France from 1973 to 1989, the nation now producing 70% of electricity from nuclear with exports adding €3 billion to the economy each year. This transition was initiated in response to the oil crisis, not decarbonisation. However, it demonstrates a national transition to secure, low-carbon electricity. Several countries have undergone similar nuclear deployments in the decade since (Fig. 11), with LCOE among the lowest LCOE generator option for those countries [194]. Implementing a nuclear energy program in non-nuclear countries is now an established, documented process that benefits from more robust material safeguards than earlier uptake [195,196].

Conventional large-scale reactors can secure vast quantities of reliable and clean power, required by grids like China and India [197]. However, new reactors must support solar and wind uptake, optimising operating flexibility, deployment speed and reduced long-term finance to support solar and wind uptake. This design shift is embodied by small modular reactors and advanced modular reactors. These reactors can provide crucial load-balancing and grid stability services, as demonstrated by submarine propulsion. Therefore, these reactors could displace fossil generators, providing a reliable alternative to energy storage given constraints to raw materials or increased concerns for life cycle impacts [198,199].

5.2. Technology: carbon management

Scenarios that lead to net-zero global emissions estimate that negative emissions technologies will reach 5–15 $GtCO_2$ per annum by 2050; however, commercial-scale lacks and the preferred technologies remain unclear [200–203]. The first large scale carbon dioxide capture and storage plant has stored 20 Mt since 1996 [204]. Recent research has investigated carbon dioxide removal to mitigate previous emissions, including forestation [189] and direct capture from air or fossil fuel burning [202]. Each method has potential impacts on land, energy, water or nutrients, which may be limited by deploying various options rather than one [201].

International organisations net-zero strategies have recognised the value of carbon removal, not for electrification, but for hard to abate sectors where it is more technically or economically feasible than low-emissions redesign [205–207]. Potential industries include transport, mining, agriculture, building and industries such as cement, steel and chemical production. The Australian government has committed $415 million to six carbon capture, utilisation and storage projects [208]. Dependence on carbon removal methods may reduce incentives to implement emissions reductions strategies in the present. Other concerns arise around risks of leakage for underground storage [209]. However, research and development of carbon management technologies may be warranted given the unique utility for the hardest to abate sectors.

5.3. Case: Australia's minerals and emissions

Australia is the world's largest coal (29.1%) and liquified natural gas

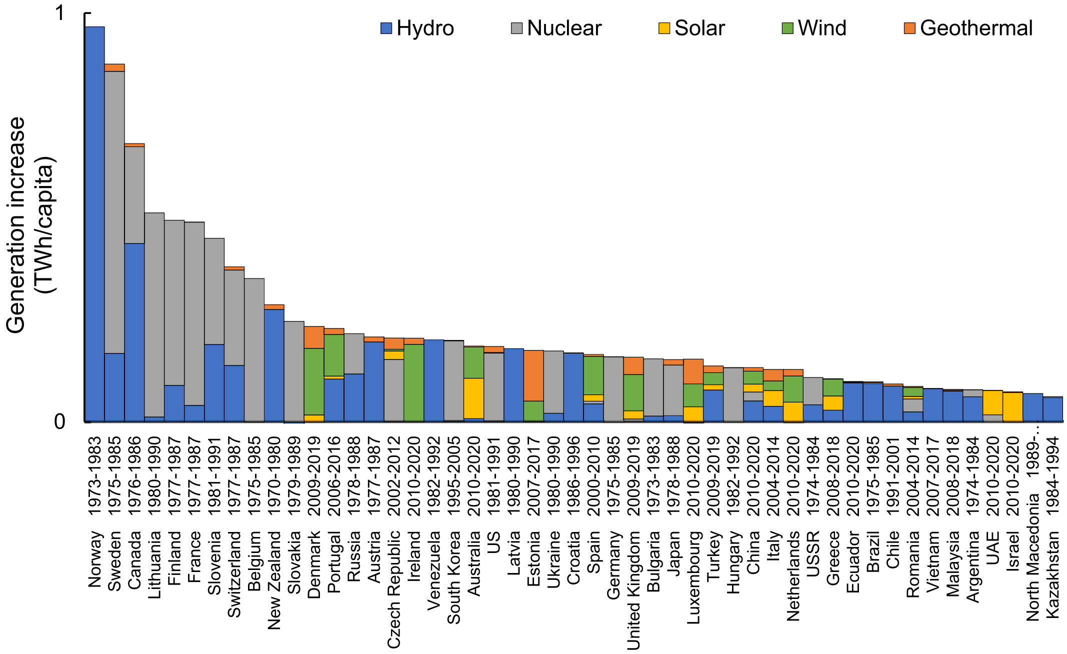

Fig. 11. Fifty largest increases in electrical generation per capita over ten years. Iceland 1998–2008 was omitted due to its small population but added 2.637 TWh/capita of hydro and 1.337 TWh/capita [8].

(21.8%) exporter [8]. Mining represents Australia's largest industry by GDP and employs about 2% of the workforce (Fig. 12A). However, associated emissions make Australia an emissions superpower per capita (Fig. 12B) [38]. Demand for coal is declining in most advanced economies, with prospects dependent on China and India [210]. Therefore, the industry must adapt to decarbonisation policies and shifting mineral resource values.

Mining sites are already adopting renewable technologies to reduce operating costs. Mines account for roughly 10% of Australia's electricity consumption, from diesel 41%, natural gas 33% and the electricity grid 22% [214]. The dependency on diesel exposes mining sites to volatile oil prices and international supply chains. Additionally, sites are often on the fringe of electricity and gas networks, susceptible to increased transmission costs and reliability issues such as natural disasters [127]. Solar is increasingly being used to mitigate these issues and reduce daytime operation costs. The Nova mine in Western Australia uses a hybrid PV-diesel system to save 6500 L of diesel a day without subsidy support [215]. Fortescue is also investing $450 million on a hybrid solar (60 MW), battery (35 MW/11 MWh) and gas (145 MW) facility to reduce diesel consumption by 100 million litres a year while reducing emissions by 40% [216].

The mining industry faces threats and opportunities from shifting resource values, given that renewable technologies are more minerally intensive than fossil fuel counterparts [217]. The minerals required for a new unit of power have increased 50% since 2010 and may increase 2–6 times by 2040 [35]. Australia may benefit from a 119% increase in aluminium demand (103 Mt by 2050) driven by PV uptake [218,219]. Australia has the world's second-largest bauxite reserve, producing 104 Mt in 2020 [220,221]. However, 80% of these extracts were exported for reining due to costs. Renewable electricity cost reduction may enable feasible domestic refining and reduce electrolysis emissions by 62% [222]. Production and recycling innovations are required to eliminate the remaining emissions. Australia also extracts 52% of lithium globally and could benefit from growing energy storage demands [45,82]. The Australian government has recognised these economic opportunities and strategic risks [223].

Critical minerals exist in higher concentrations than fossil fuels. The average share of the top three producing countries for fossil fuels (oil and gas) is 45%, whereas, for critical minerals (copper, nickel, cobalt, graphite, rare earths and lithium), it is 70% [35]. Diversification of the energy mix may reduce mineral requirements, such as low-resource use nuclear power, hydropower and bioenergy.

The concentration of resources and exporters has historically increased the risk of price volatility and conflict [224]. COVID-19 has also highlighted supply chain vulnerabilities, with increasing global tensions observed [225,226]. Disputes in an Australian lithium mine with American and Chinese ownership provide a pertinent example [227], with another in Africa [228]. Potential outcomes here are highly uncertain. For example, Australia has been exposed to high liquid fuel imports (90%) for 40 years without significant disruption [229], and

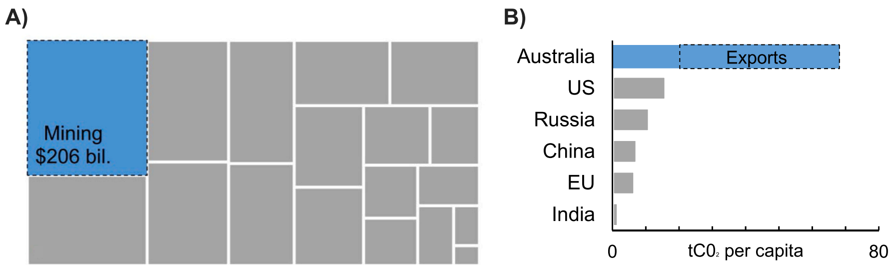

Fig. 12. A) Mining contributed 16% ($206 bil.) of Australian GDP by industry in 2019–20 [211,212] B) Australian per capita CO_2 emissions, including resource exports, outweigh the US by a factor of 4 [213].

joint Australian, Chinese and American ventures were also responsible for exponential PV cost reductions [230].

6. Conclusion

Energy systems are changing. Political commitments to net-zero are accumulating, and renewables now offer some of the lowest recorded electricity prices. Preparing for this change is crucial. However, the reactive, dynamic environment makes precise outcomes challenging to forecast. Given this uncertainty, this foresight study prepares stakeholders for the change by examining three visions that constitute probable, plausible and possible components of future clean energy systems. These visions were extrapolated via an expert-led review of clean energy technologies and case studies within the Australian context:

Abundant envisages a high penetration of solar and wind, with balancing services becoming increasingly valued. Solar and wind account for most new capacity each year, with virtuous cycles accelerating deployment. The high variable and distributed generation of zero marginal cost generation present a paradigm shift for energy systems. Energy storage technologies offer solutions over complimentary timescales, batteries for short and pumped hydro for long. Grid stabilisation may be augmented by regional interconnectors, while gas-generators balance the dominant generation of wind and solar, as in SA. Given the current commercial deployment and technological maturity, the Abundant future is judged as a probable component of future clean energy systems.

Traded envisages new power and powerfuel exchanges enabled by hydrogen and HVDC technologies. Clean energy carriers gain value as nations shift from fossil fuels to low-emissions alternatives. The market opportunity of green hydrogen has been signalled by a surge in private and public sector investments. Australia's national strategy aims to leverage rich renewable resources and trade partnerships in establishing itself as a hydrogen economy. However, significant challenges remain in scaling production, storage and transport, and fostering demand. HVDC may enable supergrids at national and intercontinental scales. However, feasibility depends strongly on individual project conditions and technological advances. Australia's longitudinal transmission network may benefit from proposed long-distance lines, connecting states to improve grid reliability and connecting South East Asia to open export opportunities. Given the limited commercial deployment and technological maturity, the Traded vision is judged a plausible component of future clean energy systems.

Zero is built on the escalating challenges of deep decarbonisation, envisaging the application of nuclear power and carbon removal technologies, and adaption of hard to abate sectors like mining. Political net-zero targets are accumulating. However, fossil fuels still supply the majority of global energy consumption. Despite economic benefits, mining fossil fuels has made Australia an emissions superpower. A national strategy signals the potential opportunity of critical minerals and their strategic threat after a pandemic that highlights global supply weaknesses. Although prohibited, nuclear power may be reconsidered as a secure firming generator with low emissions and low-resource use. Carbon removal methods may find unique value for the hardest to abate sectors where eliminating emissions is not technically or economically feasible. Given the physical and temporal scale of deep decarbonisation, many outcomes are possible. Therefore, the Zero future is judged as one possible component of future clean energy systems.

These probable, plausible, and possible future components of future clean energy systems prepare stakeholders for the uncertain transformation of energy by facilitating discourse and enhancing decision making. The visions provide a flexible framework suited to the uncertain changes to energy systems. The visions are intentionally simple, providing an accessible platform for discussing issues that depend on diverse disciplines. The brain uses visions like real memories during decision making, this heuristic allows consideration of issues from new perspectives. Stakeholders' appraisal of preferred futures may lead to new aspirations or recognition of changes as positive or negative to guide choices. Lastly, preparations are supported by trends discerned in the expert-led review of clean energy technologies and case studies.

This foresight study does have limitations. Foresight findings should be partnered with forecasting, modelling specific scenarios for feasibility assessments, and planning requirements. The futures are also dependent on local conditions. For example, Australia's high solar insolation and low seasonal variability incentivise different solutions than northern European countries without nuclear power restrictions and high residential heating requirements. Stakeholders should account for different local conditions when applying findings. Alternatively, the methodology may be repeated for other regions of interest. The national focus also limits the granularity of case study analysis. If grids become increasingly decentralised, focused studies on social, political, technical and commercial effects may be warranted.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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