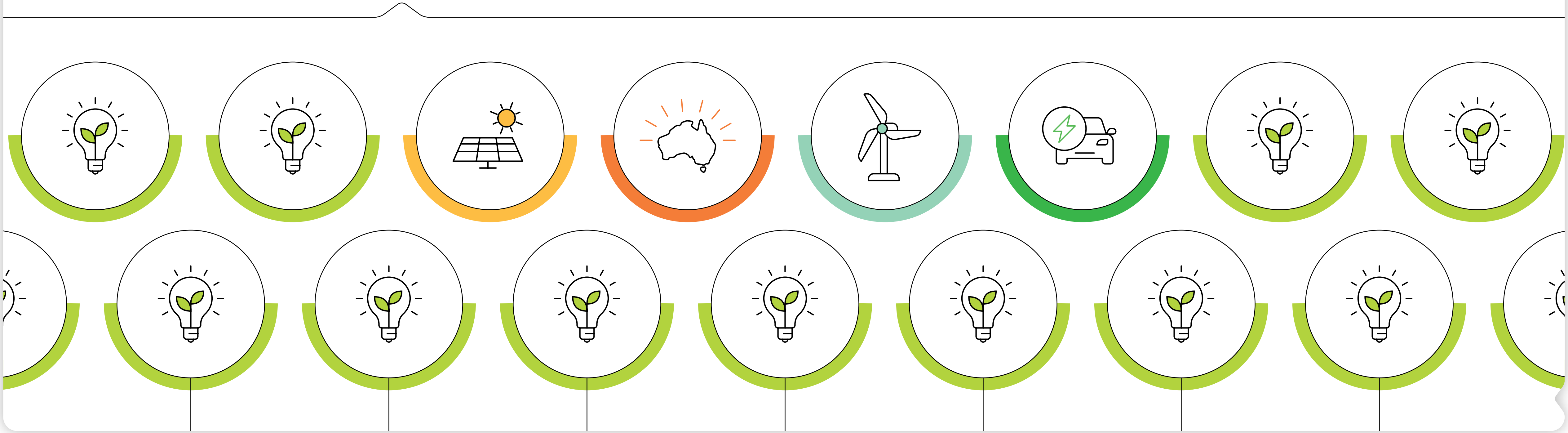
Energy Vision

A **clean energy future** for Australia

Transgrid



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Foreword

As the world responds to climate change and the cost of renewables plunges, the transition from a fossil fuel to renewable energy based power system is unstoppable. During this energy transformation, Australia's patterns of electricity supply and demand will change dramatically.

Transgrid is working with a broad range of stakeholders to plan for this future energy landscape, including State and Federal Governments, the Australian Energy Market Operator (AEMO) and transmission and distribution network service providers.

Transmission will be central to Australia's successful transition to a clean energy future. Decarbonisation, electrification and new green industries will require a significant expansion of renewable generation, storage and associated transmission infrastructure. We need to achieve the biggest energy transformation of our lifetime without sacrificing the grid security and reliability to which we have become accustomed.

To better understand what our energy future could look like, Transgrid has partnered with independent experts, CSIRO, ClimateWorks Australia and The Brattle Group to model the implications of a range of scenarios on the evolution of our energy system. This detailed scenario modelling guides our long-term planning, helping to ensure our network is robust, resilient and flexible to future challenges and opportunities.

This Energy Vision explores six possible futures for our energy system over the coming 30 years to 2050. The scenarios range from a future based on current trends, to a backwards-looking sharp slump in Australia's economic growth, to more optimistic scenarios in which Australia hits the Paris Agreement's aspirational 1.5°C decarbonisation target and becomes a global, clean energy superpower.

Each scenario is underpinned by detailed modelling to assess the implications and opportunities of emerging technologies, trends and policies on the development and operation of Australia's energy system. We have also assessed the implications of each scenario on Australia's decarbonisation trajectory, the creation of electricity sector jobs and the impact on market and consumer electricity prices.

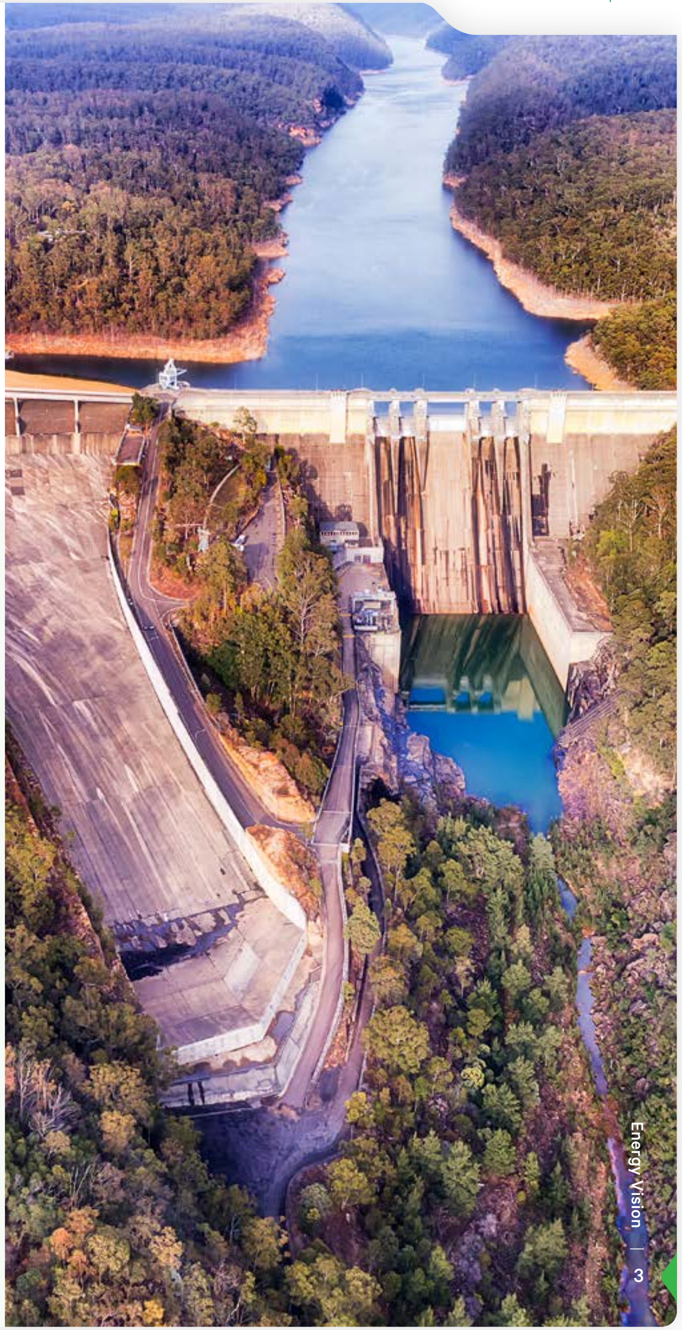
Our analysis indicates that the transition towards a clean energy future can create immense opportunity for Australia if we set ourselves on the optimal course – a course that will support not just decarbonisation, but also job creation and economic growth.

Our modelling shows that this future is achievable. But to realise this potential, the pace of change needs to rapidly accelerate. There is no time to waste.

This Energy Vision sets out the least cost evolution of the energy system under a range of possible future scenarios and presents an evidence-based vision for a future that provides clear long-term benefits for Australians.

We trust these insights will support energy system stakeholders in formulating the policies, reforms and investments required to enable the rapid and orderly decarbonisation of our energy system and to build Australia the energy system we need to thrive in a clean energy future.

Jerry Maycock
Chair of Transgrid
October 2021



Executive summary

Australia's energy system is undergoing a once in a-lifetime transformation. This Energy Vision provides evidence-based, data-driven insights into what that transformation could look like over the next 30 years. By planning for a diverse range of future scenarios, we can ensure our energy system is robust, resilient and flexible, as we navigate the challenges and opportunities ahead.

In partnership with independent experts, CSIRO, ClimateWorks Australia and The Brattle Group, we have developed and modelled six possible futures for Australia's energy system to 2050.

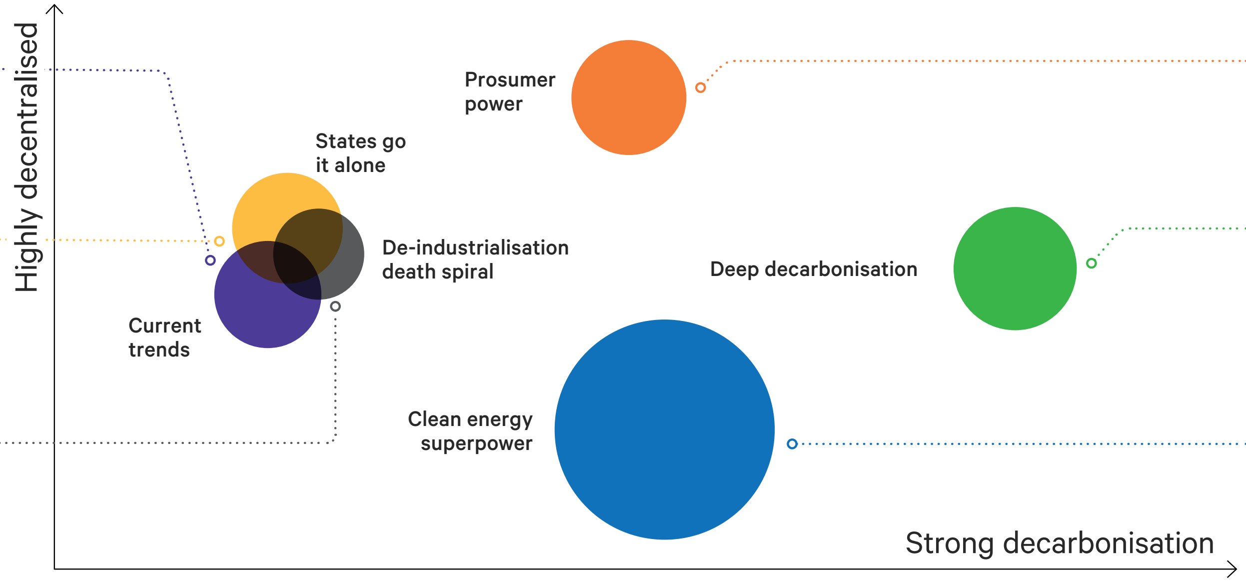
Six scenarios for the future

Figure 1: Comparing scenarios against their level of decarbonisation, decentralisation and the underlying electricity consumption in 2050 (represented by the size of the bubble)

Current trends
Ageing coal power stations are replaced with competitively priced large and small-scale renewables and storage

States go it alone
A breakdown of National Electricity Market (NEM) regulations sees a siloed approach from the states, which establish their own policies and local energy solutions. A regulatory impasse prevents new interstate transmission developments from proceeding

De-industrialisation death spiral
A global economic downturn causes Australia's economic growth to slump, particularly impacting the industrial sector



Prosumer power
Consumer choices and technology advancement drive a very high penetration of well-coordinated distributed energy resources into the system

Deep decarbonisation
Market forces, international and domestic politics and consumer expectations drive a huge reduction in carbon emissions across all sectors of our economy. Australia commits to limit global warming to 1.5°C, in line with the aspirations of the Paris Agreement

Clean energy superpower
Australia leverages its abundant renewable energy resources and mineral ores to become a global clean energy superpower, exporting green hydrogen and metals to the world

Seven key insights

Our analysis has identified seven key insights for the future of Australia's energy system.

The transition to renewables is unstoppable

- The findings are clear – the transition towards a clean energy future is unstoppable.
- In all scenarios examined, renewable energy supplies the majority of the NEM's electricity needs by 2050. In five out of the six scenarios, renewable energy supplies more than 70% of the NEM's annual energy needs by 2035 and more than 90% by 2050.
- The economic viability of Australia's coal generators is being challenged by the influx of renewables. Our analysis indicates that, by 2030, with decarbonisation objectives aligned to a 1.5°C temperature trajectory, as much as 18GW of coal capacity could be withdrawn from the NEM – 13GW more than currently anticipated[1].
- The likely early retirement of coal generators highlights the critical need for an orderly, planned and just transition from coal, ensuring the energy system remains reliable, secure and affordable.

The power system will play a central role in achieving economy-wide decarbonisation

- The electricity system will play a central role in supporting Australia's decarbonisation, underpinned by a rapid transition to renewable energy and the electrification of road transport, industry and buildings.
- If the vast majority of Australia's vehicle fleet is electrified, as in **Deep decarbonisation**, almost 100TWh/year of energy demand could be added to the NEM by 2050, equivalent to half of the NEM's current annual demand. In this scenario, the electrification of industry and buildings is projected to add another 40TWh/year by 2050.
- Electricity generation currently accounts for 33% of Australia's greenhouse gas emissions[a]. Under our business as usual **Current trends** trajectory, the NEM's electricity system is projected to reduce its emissions 93% by 2050, while the remainder of the economy only sees a 7% reduction in emissions.
- To facilitate the **Deep decarbonisation** of Australia's economy, the electricity system is fully decarbonised by 2035. The remainder of the economy achieves an 87% reduction in emissions by 2050.
- In our business as usual **Current trends** scenario, we project 108GW of largescale wind, solar photovoltaics (PV) and rooftop solar capacity is required in the NEM by 2050. This increases to 159GW in **Deep decarbonisation**, and 417GW in **Clean energy superpower**.

The transmission system is a key enabler of Australia's energy transformation

- Surging demand for electricity, an influx of geographically diverse renewable energy generation and an increasingly important role for energy storage will reshape our energy system, requiring a significant expansion of the transmission network.
- The role of the transmission system remains crucial in all scenarios, moving 73-95% of all electricity consumed in the NEM in 2050 from largescale generators to distributors and large customers, even in scenarios with exceptionally high rooftop solar uptake.
- New interstate transmission interconnection will be critical to maintain the sharing of low-cost, secure and reliable electricity between states, providing $20 billion in savings to the energy system by 2050.
- Modelling suggests that 25GW of new inter-regional transmission is required NEM-wide by 2050 in **Current trends** and 47GW in **Deep decarbonisation**, to support the least cost evolution of our energy system.

> **"A decarbonised power sector, dominated by renewable sources, is at the core of the transition to a sustainable energy future"**
>
> *IRENA, 2018, Global Energy Transformation: A roadmap to 2050*

> **"Spreading the use of electricity into more parts of the economy is the single largest contributor to reaching net-zero emissions"**
>
> *International Energy Agency, 2020, Energy Technology Perspectives*

1. Based on announced retirement dates for coal generators, or at the end of their technical life, as recorded by AEMO.

Seven key insights

Distributed energy technologies and increasingly sophisticated consumers will play a key role in Australia's future energy system

- Rooftop solar capacity is projected to surge in the coming decades, increasing 3-9 times in the NEM, possibly to as high as 82GW by 2050.
- Distributed batteries in Virtual Power Plants and electric vehicles with Vehicle-to-Grid technology could provide 30% of the NEM's storage requirements in **Deep decarbonisation** and up to 80% in **Prosumer power**.
- The electricity sector must evolve to meet changing consumer expectations and leverage new distributed energy resource capabilities to support the ongoing stability of the electricity system.

Efforts to support domestic and global decarbonisation will supercharge our economy, **drive local job creation and lower energy costs for Australians.**

Australia has a unique opportunity to harness its abundant renewable energy resources to become a global, clean energy leader

- Australia's abundant renewable energy resources, large landmass, significant mineral ores and good access to Asian markets could set us up to become a **Clean energy superpower**, exporting zero-emissions green hydrogen, metals, and other products and services to the world.
- As the cost of producing hydrogen from electrolysis falls, our modelling projects that renewable electricity becomes the dominant energy source for Australian hydrogen production, representing 94% of total hydrogen production in 2050.
- With appropriate support, the levelised cost of green hydrogen is projected to fall below $2/kg in the early 2030s, reaching $1/kg by 2050 at major hydrogen producing locations on the south and east coast of Australia.
- Our modelling projects that QLD dominates the production and export of hydrogen and green steel from the 2030s, followed by NSW and WA in the 2040s.
- By 2050, North Queensland and the Hunter Valley in NSW are projected to produce and export the largest quantities of hydrogen and green steel in Australia.
- Demand for electricity could surge in a **Clean energy superpower** future, increasing the NEM's electricity requirements six times by 2050.

Becoming a clean energy leader provides clear long-term benefits for Australians

- Efforts to support domestic and global decarbonisation will supercharge our economy, drive local job creation and lower energy costs for Australians.
- A **Deep decarbonisation** of the Australian economy supports 41,000 electricity sector jobs across the NEM this decade, 45% more than in our business as usual future (**Current trends**).
- A **Clean energy superpower** future supports 68,000 electricity sector jobs on average from 2030-50, more than twice the level of jobs projected in **Current trends**.
- Modelling suggests a significant proportion of new renewable energy and downstream hydrogen and green steel production jobs will be created in regional areas in **Clean energy superpower**, many in similar locations to where existing coal industries are located, such as the Hunter Valley in NSW.
- Our modelling shows these regions can be at the forefront of Australia's clean energy future. In an orderly transition of the energy system, no cohort of workers should be left behind. Communities should be provided every opportunity to harness the full potential of new export industries. Proper planning and investment in reskilling and upskilling is required.
- A **Clean energy superpower** future would deliver the lowest cost of electricity, 12% lower than **Current trends** over the period 2021-50.
- The decarbonisation of the Australian economy can deliver lower energy expenditure for residential consumers. Those with a single electric vehicle could be at least $900/year better off under a **Deep decarbonisation** scenario, when considering expenditure on electricity, rooftop solar, batteries and electric vehicles.

A new suite of technologies, services and products will be required to maintain safe, reliable and secure power system operations as the energy system transforms

- Maintaining power system security will become increasingly complex as the energy system transforms.
- Demand response, largescale storage, aggregated behind-the-meter batteries, flexible hydrogen electrolysis, and electric vehicles with Vehicle-to-Grid technology are likely to become increasingly critical to help balance our energy system.
- Modelling projects that 18GW of dispatchable storage capacity is required by 2050 in **Current trends**, and 33GW in **Deep decarbonisation**.
- Grid forming inverters are projected to play a crucial role in supporting energy security as synchronous generators are withdrawn.
- Our modelling suggests that inertia and system strength ancillary services will represent between 1-3% of total system costs.
- Australia is already experiencing the effects of climate change. Building a more resilient energy system is a critical task for the coming decades.

Executive summary

Our vision for Australia's energy system

To guide Australia's energy transition, we need a clear vision for the future that we can collectively strive towards.

Our vision is for Australia to become a global clean energy leader, benefitting communities, the economy and the environment.

This vision is centred on three themes: a decarbonised economy, a transformed economy (with new export sectors) and a resilient and affordable energy system.

- We see optimal advantage for Australia represented through a combination of **Deep decarbonisation** (medium-term) and **Clean energy superpower** (long-term). These two scenarios bring together the economic and climate benefits captured through proactively embracing the energy transition and Australia's natural advantages to become a renewable powerhouse.
- Our analysis indicates that the transition towards a clean energy future can create immense opportunity for Australia – if we set ourselves on the optimal course. As a nation, we have the choice of how we respond to this transition, not whether it happens at all.

About Transgrid

TransGrid operates and manages the high voltage electricity transmission network in NSW and the ACT. We offer a range of infrastructure and telecommunications services to meet the growing needs and expectations of our customers. Our network connects NSW to Queensland and Victoria, and forms the backbone of the National Energy Market (NEM).

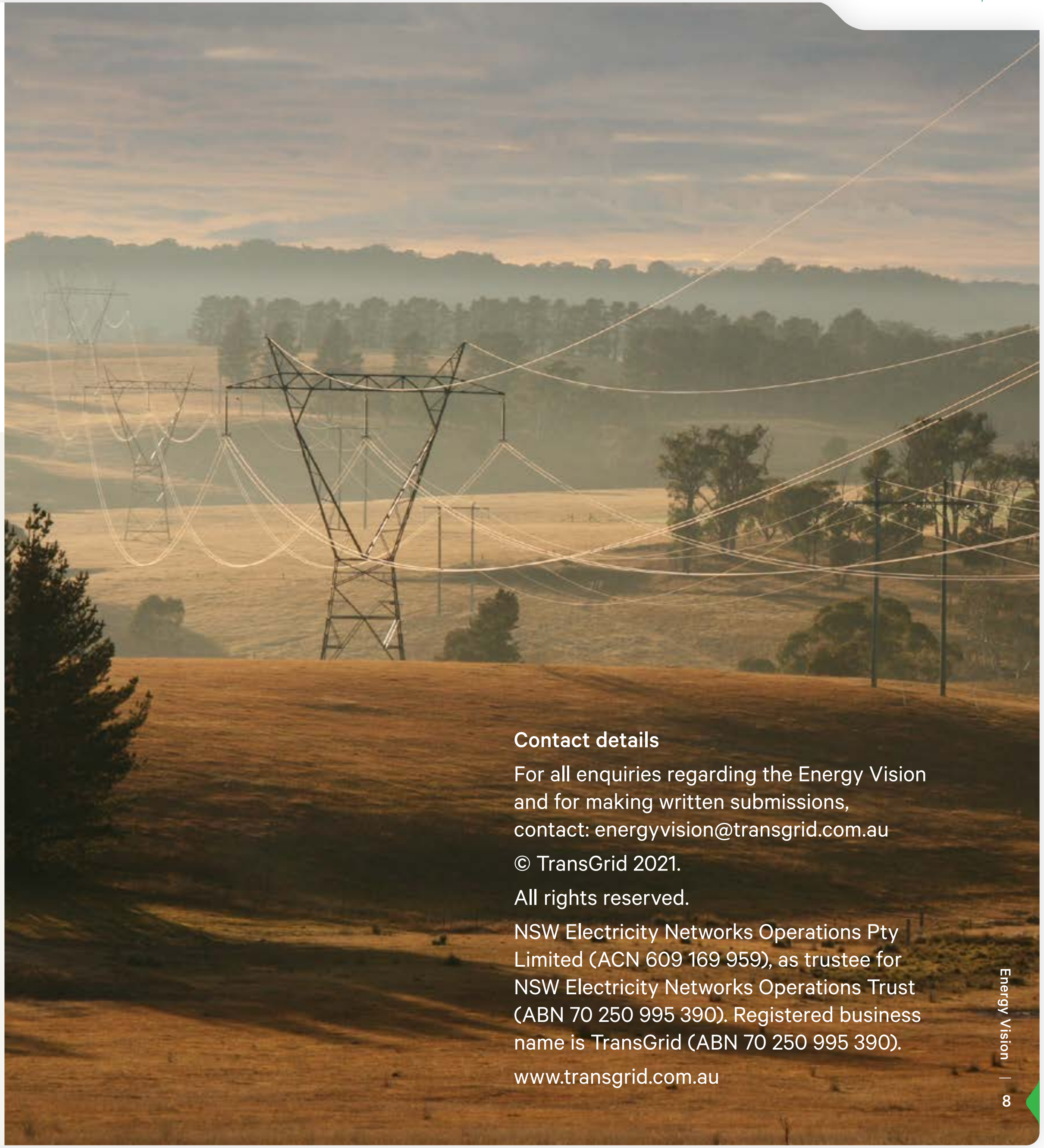
Our network transports electricity from multiple generation sources, such as wind, solar, hydro, gas and coal power plants, to large directly connected industrial customers and the distribution networks that deliver it to homes and businesses. Comprising 119 substations and 13,204 kilometers of transmission lines and cables and five interconnections to QLD and VIC, the network is instrumental to the electricity system and economy and facilitates energy trading between Australia's largest states.

The National Electricity Market (NEM) is currently undergoing a period of transition as the generation mix changes to include more renewables and technology, allowing greater participation from customers in the energy market. We are working with our customers and stakeholders across the energy supply chain and decision-making bodies to ensure we make a better power system for Australians.

This Energy Vision is underpinned by detailed scenario modelling. Transgrid partnered with independent experts, CSIRO, ClimateWorks Australia and The Brattle Group, to model the implications of a range of futures for Australia's energy system out to 2050.

The Brattle Group facilitated the development of our future energy scenarios. CSIRO and ClimateWorks Australia undertook quantitative market and system modelling on each scenario.

CSIRO | ClimateWorks AUSTRALIA | Brattle



Contact details

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NSW Electricity Networks Operations Pty Limited (ACN 609 169 959), as trustee for NSW Electricity Networks Operations Trust (ABN 70 250 995 390). Registered business name is TransGrid (ABN 70 250 995 390).

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Drivers of change

Australia's energy system is undergoing a once-in-a-lifetime transformation. Globally, the way energy is generated, stored, distributed and consumed is changing at an unprecedented pace.

Six forces are shaping the future of Australia's energy system, underpinned by rapid technological advancements and government actions to decarbonise their economies.

Six forces shaping the future of Australia's energy system

The evolution of Australia's energy system will be influenced by six forces – shaped by technological, economic, social and political trends.

Technology advancement

- Disruptive technological advancement is occurring across the energy supply chain, from renewable energy and storage technologies to distributed energy resources and smart-grid capabilities. These advancements are supported by digitisation, automation and artificial intelligence
- A combination of innovation and global deployment is driving significant cost reductions

The decarbonisation imperative

- Global emissions reductions are not on track to meet the Paris Agreement's 1.5°C aspiration or 2°C goal. A rapid transformation is required
- While current progress is insufficient, more than three-fifths of global CO_2 emissions are under net zero emissions targets [b]

Consumer preferences and decentralisation

- Consumers are expressing a desire to be more in control of their energy supply and use, enabled by distributed energy resources
- Consumers are likely to have a greater interaction with the electricity system, through Virtual Power Plants, smart electric vehicle charging and Vehicle-to-Grid technology. These 'prosumers' will be more sophisticated and diverse, not simply 'price takers' from the grid

Demand for electricity

- Long-term economic conditions are uncertain, including the ongoing viability of energy-intensive industries in Australia
- There is scope for a substantial growth in distributed generation and energy efficiency, which could reduce the demand for grid connected electricity
- New demand sources are emerging, which may significantly increase the demand for electricity, through the electrification of road transport, buildings and industry and from electricity-intensive industries, such as green hydrogen [1] and green metal production

Energy market rules and regulations

- Rules and regulations built for Australia's legacy energy system are in a state of flux. Australia's Energy Security Board has been tasked with a wholesale redesign of the NEM by 2025

Community expectations

- There are increasing community expectations to reduce our impacts on the environment
- Disruptions and benefits of Australia's energy transition will be felt differently by different communities

1. Green hydrogen is the production of hydrogen via electrolysis, powered by renewable energy. Green steel is the production of steel using green hydrogen and renewable electricity through a direct reduction process. Green metals and products refer generally to metals and products produced using renewable energy.

Technological advancement

Disruptive technological advancement is occurring across the energy supply chain, from renewable energy and storage technologies to distributed energy resources and smart-grid capabilities, leading to rapid cost reductions.

Already, we can see that the transition towards renewables is unstoppable. Globally, the cost of solar PV has fallen 87% and wind 63% since 2009, and battery storage has fallen 80% since 2013[c]. For projects with low-cost financing that tap high-quality resources, solar PV is now the cheapest source of electricity in history[d].

In Australia, the share of electricity generated from coal in the NEM has fallen from 78% to 65% since 2010. The share of electricity generated from variable renewable energy has increased from 2% to 21% over the same period[e].

By the end of 2020, more than 11GW of largescale wind and solar PV were deployed and 76 largescale wind and solar PV projects were under construction[f]. And this is just the beginning – 55GW of largescale wind, solar PV and storage have been proposed for connection across the NEM[g].

In parallel, everyday Australians have embraced rooftop solar at an unprecedented pace. More than one in four Australian households now have solar panels on their homes[h]. In 2020 alone, 3GW of new capacity was added[i], bringing the total Australian residential rooftop solar capacity to more than 14GW[j].

Continued technological advancement and energy cost reductions are likely to further reshape the energy system. The cost of solar PV in Australia is projected to fall a further 70% by 2050, 50% for wind and 60% for grid batteries[k].

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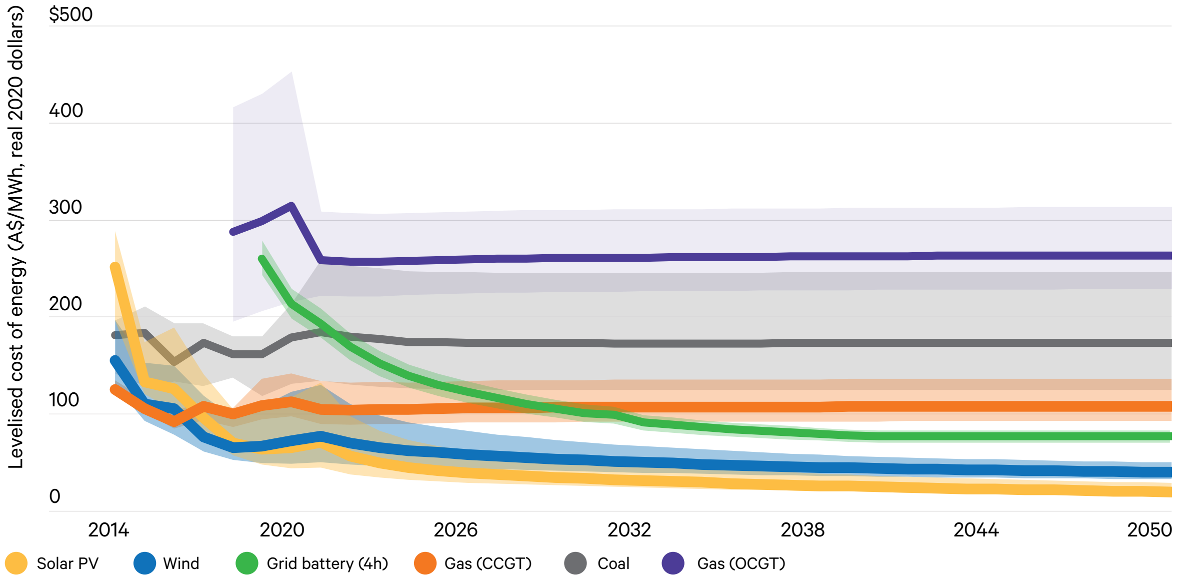
Globally, the cost of solar PV has fallen 87% and wind 63% since 2009, and battery storage has fallen 80% since 2013

Figure 2: Projections of the levelised cost of energy in Australia for new capacity[1]



1. Shaded area represents the minimum and maximum cost projections, cost converted to Australian dollars with a 2020 average conversion rate of US$1 = A$0.69. Source: BloombergNEF, 1H 2021, Levelised Cost of Energy Data Viewer.

The decarbonisation imperative

In 2015, as the world woke up to the catastrophic consequences of unchecked climate change, the Paris Agreement was adopted by 197 parties, including Australia, representing 97% of global greenhouse gas emissions [l]. The Paris Agreement is a legally binding international treaty, with its goal to limit global warming to well below 2°C, preferably to 1.5°C, compared with pre-industrial levels [m].

At the same time, positive community sentiment towards action on climate change continues to grow. The majority (71%) of Australians agree that we should be world leaders in finding solutions to climate change [n].

Significantly, all Australian states and territories have made commitments to reach net zero emissions by 2050. Australian businesses are also taking direct action, with 18% of organisations surveyed committed to net zero by 2050 for some emissions [o].

But, despite the Paris Agreement and mounting efforts by governments, businesses and consumers to reduce their carbon footprints, the world is not on track to avoid dangerous climate change. Our current trajectory will lead to catastrophic warming. We are at "code red for humanity" [p].

Deloitte Access Economics has modelled the impacts of unchecked climate change on the Australian economy. The analysis suggests that, by 2070, Australia's GDP would have shrunk by 6%, a $3.4 trillion loss in GDP (present value) – at a cost of 880,000 jobs [q].

"Under policies firmly in place, the world is headed for 2.7°C of warming. Even if countries meet their net-zero targets in full, temperatures would rise 2.1°C"

International Energy Agency, 2021, Net Zero by 2050

"Unchecked, climate change could shrink Australia's GDP 6% by 2070, at a cost of 880,000 jobs"

Deloitte Access Economics, 2020, A new choice – Australia's climate for growth

Spotlight

Drivers of change

Climate change and the energy sector

Building a more resilient energy system is a critical task for the coming decades.

In February 2021, Texas's electricity infrastructure was overwhelmed by an extreme polar vortex, triggering the largest forced power outage in United States' history. Freezing weather shut off natural gas supplies, froze instruments in gas, coal and nuclear power plants and iced over wind turbines. As demand for heating soared to record levels, more than five million homes and businesses were left without power for nearly four days straight [r].

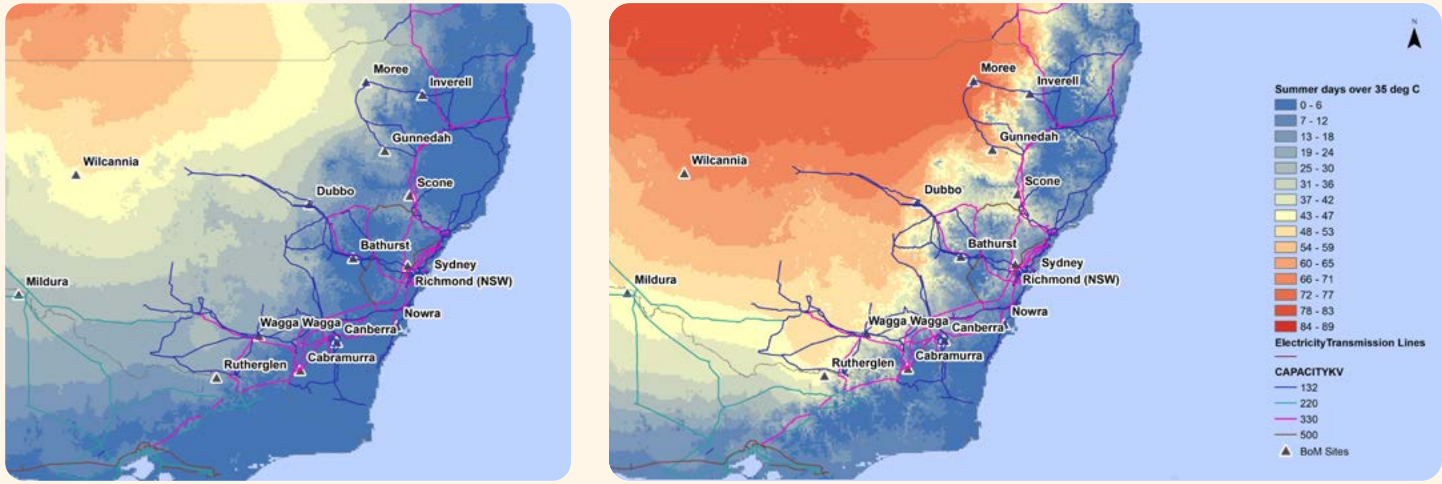
In June 2021, a heatwave hit north-western United States and Canada, with temperature records being broken by as much as 5°C. The heatwave was linked to several hundred deaths and, in some regions, caused rolling blackouts and even melted power cables and road surfaces. The event was assessed to be a once in a thousand year event, made at least 150-times more likely because of climate change [s].

On the other side of the world, a once in a thousand year rainfall event hit China in July 2021, causing widespread flooding, death and destruction. In the same month, heavy floods wiped out villages, infrastructure and killed more than 200 people in Germany. And, in India, the heaviest monsoon rains in decades overflowed rivers, triggered landslides, killed more than 125 people and left entire neighbourhoods submerged [t].

Australian land areas have already warmed by around 1.4°C since 1910[u] and future impacts will affect all sectors of our economy, our communities and ecosystems. Water supply reliability is expected to decline in southern and eastern Australia, temperatures will rise, heatwaves, storms and floods will become more common and risks to infrastructure will increase [v].

The projected increase in the number of days where temperatures will rise above 35°C in NSW is shown in Figure 3, under a high global warming scenario.

Figure 3: Historical (1981-2010), left, and projected (2070), right, number of days above 35°C during the December to February period for a RCP8.5 scenario [w]



Future energy scenarios

In partnership with independent experts, CSIRO, ClimateWorks Australia and The Brattle Group, we have developed and modelled six possible futures for Australia's energy system out to 2050.

The following scenarios explore the impact of different combinations of the six forces listed on the previous page. More details on the approach can be found in Appendix 1.1.

Effective scenario planning requires scenarios that span the range of plausible future outcomes.

Current trends

Ageing coal power stations are replaced with competitively priced large and small-scale renewables and storage

- Economic growth, immigration and energy efficiency are consistent with historic and projected growth rates under present trends, taking into account current projections for the recovery from COVID-19
- Electric vehicle, rooftop solar and behind-the-meter battery uptake is consistent with current central projections

Deep decarbonisation

Market forces, international and domestic politics and consumer expectations drive a huge reduction in carbon emissions across all sectors of our economy. Australia commits to limit global warming to 1.5°C, in line with the aspirations of the Paris Agreement

- Australia achieves net zero emission by 2035 and then net-negative emissions beyond
- Our electricity system is powered by 100% renewable energy from 2035
- Internal combustion engine vehicles are completely phased out by 2050, replaced primarily by electric vehicles
- Hydrogen is used for some domestic heavy-transport and industry applications and for peaking electricity generation

Prosumer power

Consumer choices and technology advancement drive a very high penetration of well-coordinated distributed energy resources into the energy system

- Extremely high uptake of rooftop solar, behind-the-meter storage and electric vehicles (many equipped with Vehicle-to-Grid capabilities)
- Artificial intelligence and automation enable the coordination of consumer devices to respond to local system and market conditions
- A net zero emissions economy is achieved by 2050

De-industrialisation death spiral

A global economic downturn causes Australia's economic growth to slump, particularly impacting the industrial sector

- Industrial electricity consumption in the NEM declines by 50% to 2025. Australia's aluminum and steel production facilities close by 2025
- Commercial electricity demand falls by 9% in the NEM before slowly growing in the 2040s

States go it alone

A breakdown of NEM regulations sees a siloed approach from the states which establish their own policies and local energy solutions. A regulatory impasse prevents new interstate transmission developments from proceeding

- New transmission links between states cannot be built, although existing links remain in use
- Each state must generate and balance its own electricity to maintain energy reliability
- Other modelling assumptions align to the **Current trends** scenario

Clean energy superpower

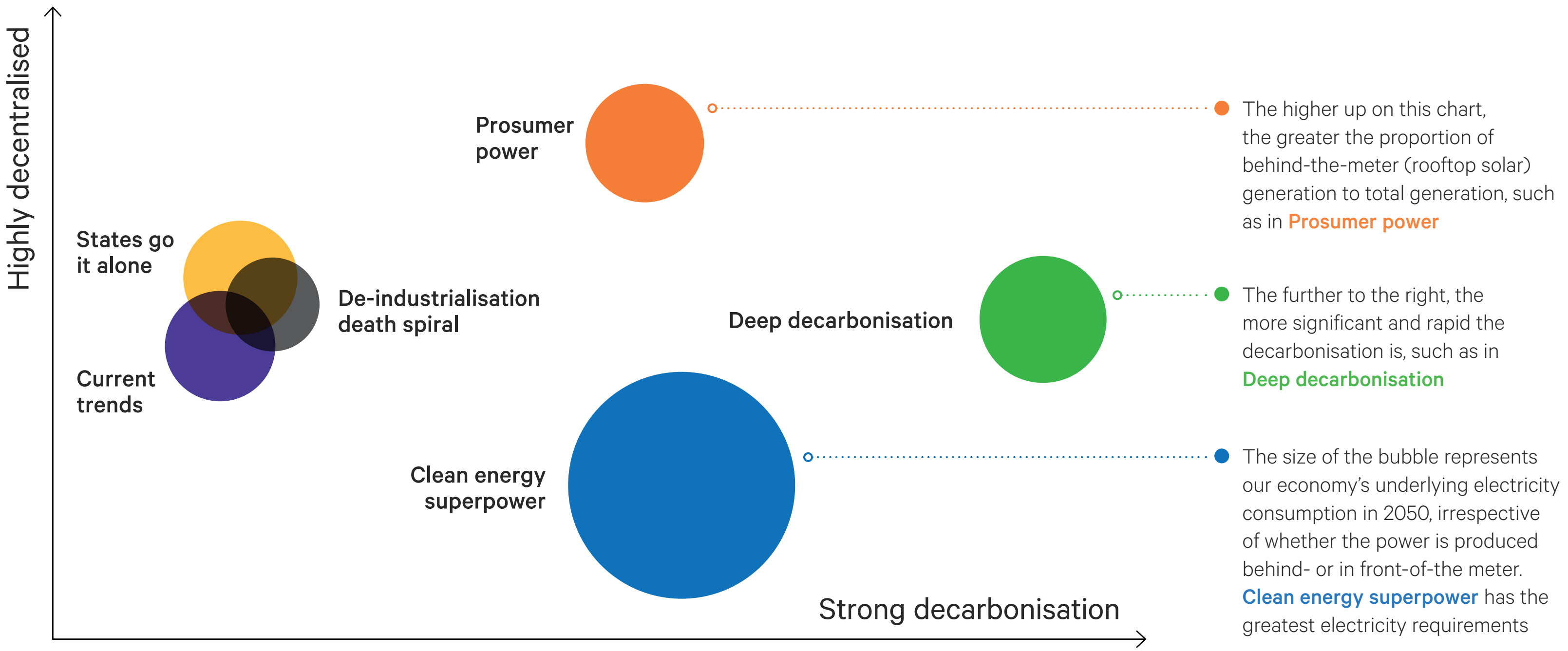
Australia leverages its abundant renewable energy resources and mineral ores to become a global clean energy superpower, exporting green hydrogen and metals to the world

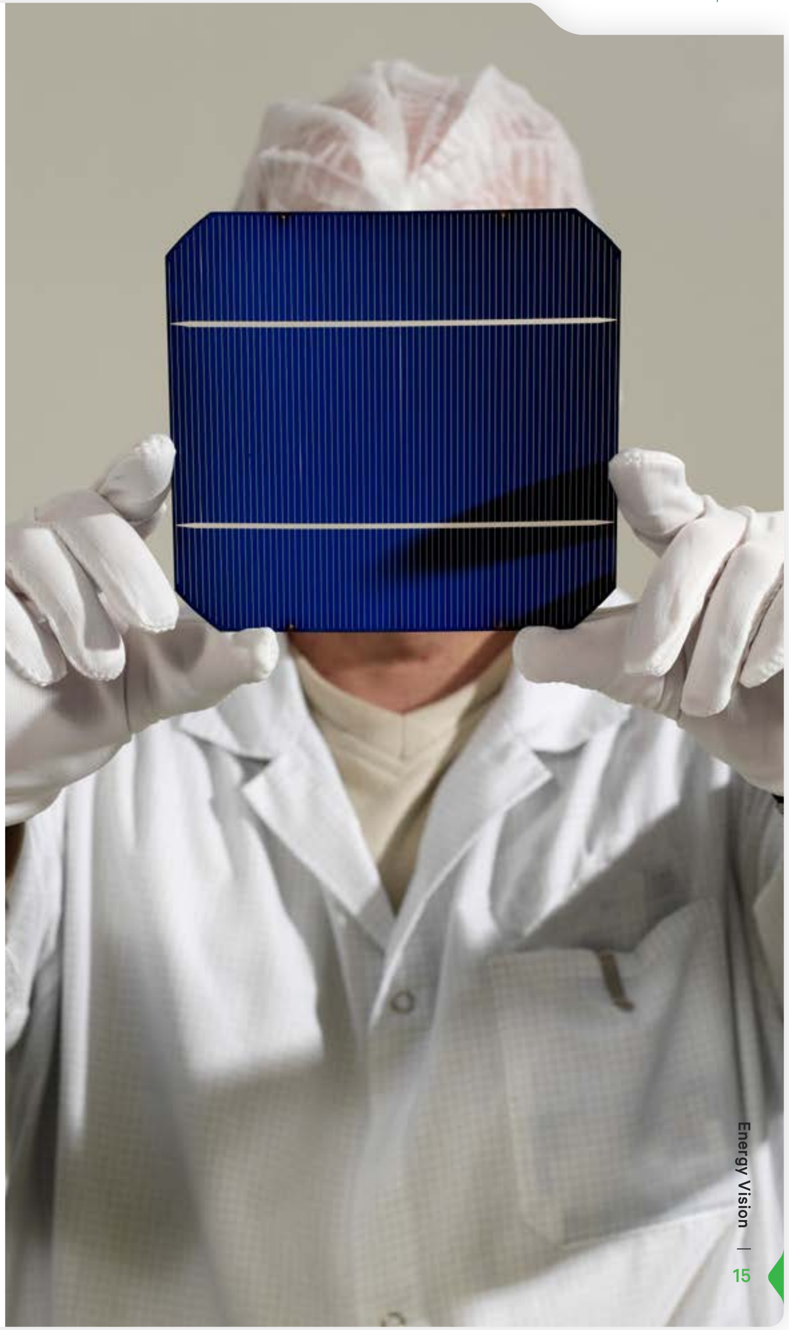
- Australia's hydrogen sector grows to produce 19.2 million tonnes (MT) of hydrogen annually by 2050. This is broadly consistent with the high scenario from Australia's National Hydrogen Strategy
- 61% of the hydrogen produced is exported to our trading partners, 22% is used to produce green steel for export and 17% is for other domestic purposes
- Australian steel production increases significantly (from 0.3% to 5% of global steel output) and aluminum production (a five-fold growth)
- A net zero emissions economy is achieved by 2050

Scenario comparisons

Scenarios can be compared against their level of decarbonisation, decentralisation and underlying electricity consumption in Figure 4. Detailed scenario assumptions are presented in Appendix 1.2.

Figure 4: Comparing scenarios against the level of Australia's decarbonisation, the decentralisation of the electricity system and the underlying electricity consumption in the NEM in 2050 (represented by the size of the bubble)

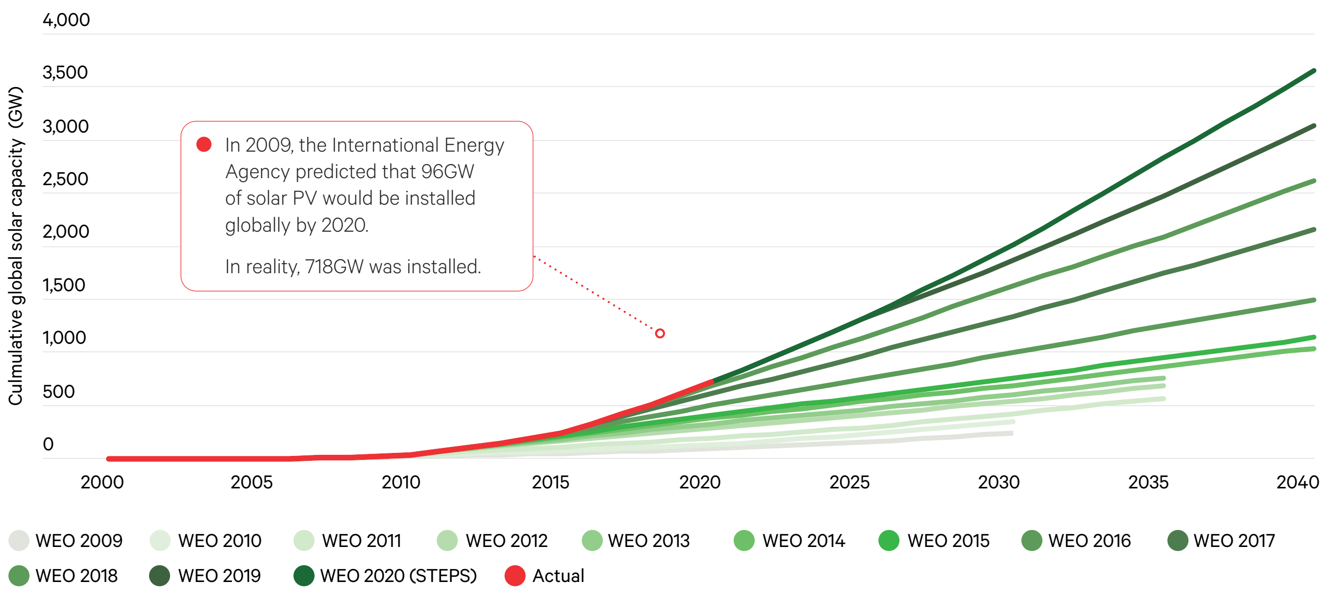




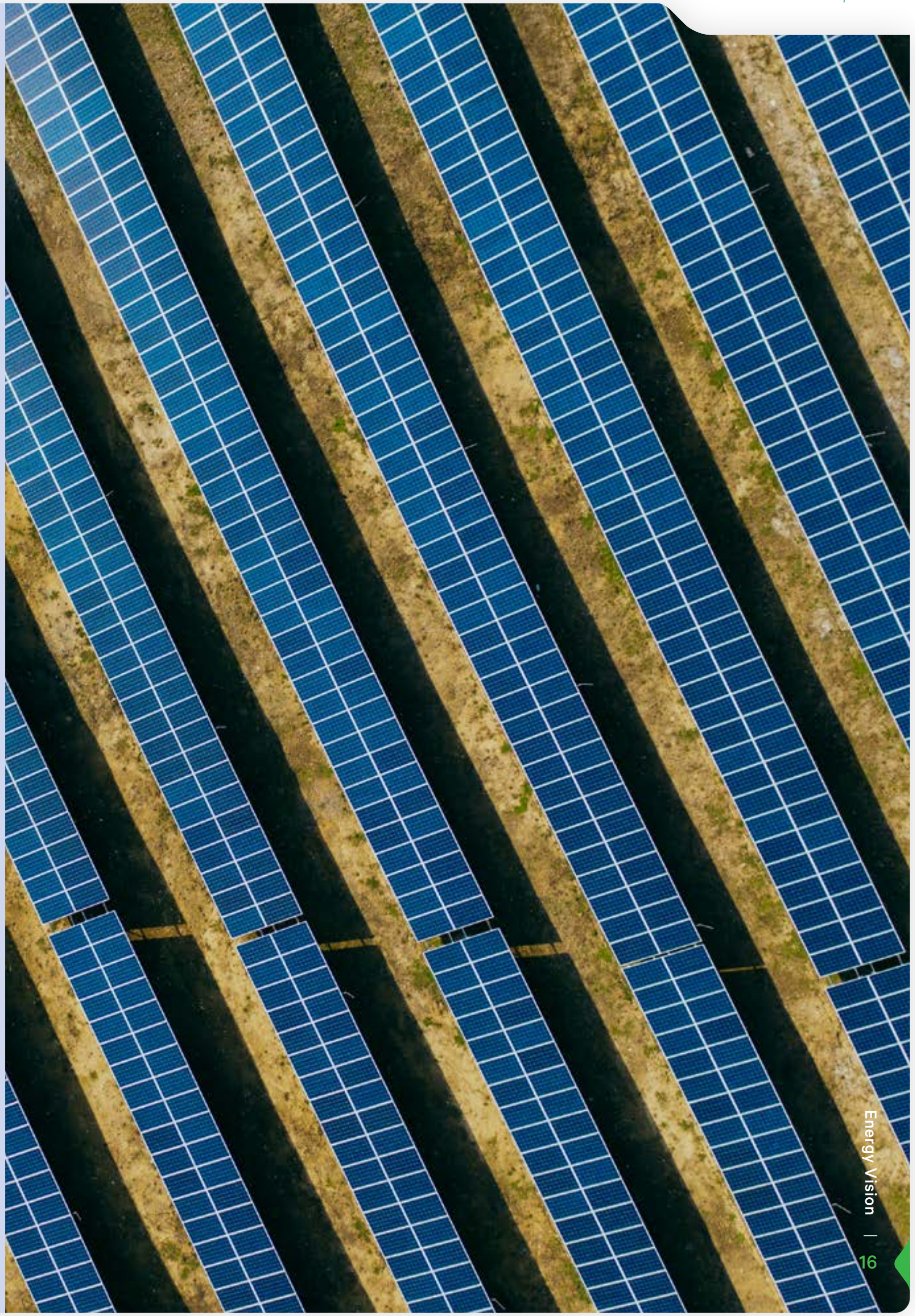
The importance of scenario planning

Scenario-based planning is essential to ensure a robust energy system into the future. It is particularly useful in times of rapid change and disruption. The global growth in solar PV is a good example of why planning for divergent and unexpected future outcomes is crucial.

Figure 5: Cumulative global solar capacity. Historical data is shown in red and central outlooks from the International Energy Agency's World Energy Outlook (WEO) are shown in green.



Source: Transgrid analysis of Carbon Brief [x], from the World Energy Outlook 2020 [y] and previous editions



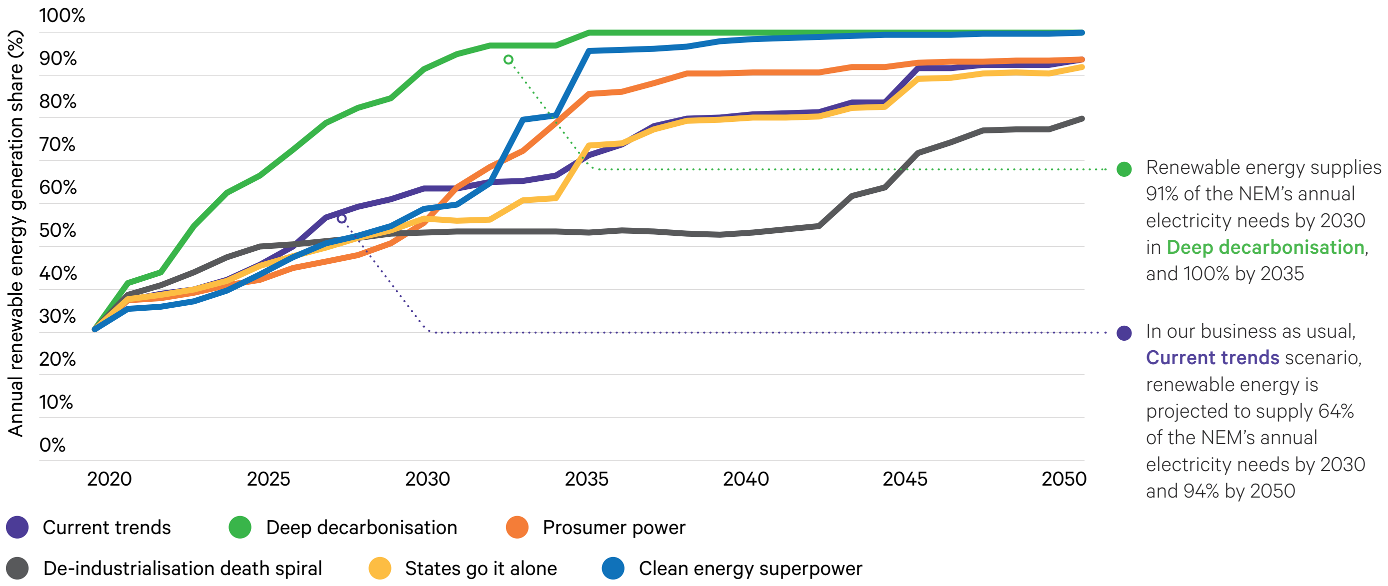
Key trends

This section explores the key electricity sector trends that unfold under our six scenarios, as modelled by CSIRO and ClimateWorks Australia. We can already see signs of some of our future scenarios, with many of their indicators forming clear trends that should inform investment in the energy system.

Unstoppable transition to renewables

In all future scenarios, our least-cost modelling shows that renewable energy will supply the vast majority of Australia's electricity production by 2050 – 94% in **Current trends** and 100% in **Clean energy superpower**. All the evidence points to the fact that the transition from a fossil fuel to renewable energy based power system is unstoppable.

Figure 6: Annual share of renewable energy generation to total generation in the NEM, inclusive of largescale wind and solar PV, rooftop solar, hydro and biomass



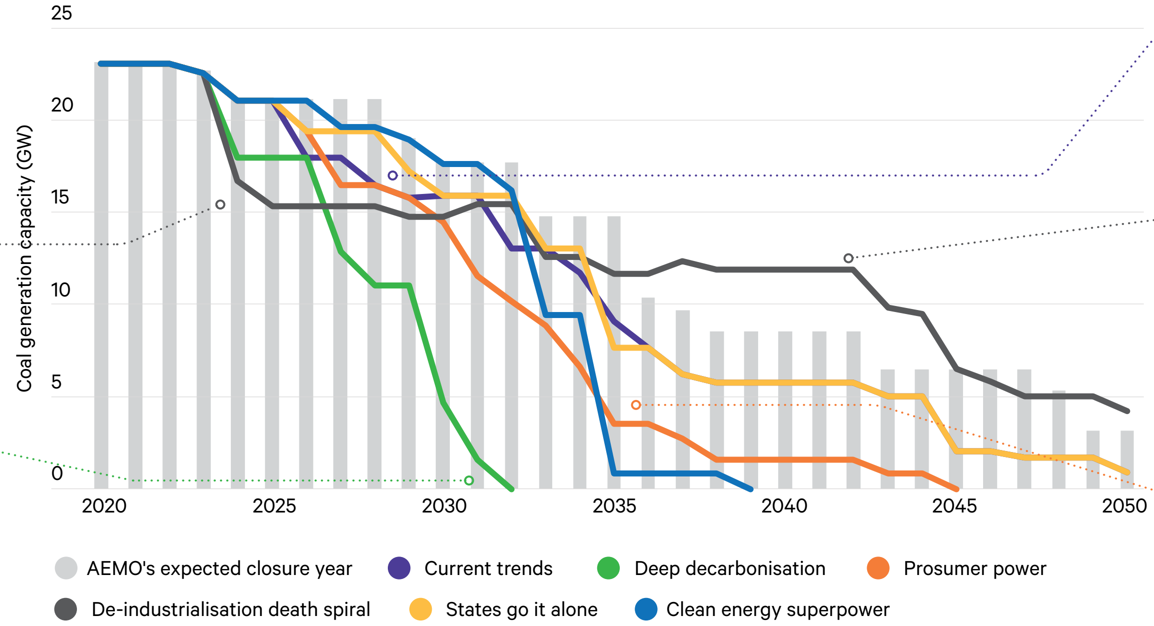
Early coal retirement is increasingly likely

The growth of renewables is challenging the economic viability of Australia's aging coal generators. Our analysis indicates a high likelihood of early coal withdrawal across a range of future scenarios.

Figure 7: Projected coal generation capacity in the NEM. Grey bars represent AEMO's expected closure years[1]

De-industrialisation death spiral suggests that if a significant proportion of Australia's industrial demand was lost, excess supply would precipitate the early withdrawal of some coal generators

In **Deep decarbonisation**, all coal generation ceases by 2032, reducing economy-wide emissions at the lowest cost



In **Current trends**, 7GW of coal capacity is withdrawn from the NEM by 2030, 2GW more than currently anticipated

If Australia's climate ambitions were dropped and we experienced low fossil fuel prices, coal life extensions may be economic, as shown in **De-industrialisation death spiral**

A rapid withdrawal of coal capacity is seen in the mid-2030s in **Clean energy superpower** and **Prosumer power**

1. Expected closure years are sourced from AEMO's 2020 Integrated System Plan Chart Data, reflecting committed retirement dates from coal generators or at the 50th year of operation, whichever comes first. The baseline closure year for Yallourn Power Station has been updated to 2028. Source: https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp.

Multiple factors could accelerate the NEM's current transition from a coal to renewable-based power system, including:

- Further cost reductions and deployments of renewables and storage driving down the price of electricity, making it more difficult for coal generators to remain profitable
- More ambitious climate change policies
- The technical failure of coal units, driven by age and increased ramping in response to variable renewable energy
- A growing consumer preference for low emissions electricity

The increased likelihood of early coal closures highlights the importance of an orderly and planned transition, ensuring there is reliable, secure and affordable power as the system transitions to firmed renewables.

The Institute for Energy Economics and Financial Analysis and Green Energy Markets recently concluded that, by 2025, coal plants in the NEM are likely to see a 44-67% reduction in revenues, the financial viability of several generators will be severely compromised and at least one generator may close

Edis, T., Bowyer, J., 2021, Green Energy Markets and Institute for Energy Economics and Financial Analysis, Fast Erosion of Coal Plant Profits in the National Electricity Market

Key trends

Rise of the prosumer

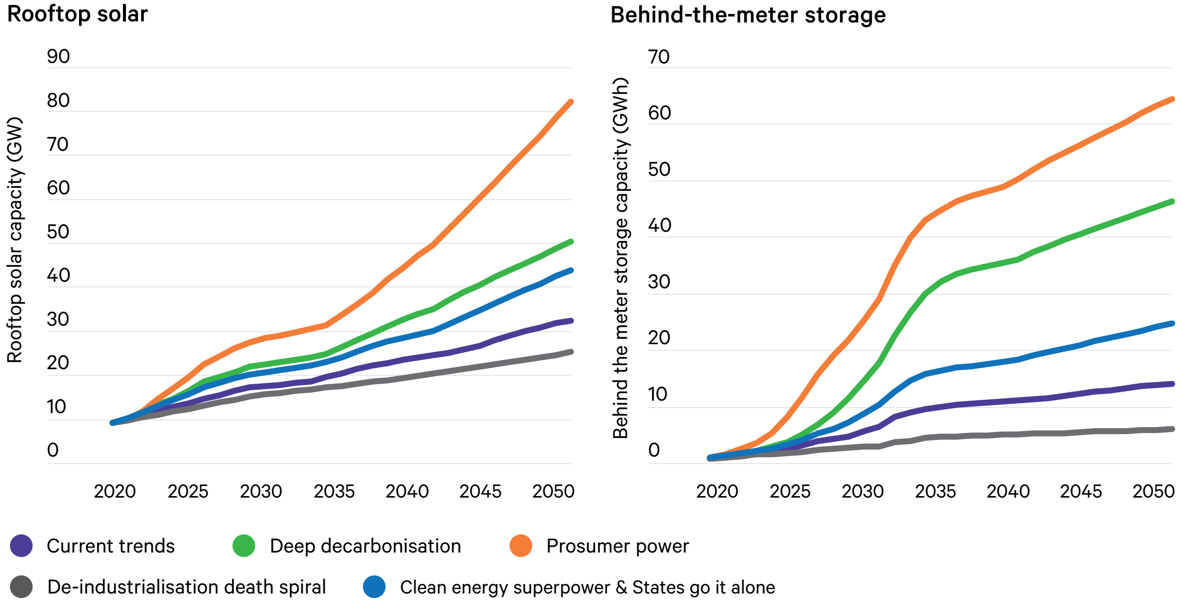
In all scenarios, distributed energy technologies and increasingly sophisticated consumers will play a key role in Australia's future energy system.

Evolving customer expectations and a growing range of technologies are facilitating the democratisation of energy. Previously passive electricity consumers are becoming empowered 'prosumers' who make their own choices about how their energy is produced, stored and used.

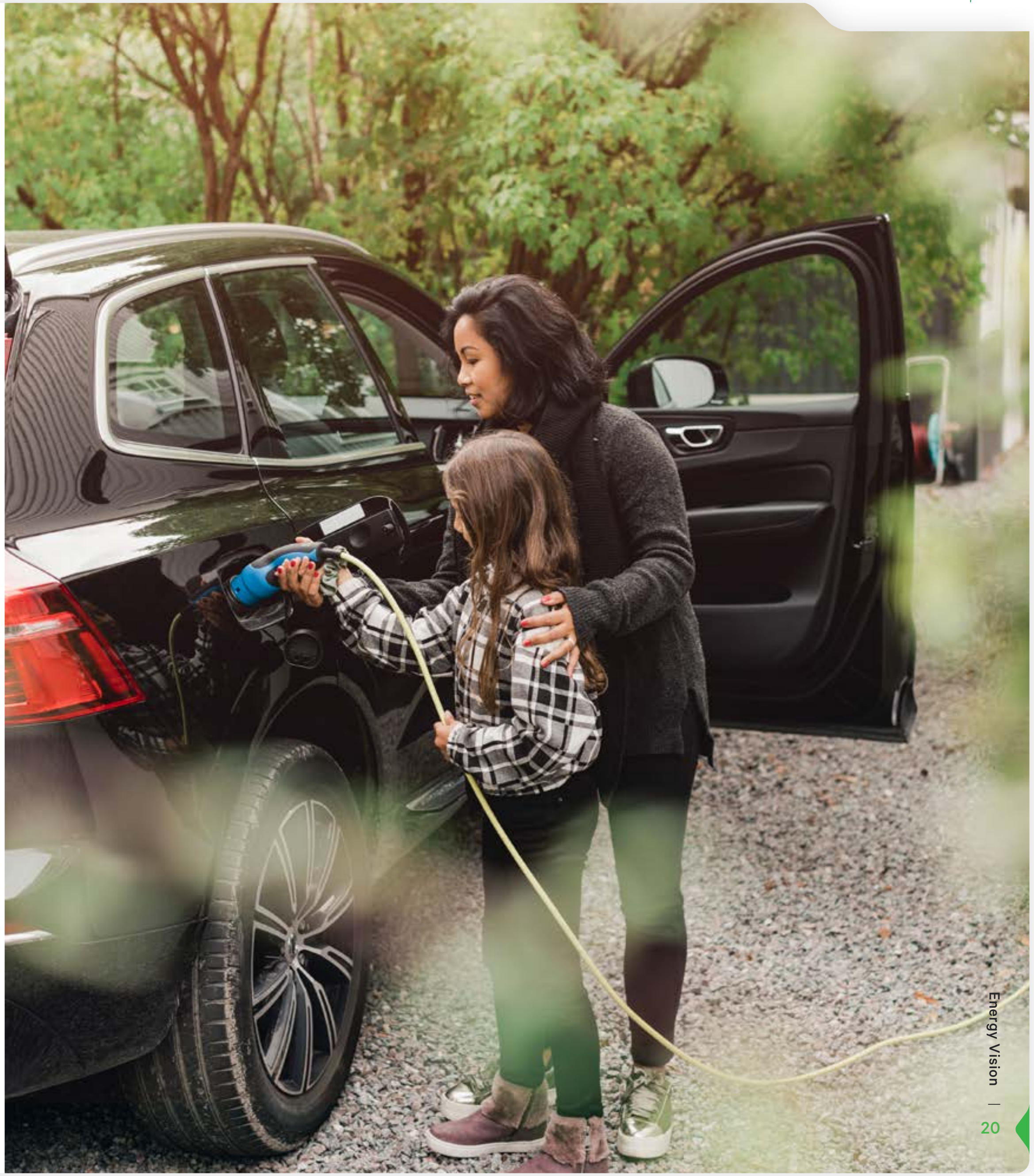
Rooftop solar and behind-the-meter storage

Rooftop solar and behind-the-meter storage capacity is projected to surge in the coming decades, as projected in Figure 8. **Prosumer power** stress tests the implications of exceptionally high distributed energy resource penetration on the design and operation of our energy system. By 2050, more than 80% of Australian homes have rooftop solar[1].

Figure 8: Projected growth in rooftop solar and behind-the-meter storage in the NEM



1. This is considered a fully saturated market, including penetrating into most rental residential homes and many business rentals.



Spotlight

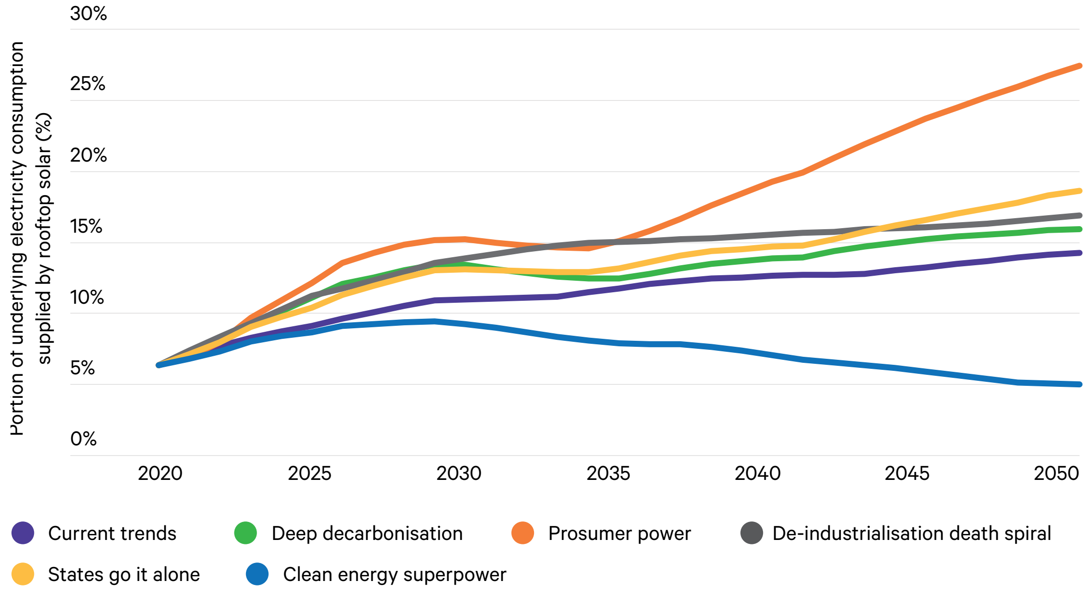
Key trends

Critical role for both behind- and in front-of-the-meter generation

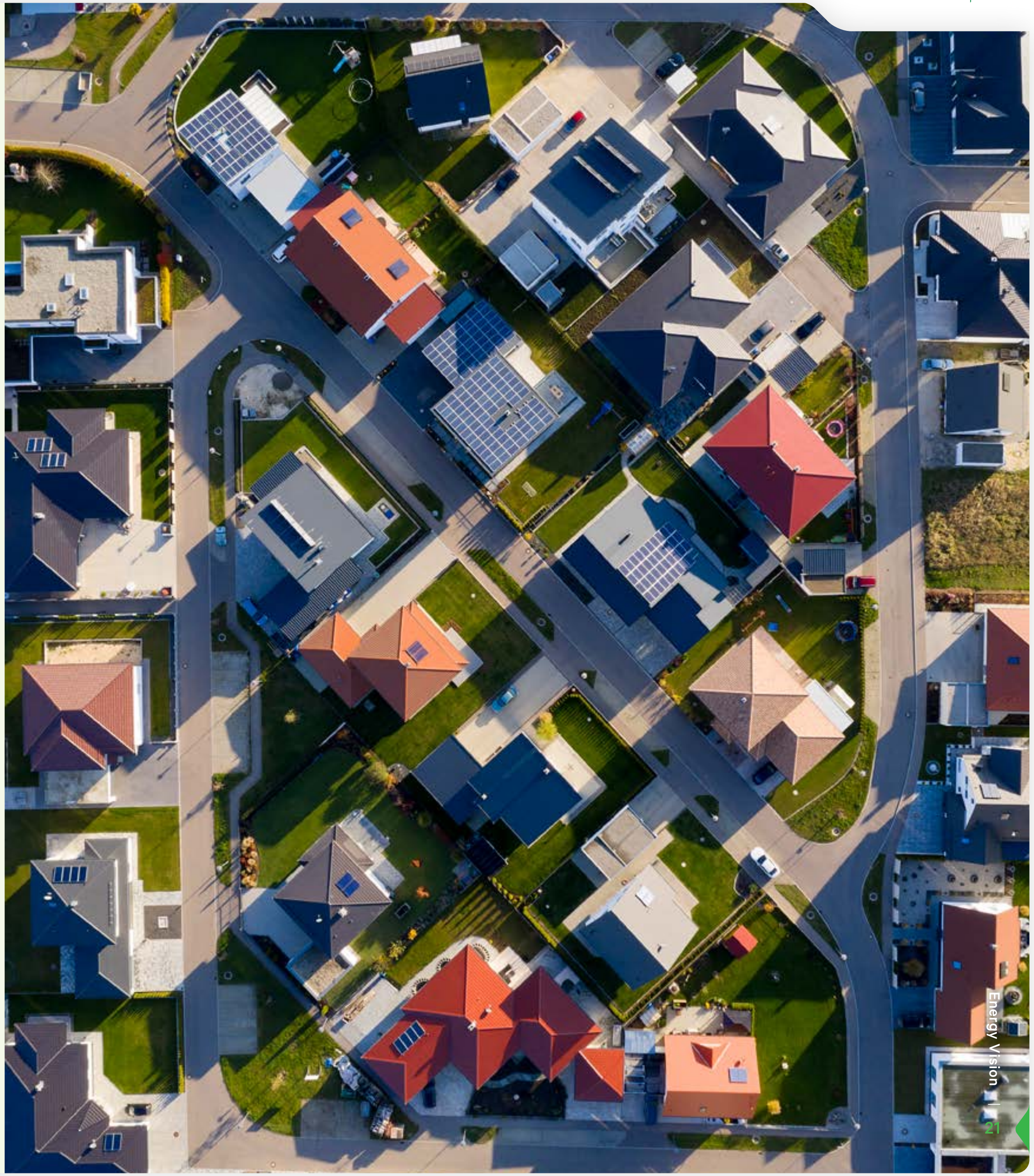
Prosumer power has the highest proportion of behind-the-meter generation, with rooftop solar providing 27% of the NEM's electricity needs by 2050.

The remaining 73% of our electricity requirements are met from largescale generators, delivered through the transmission backbone. It isn't an either/or; both small and largescale generation is required to meet Australia's changing electricity needs.

Figure 9: The proportion of underlying electricity consumption[1] met by rooftop solar in the NEM



1. Underlying electricity consumption represents the amount of electricity consumed, irrespective of whether it is supplied from behind-the-meter (e.g. rooftop solar) or in front-of-the-meter sources.



Electric Vehicles

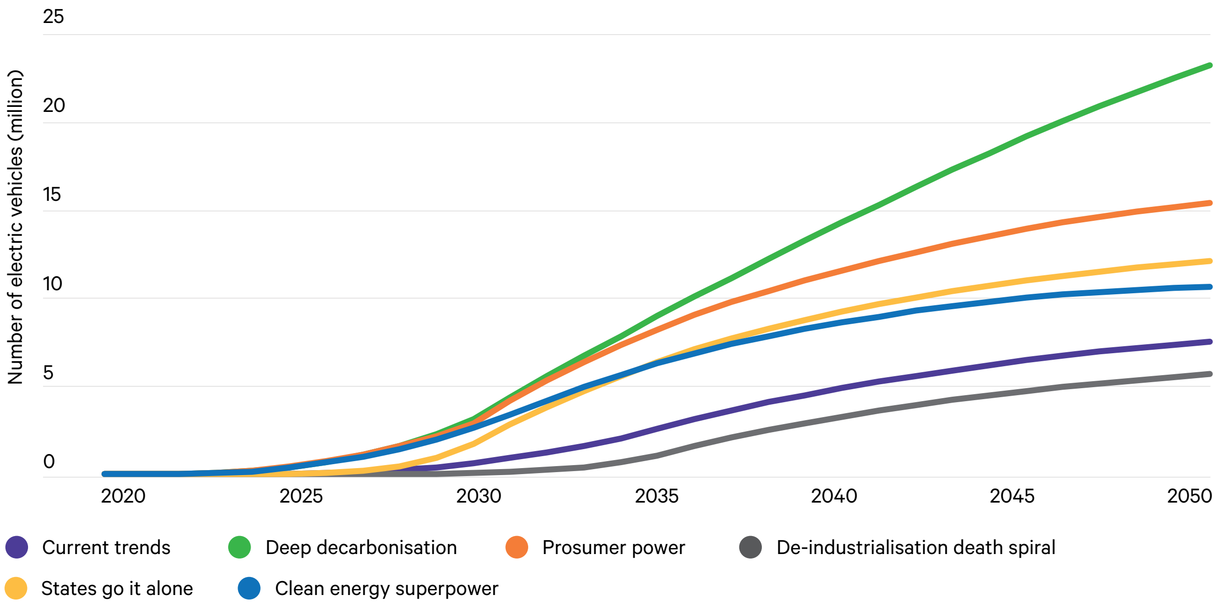
Under **Deep decarbonisation**, we project there will be more than 3 million electric vehicles on roads in NEM states by 2030, 14 million by 2040 and 23 million by 2050

Electric vehicles are projected to see mass-market penetration in the coming decade. While global passenger vehicle sales dropped 16% during the COVID-19 pandemic, sales of electric vehicles jumped 47% [z]. This trajectory is expected to accelerate, with falling electric vehicle costs driven by falling battery prices, dedicated electric vehicle manufacturing platforms and government support and incentives. In Europe, battery electric vehicles are expected to reach price parity with internal combustion engine vehicles between 2025 and 2027 [aa].

Australia currently lags other major economies in the growth of electric vehicles, with electric vehicle sales accounting for only 1.1% of all new car sales, behind the global average of 5%. However, in the first half of 2021, Australia's electric vehicle sales were twice that of the whole of 2020 [ab].

Across all scenarios, electric vehicle [1] uptake is projected to surge. Eight million electric vehicles are projected to be on the road across the NEM by 2050 in **Current trends**. Under **Deep decarbonisation**, we project there will be more than **3 million** electric vehicles by 2030 and 14 million by 2040. By 2050, all road transport is electrified, with the exception of 50% of articulated trucks. Patterns of vehicle use will also change; for example, as autonomous vehicles are introduced for ride sharing.

Figure 10: Projections of electric vehicle uptake across the NEM



To support the decarbonisation of our economy, by 2050, all road transport is electrified (with the exception of 50% of articulated trucks), with 23 million electric vehicles on roads in NEM states

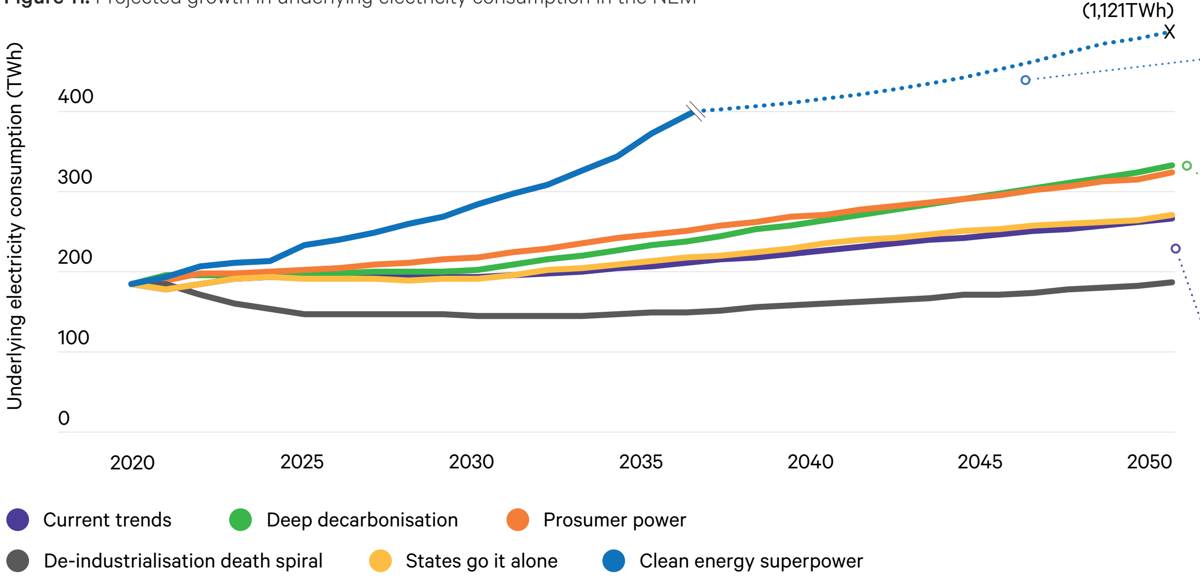
1. Including passenger vehicles, light commercial vehicles, trucks, busses and motorcycles.

Key trends

Surging demand for electricity

Surging demand for electricity in the coming decades could reshape our electricity system. Underlying electricity consumption is projected to grow over six times to 2050 in **Clean energy superpower**. Electricity consumption also grows significantly in **Prosumer power** and **Deep decarbonisation**, primarily due to the electrification of road transport and industry.

Figure 11: Projected growth in underlying electricity consumption in the NEM



NEM demand doubles by 2035 and then triples again by 2050 in **Clean energy superpower**, driven by the production of hydrogen and green steel

Even with significant efficiency improvements, electrification and hydrogen production drives a near doubling of underlying electricity consumption in **Deep decarbonisation** (electrification adds an extra 134TWh and hydrogen production an extra 39TWh in 2050)

In our business as usual **Current trends** scenario, NEM consumption grows 40% by 2050, primarily driven by vehicle electrification (48TWh additional by 2050)

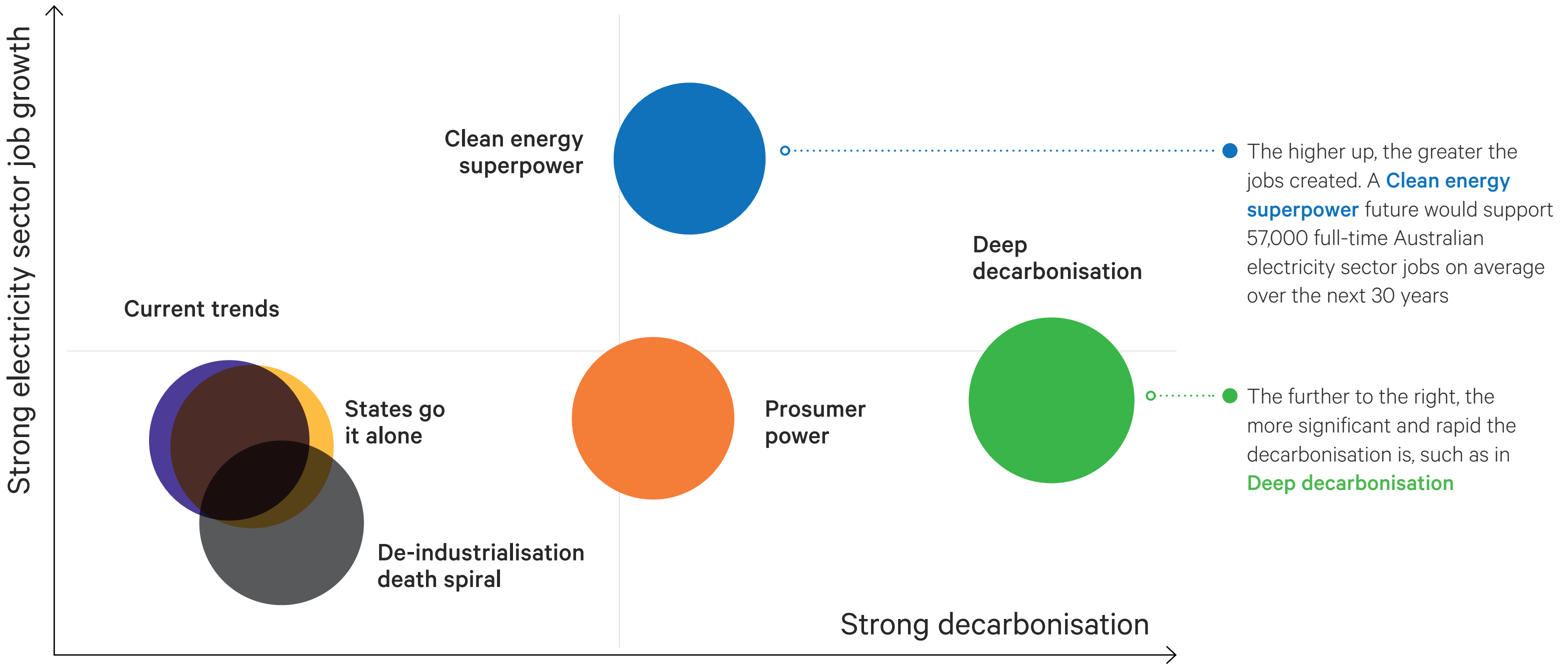
Note: Our modelling includes the economic and population impacts of COVID-19 on electricity demand, on changes in commercial and industrial activity in the short term and a decline in immigration in the medium term.

Transgrid

Decarbonisation, jobs & costs

The modelling offers clear insight into which scenarios will set Australia up to achieve net zero emissions, while also maximising job creation and keeping energy prices affordable. Figure 12 presents the six scenarios across these three key dimensions: decarbonisation, job creation and energy costs.

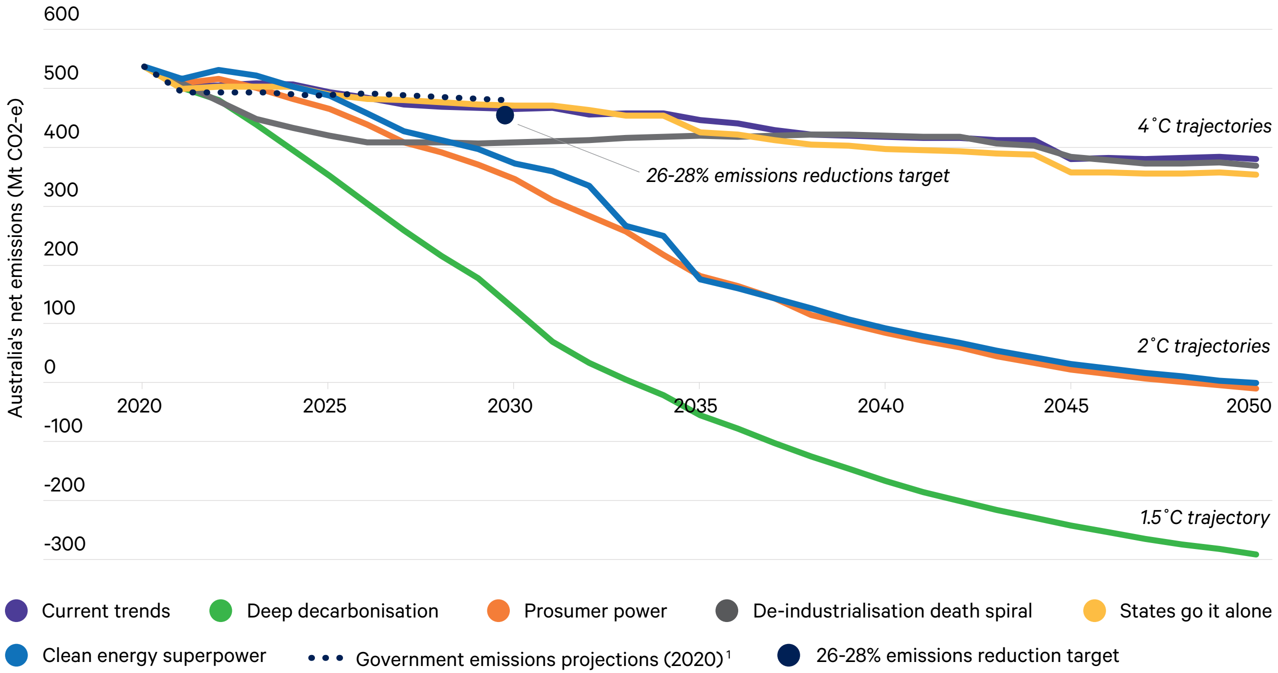
Figure 12: Comparing scenarios against their level of decarbonisation and electricity sector jobs created. The size of the bubble represents the average cost of electricity between 2021-50



Decarbonisation

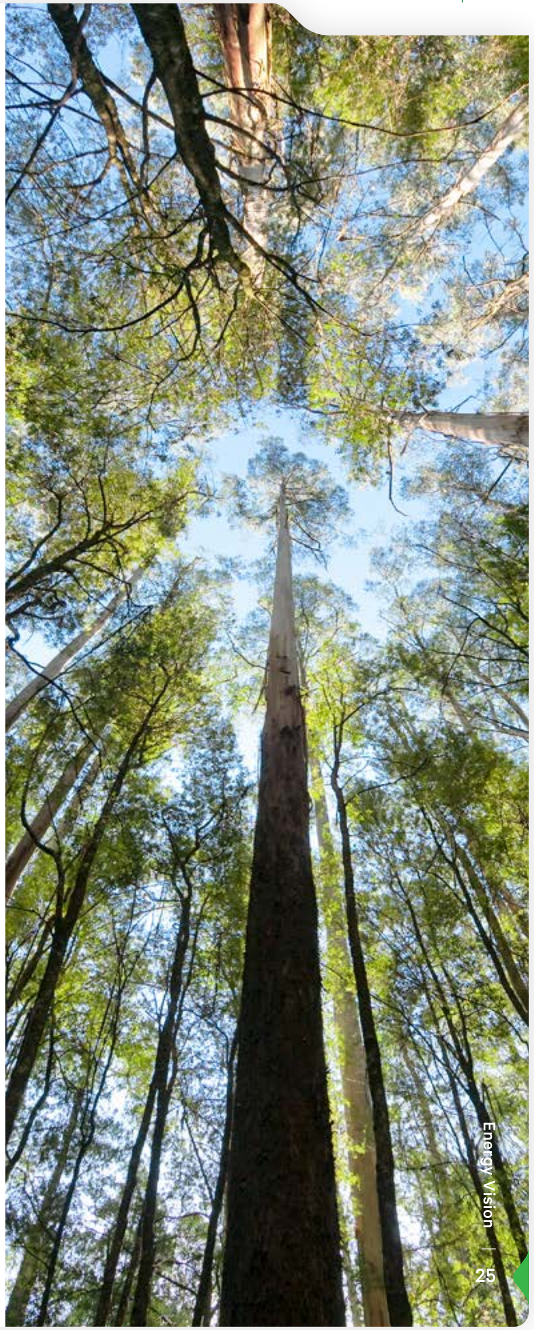
Figure 13 projects the outlook for Australia's greenhouse gas emissions across the six scenarios modelled. Our business as usual, **Current trends** scenario follows a 4°C temperature rise trajectory. Only a **Deep decarbonisation** of the Australian economy is consistent with the Paris Agreement's aspirational 1.5°C trajectory.

Figure 13: Emissions projections for the Australian economy



"Choosing net zero is an economic necessity. Holding global temperature rise to 1.5°C could increase GDP by 2.6% and add 250,000 jobs to the Australian economy by 2070"

Deloitte Access Economics, 2020, A new choice – Australia's climate for growth



1. Business as usual, without additional emissions reduction activities. Source: Australian Government, Department of Environment and Energy, 2020, Australia's emissions projections 2020, https://www.industry.gov.au/data-and-publications/australias-emissions-projections-2020

Electricity sector jobs

A **Clean energy superpower** future supports 68,000 electricity sector jobs on average from 2030-50, more than twice the level of jobs projected in **Current trends**

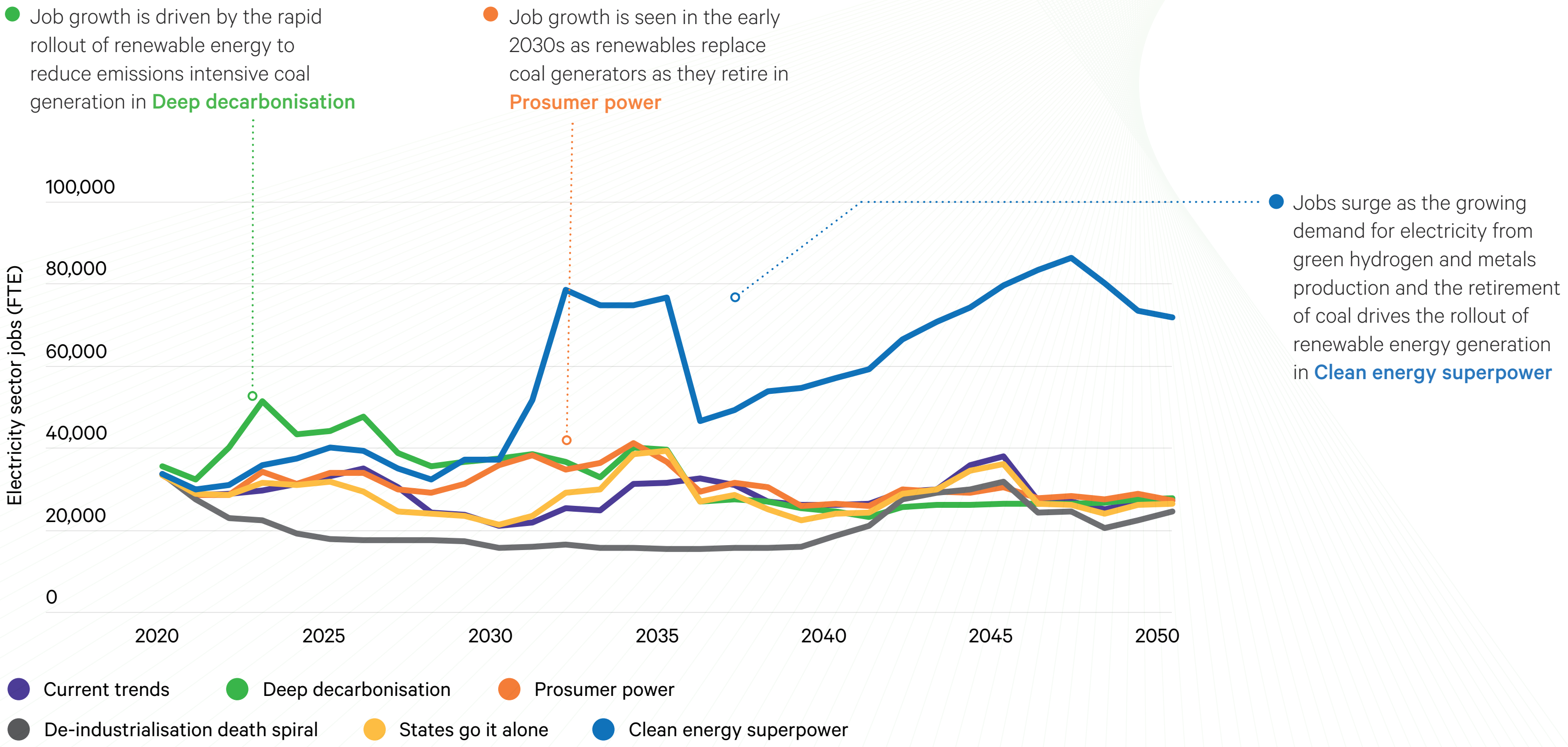
As our energy system transforms, new electricity sector jobs will be created. Many of these jobs will be located in regional Australia, supporting the construction and operation of generation, storage and transmission within and around renewable energy zones.

A **Deep decarbonisation** of Australia's economy would require 41,000 Australian electricity sector jobs on average over the next 10 years (full time equivalent), 45% more than projected in **Current trends**. In the following two decades, a **Clean energy superpower** future would support 68,000 electricity sector jobs, more than twice the level of jobs projected in **Current trends**.

This analysis considers Australian jobs required to enable the production of electricity in the NEM [ac]. Sectors include coal, gas, largescale wind and solar PV, grid batteries, pumped hydro storage, rooftop solar and behind-the-meter batteries, and the construction of new electricity transmission infrastructure. These sectors can be broken down into construction, installation, manufacturing, operations and maintenance and thermal coal and gas extraction for our domestic electricity sector.

Note: Our analysis does not assess additional indirect and downstream jobs created, for example in the production of hydrogen, green steel or any other use of electricity, which are likely to be multiples of the figures presented here.

Figure 14: Projections of electricity sector jobs in the NEM



Electricity sector jobs

Largescale wind, solar PV and rooftop solar make up the majority of jobs in **Deep decarbonisation**, as well as pumped hydro and electricity transmission jobs in **Clean energy superpower**, as shown in Figure 15. Coal and gas jobs decline in both scenarios, from a high of approximately 11,000 jobs in 2021.

Jobs aren't only created by the construction or installation of renewables. Operations and maintenance jobs also increase steadily over time, as shown in Figure 16.

Figure 15: Jobs required to support the NEM's electricity sector in **Clean energy superpower** and **Deep decarbonisation**, split by technology

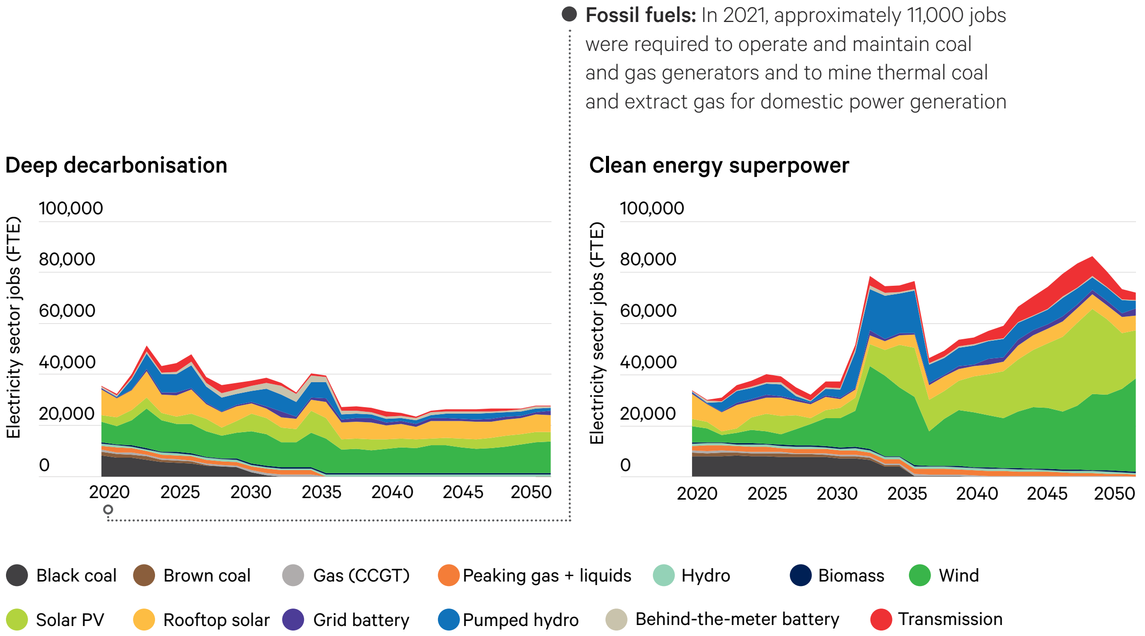
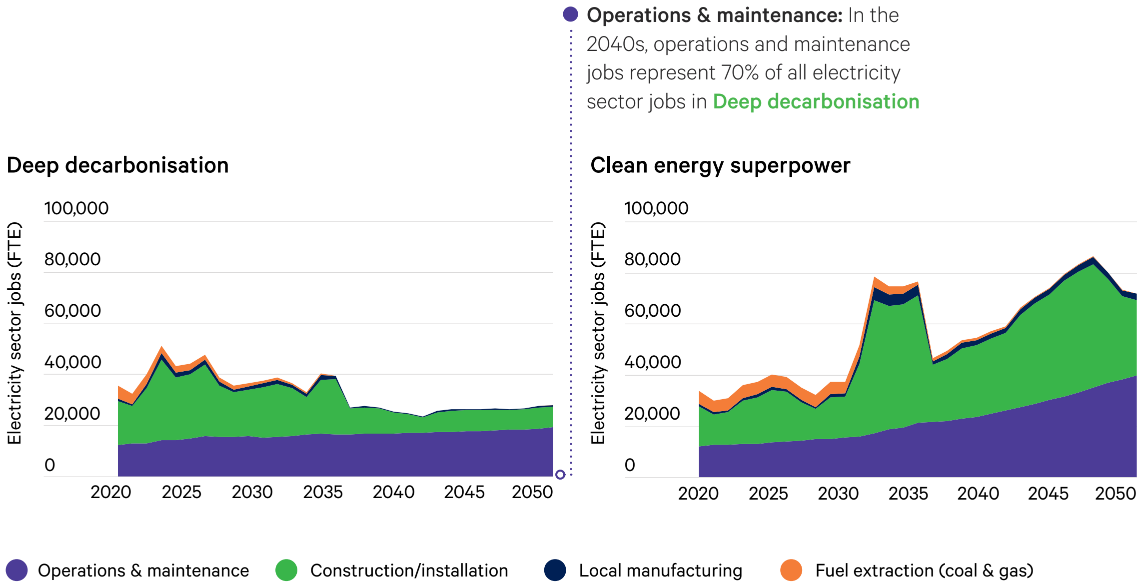


Figure 16: Jobs required to support the NEM's electricity sector in **Clean energy superpower** and **Deep decarbonisation**, split by type of work



Spotlight

Decarbonisation, jobs & costs

The orderly transition from fossil fuel jobs

Australian thermal coal mining, for export and domestic use [ad], creates almost 25,000 direct and many more indirect jobs.

Our modelling suggests that domestic demand for thermal coal will decline to zero or near-zero by 2050 across all scenarios. Globally, our top three thermal coal export markets [ae], Japan, China and South Korea, have all announced their intention to achieve net zero emissions by the middle of the century (2060 for China). NSW Treasury projects that, by 2050, NSW coal volumes will fall by almost 40% under a high global coal demand scenario, and NSW will cease producing coal by 2041 under a low global coal demand scenario [af].

It is essential that Australia plans and ensures a *just transition* for workers and communities reliant on fossil fuel mining and electricity generation, including direct and indirect workers. Our modelling suggests that a **Clean energy superpower** future will create a significant quantity of new jobs in renewable energy, storage, transmission and downstream hydrogen and steel production, many in similar locations to where existing fossil fuel industries are located, such as the Hunter Valley in NSW.

These regions can be at the forefront of Australia's clean energy future. But we need an orderly transition of the power system to not only ensure no community is left behind, but that communities are provided every opportunity to harness the full potential of new export industries. Proper planning and investment in reskilling and upskilling is required.

Electricity prices

Since 2016, the unexpected retirement of two power stations triggered a rapid rise in Australia's average wholesale electricity prices, peaking at just over $90/MWh in 2019. In mid-2020, prices fell by up to 58% compared with 2019 [ag], driven by:

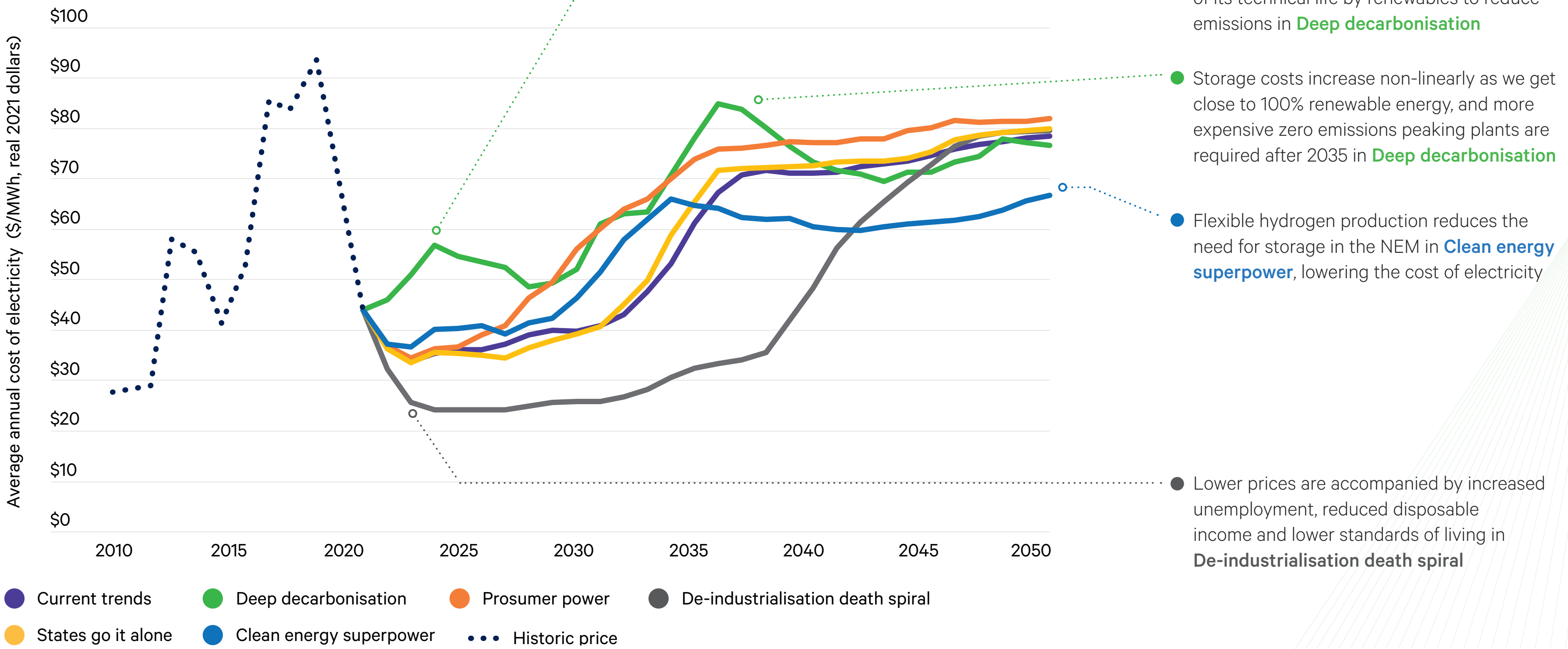
- Increased renewable generation, both largescale solar PV and wind and rooftop solar
- A reduction in electricity consumption due to the impacts of the COVID-19 pandemic
- A temporary reduction in domestic gas prices, corresponding with a reduction in international gas and oil prices
- A reduction in coal-fired generation to levels below what was seen prior to the retirement of Northern and Hazelwood power stations

Looking ahead, our analysis finds the cost of electricity in the NEM will remain below that of the previous five years for the coming three decades.

The influx of new renewable generation is likely to support low electricity prices for the coming 5-10 years [1], due to a short term oversupply in generation capacity, before the cost of electricity rises and then stabilises at around $70-80/MWh in all scenarios, except **Clean energy superpower**.

The comparisons presented in Figure 17 reflect the multiple complex drivers included in each scenario. Consequently, lower electricity costs do not necessarily mean a better outcome but merely a different outcome.

Figure 17: Historical and projected average annual cost of electricity in the NEM, including the cost of transmission and system security services



Note: Figure 17's projections represent the long run marginal cost of electricity and include the cost of transmission and system security services.

1. Our modelling has not considered the impact of unexpected plant failures on the price of electricity; for example, as was seen following the explosion at Callide Power Station in May 2021.

Electricity prices

Five of the six scenarios (except **De-industrialisation death spiral**) converge to 90-100% renewable energy share by 2050, translating to an 85-95% variable renewable energy share. The rise in the cost of electricity in the 2030s and the convergence of these costs can therefore be explained by:

- The retirement of sunk-cost coal generation capacity in the 2030s
- The increase in renewable generation, which increases the requirement for electricity storage. The duration of storage required increases non-linearly with increasing variable renewable energy share, and the capital cost of storage technology increases with storage duration
- Increased renewable energy deployment requires additional integration technology, such as transmission and system security services

These factors are offset by falling technology costs, as shown in Figure 2, which leads to a flattening out of electricity costs in the 2040s.

In contrast, **Clean Energy Superpower** converges towards $65/MWh by 2050 but has a renewable share of close to 100%. The reason for this lower cost outcome is the presence of a major hydrogen industry that consumes the majority of electricity in the system, but only when variable renewable energy is available[1]. This enormous source of demand management is equivalent to a much lower variable renewable energy share.

The lowest electricity costs for much of the projection period are associated with **De-industrialisation Death Spiral**. This is because falling demand is associated with very low investment. Therefore costs remain below the long-run marginal costs of new supply for a long period. Eventually, coal retirements trigger the need for investment and electricity costs rise to the level of the other scenarios.

Our analysis finds the **cost of electricity** in the NEM **will remain below that of the previous five years for the coming three decades**

1. The model is free to produce hydrogen at a flat rate but the least cost solution for the whole system is to sacrifice utilisation of the electrolysis plant and match production to renewable output.

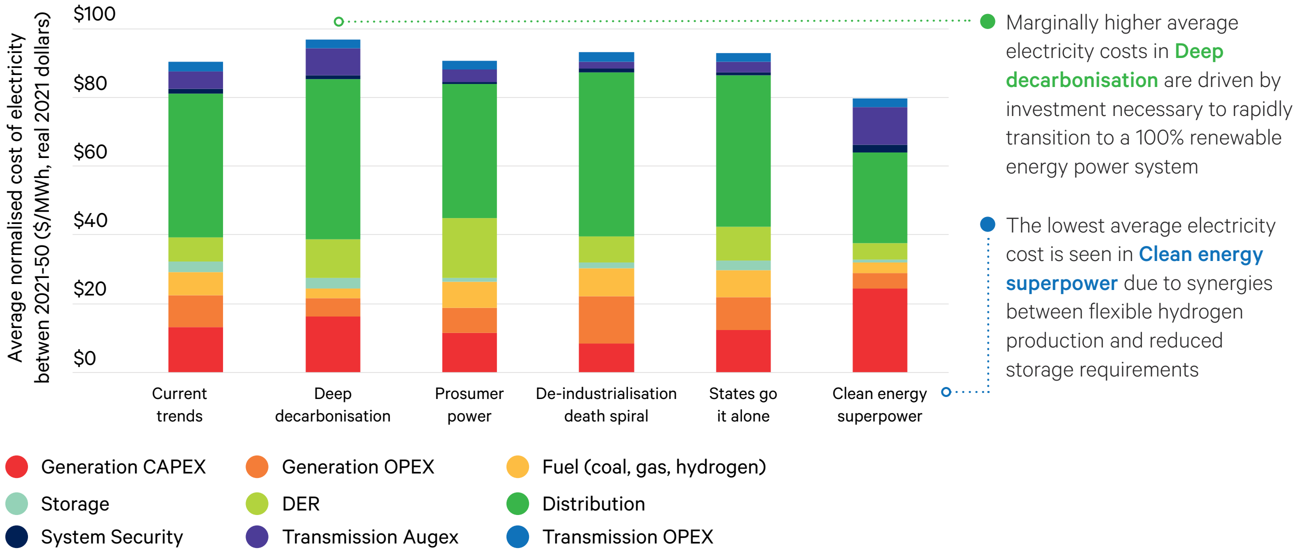
Normalised electricity system costs

Normalising for electricity consumption provides the fairest comparison of total system cost between scenarios. Figure 18 compares the six scenarios based on their 2021-50 average cost of energy ($/MWh), inclusive of distribution costs and consumer expenditure on distributed energy resources.

Clean energy superpower achieves the lowest average energy cost, 12% lower than **Current trends**. This is primarily driven by the synergy of flexible hydrogen production and lower storage requirements in the NEM from 2035 onwards.

Deep decarbonisation has 7% higher average energy costs than **Current trends**, reflecting the early retirement of all coal and gas generators to achieve a 100% renewable energy system by 2035.

Figure 18: Normalised average cost of electricity for the NEM over the period 2021-50



Comparing the breakdown of energy supply chain components in Figure 18, distribution costs account for the largest share, representing 43-51% of total system costs in all scenarios except **Clean energy superpower**. This is higher than previous estimates of around 20% by CSIRO and Electricity Networks Australia [ah], primarily because renewable generation and storage costs have fallen more significantly than expected, while productivity improvements in the distribution sector have been more incremental.

Clean energy superpower achieves the lowest average energy cost, 12% lower than **Current trends**

What it means for residential consumers

The decarbonisation of the Australian economy can deliver lower energy expenditure for residential consumers.

Residential consumers with a single electric vehicle could be at least $900/year better off under a **Deep decarbonisation** scenario, when considering expenditure on electricity, rooftop solar, batteries and electric vehicles.

Transport for NSW notes that electric vehicles are significantly cheaper to operate than internal combustion engine vehicles, with fuel cost savings of around 70% and maintenance savings of around 40%. For an average private car owner, this could amount to savings of $1,000 per year [ai].

Our modelling assesses the electricity expenditure of a typical residential consumer, when considering both their electricity bills *and* their personal spending on rooftop solar and batteries, but *excludes* the potential cost savings that come from switching away from petrol, diesel or gas to electricity.

> **"If we electrify the 'average' Australian household, with solar panels on the roof, a home battery, electric vehicles in the garage, and replacement of gas appliances with efficient electric ones, we can save $5,433 per year in household costs for the average home by 2030"**
>
> *Rewiring Australia, 2021, Castles and Cars - savings in the suburbs through electrifying everything*

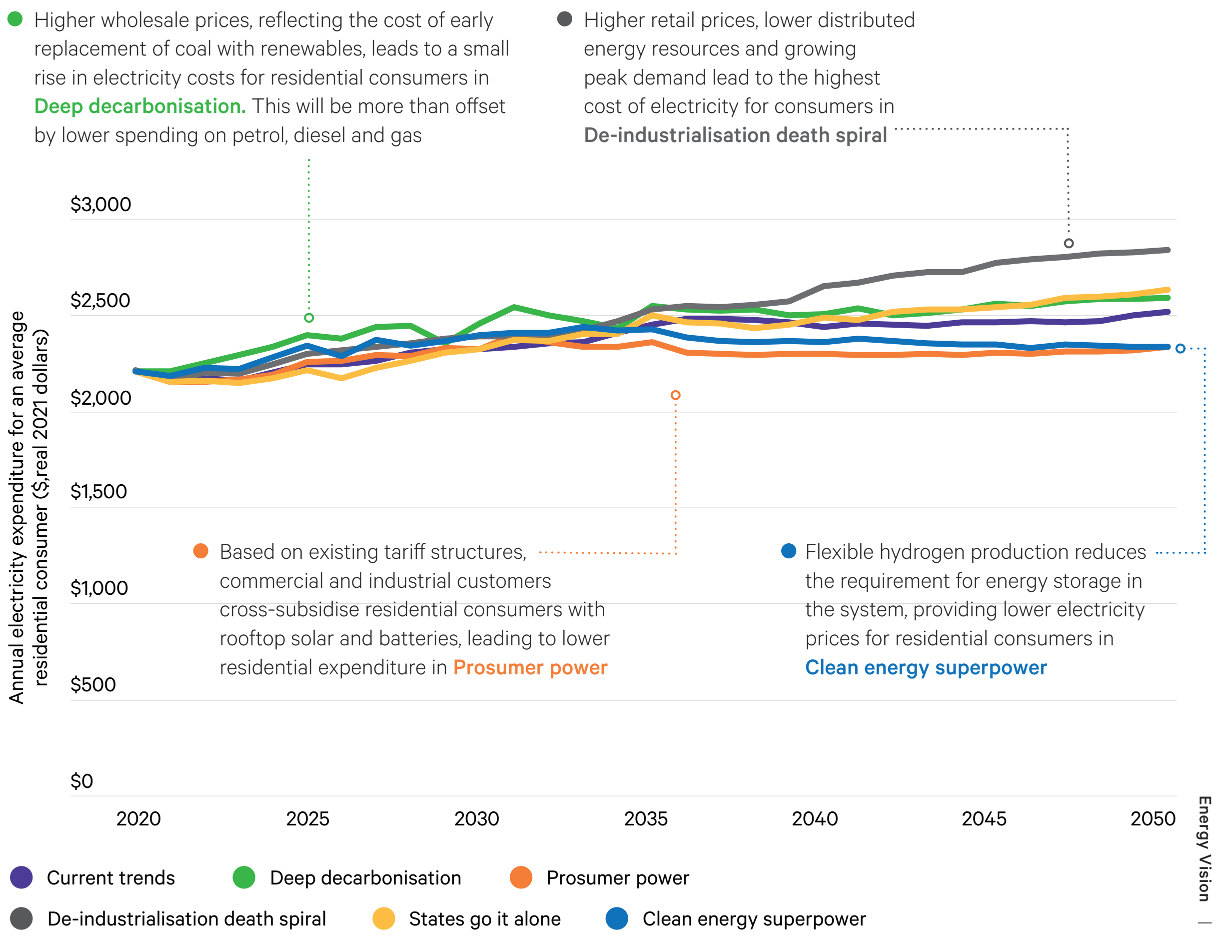
Our modelling therefore inherently disadvantages scenarios with higher levels of electrification, such as **Deep decarbonisation**. This is because the analysis *includes* additional electricity expenditure due to fuel switching (for example, switching from liquid fuels to electricity with electric vehicles or from gas to electricity for heating) but *excludes* reduced expenditure on these other fuels.

Figure 19 suggests that residential consumers' 2021-50 average expenditure on electricity, rooftop solar and batteries in **Deep decarbonisation** is only 4% higher ($90/year) than **Current trends**. Yet, electric vehicles are three times more prevalent in **Deep decarbonisation**. Once electric vehicles reach cost parity in the 2030s, the approximate $1,000 per car per year savings from electric vehicles alone will significantly outweigh the $90/year electricity expenditure increase. Thus, the net impact of **Deep decarbonisation** on residential consumers' electricity expenditure will be positive, and much lower than Figure 19 suggests.

Figure 19 shows that average household electricity spending remains between $2,300-2,500 per year across all scenarios, with the exception of **De-industrialisation** death spiral, which leads to the highest electricity expenditure for residential consumers.

While wholesale electricity prices halved in 2020, a reduction in electricity bills of this magnitude is not likely to be seen by residential consumers in the coming years, since wholesale electricity prices represent only 34% of total expenditure. The remaining components are made up of distribution costs (35%), environmental policies (9%), transmission (8%), metering (3%) and other costs (11%) [ai]. Our results suggest that average residential electricity expenditure in 2021 is likely to be 5% less than what was seen in 2019.

Figure 19: Projected electricity expenditure for an average residential consumer in the NEM, inclusive of electricity bills and consumer spending on rooftop solar and behind-the-meter batteries



Our vision

This Energy Vision sets out the least cost evolution of our energy system under a range of possible future scenarios and presents an evidence-based vision for a future that provides clear long-term benefits for Australians.

Our modelling shows that this future is achievable. But to realise this potential, the pace of change needs to rapidly accelerate. There is no time to waste.

We trust these insights will support energy system stakeholders in formulating the policies, reforms and investments required to enable the rapid and orderly decarbonisation of our energy system and build Australia the energy system we need to thrive in a clean energy future.

Our vision

Our analysis indicates that the transition towards a clean energy future can create immense opportunity for Australia – if we set ourselves on the optimal course.

Our vision is for Australia to become a global clean energy leader, benefitting communities, the economy and the environment.

As a nation, we have the choice of how we respond to this transition, not whether it happens at all.

Australia's energy system sits at the centre of this vision. It is critical to enabling a decarbonised economy and key to seizing the opportunity to grow our economy and jobs in a clean energy future.

Figure 20: Exploring our vision for Australia

Decarbonised economy

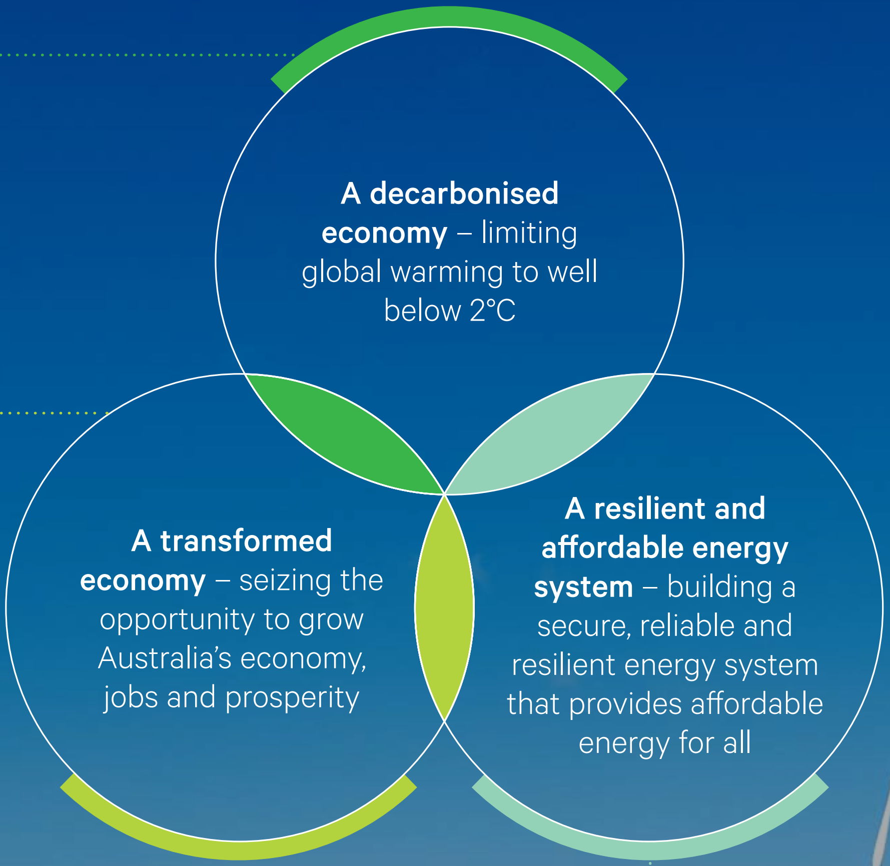
- **Net zero emissions** achieved economy-wide well before 2050
- Strong **energy efficiency**, 100% **renewable energy, electrification** of transport, industry and buildings, **fuel switching** and **carbon offsetting** are key pillars to decarbonise our economy

Transformed economy

- Harnessing Australia's renewable energy potential to become a global clean energy leader
  - **Leadership in emerging sectors** (e.g. battery manufacturing, mining of battery resources)
  - The **revitalisation of our industries** to manufacture and export green products (such as **steel, aluminium** and other metals)
  - **Export growth** through zero emissions energy (such as **hydrogen** & electricity)
- **Creating jobs and upskilling workers** for new industries

Resilient and affordable energy system

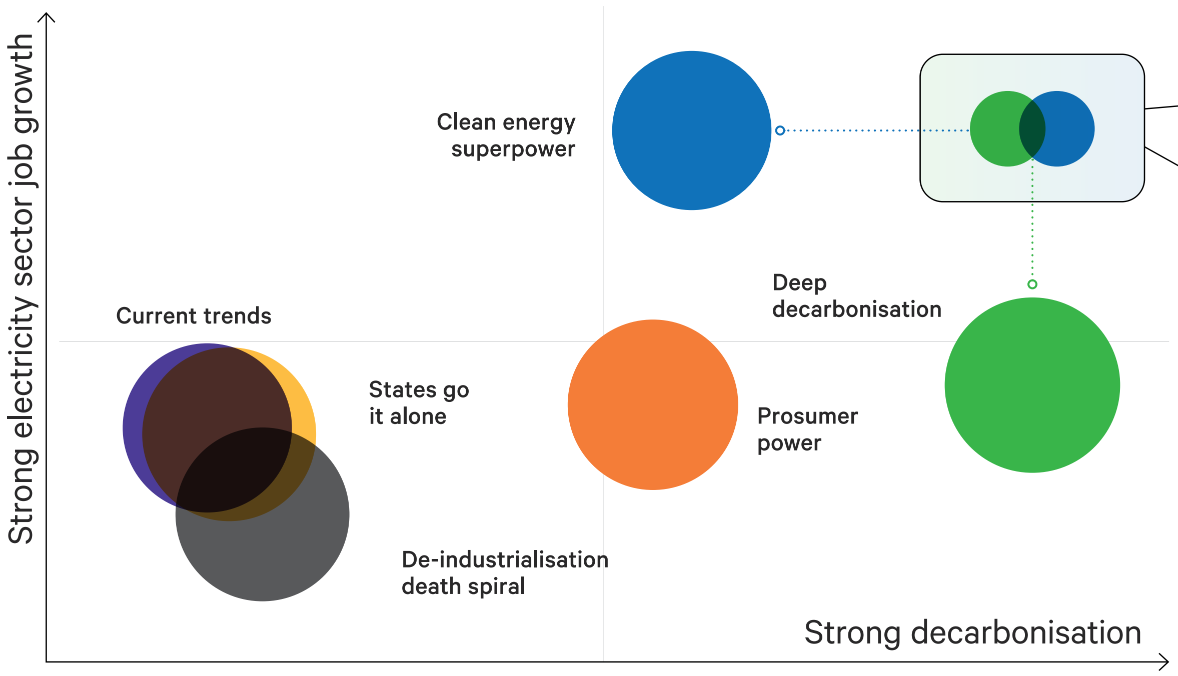
- A **resilient energy system** in the face of climate change
- A **secure** and **reliable** energy system
- **Affordable electricity**

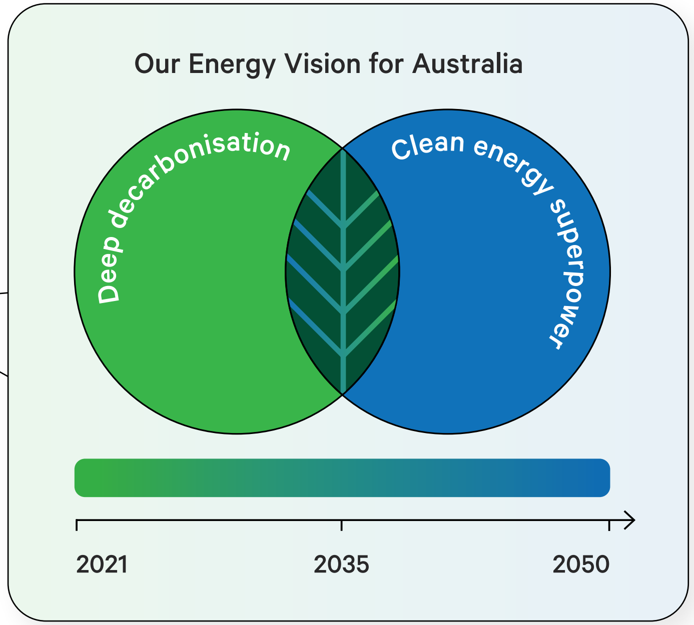


Which scenarios provide clear long-term benefits for Australians?

Our vision is for Australia to become a global clean energy leader – not just decarbonising our own economy, but also supporting the decarbonisation of the global economy. From our analysis, we see optimal advantage for Australia in a combination of two scenarios: first **Deep decarbonisation**, which then morphs into Australia becoming a **Clean energy superpower**.

Figure 21: Deep decarbonisation and **Clean energy superpower** offer a pathway to a low emissions economy that supports job creation and provides affordable electricity for Australians





This combination of future scenarios holds the most promise for Australians, in terms of decarbonisation, job creation and affordable energy prices.

These two scenarios bring together the economic and climate benefits captured through embracing the energy transition and Australia's natural advantage to become a renewable powerhouse.

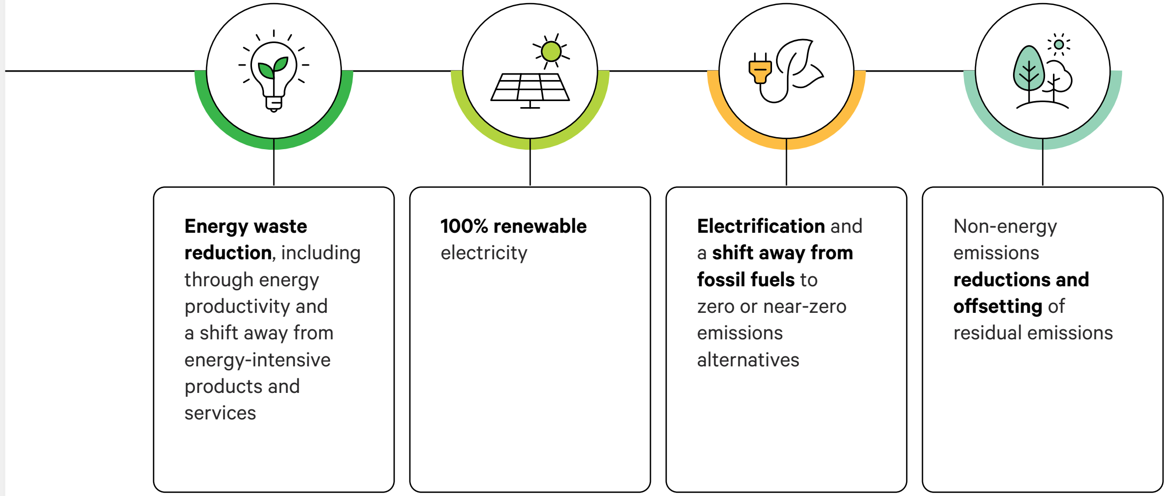
Deep decarbonisation

In this scenario, Australia achieves net zero emission and a 100% renewable power system by 2035, internal combustion engine vehicles are completely phased out by 2050, replaced primarily by electric vehicles, and hydrogen is used for heavy transport, industry and peaking electricity generation.

ClimateWorks Australia has charted the path to decarbonisation, noting four essential pillars necessary to achieve net zero emissions at the lowest cost.

The four pillars of decarbonisation

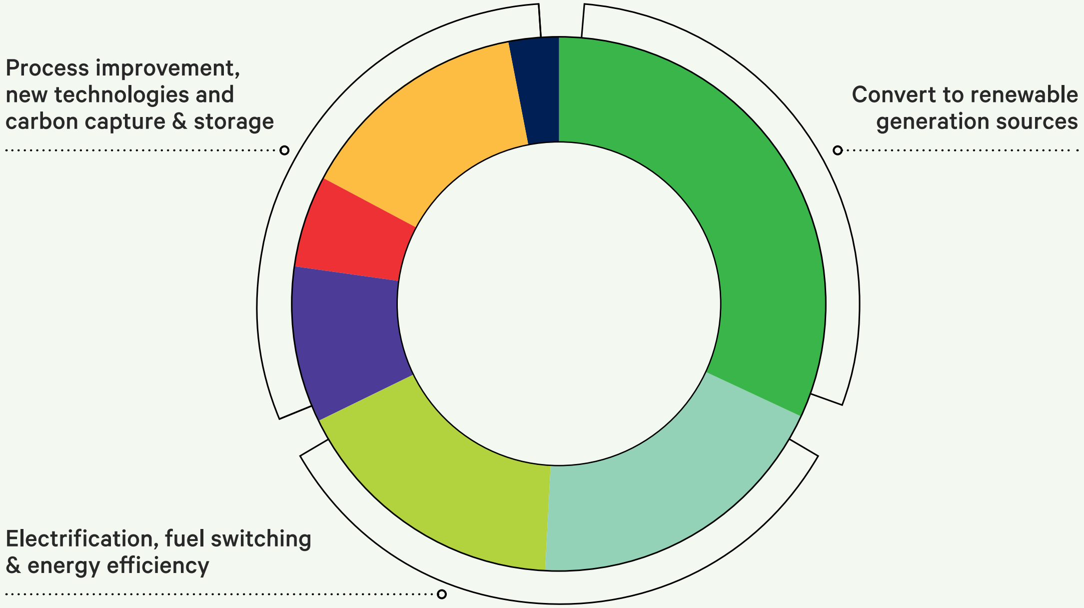
Figure 22: The four pillars of decarbonisation [ak]



Greenhouse gas emissions breakdown

Figure 23: The breakdown of Australia's greenhouse gas emissions [al] and the likely route to decarbonise each sector

- 34% Electricity
- 18% Transport
- 6% Industrial processes and product use
- 3% Waste
- 20% Stationary energy excluding electricity
- 10% Fugitive emissions
- 15% Agriculture



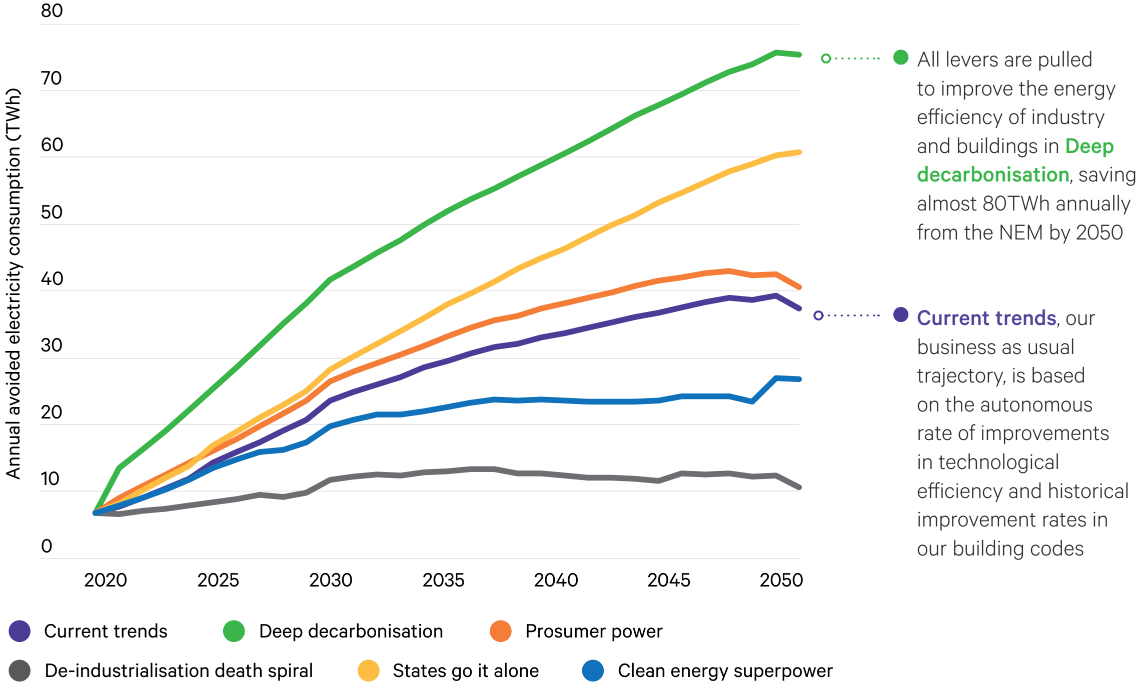
Our vision

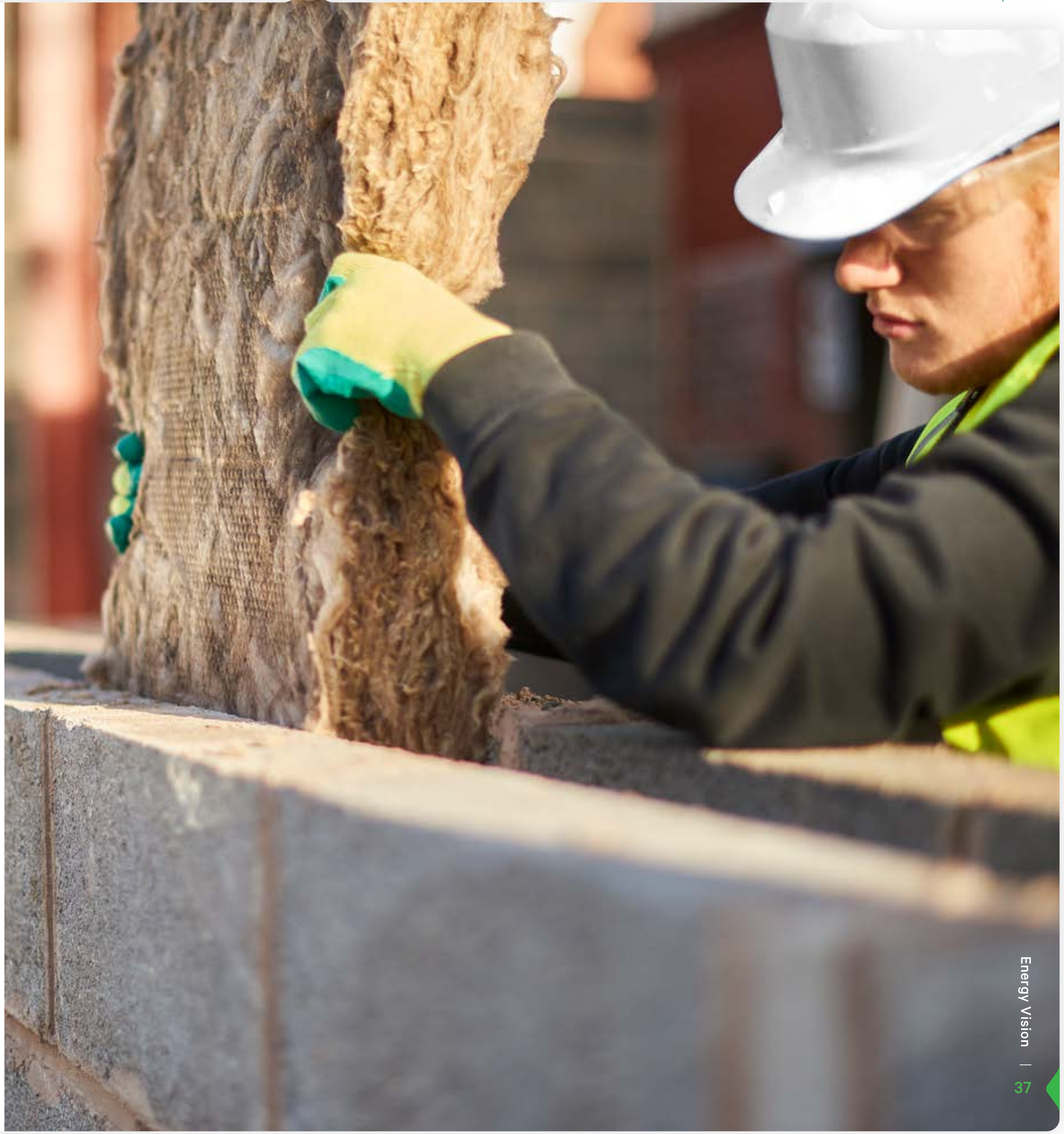
Deep decarbonisation

Pillar one: energy waste reduction

Strong policies and incentives to drive the uptake of efficiency measures could double the amount of energy we can save, as shown in **Deep decarbonisation** in Figure 24.

Figure 24: Projections of avoided electricity consumption from energy efficiency in industry and buildings in the NEM





Transgrid

Deep decarbonisation

Pillar two: 100% renewable electricity

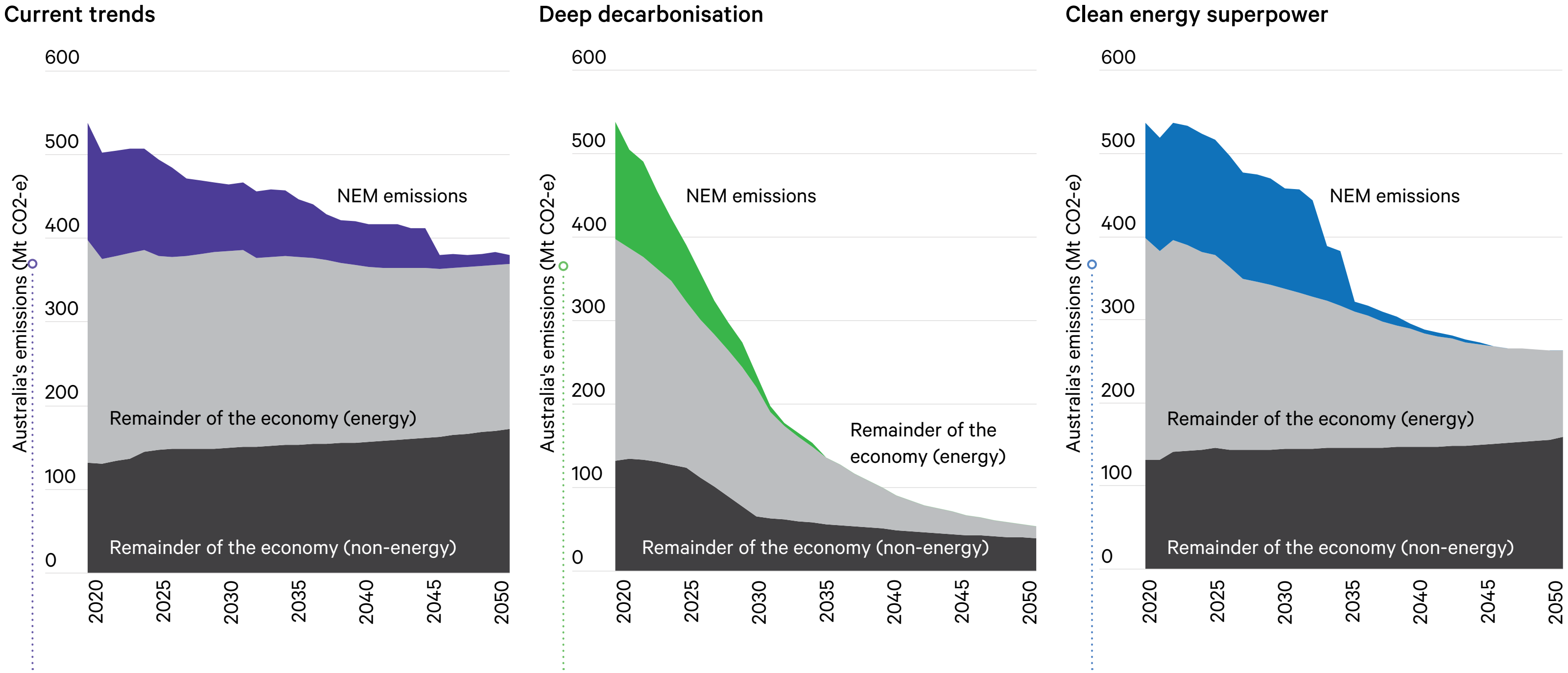
Electricity generation is Australia's highest emitting sector, accounting for 33% of total emissions [am]. Rapidly switching to renewable energy enables the decarbonisation of electricity generation and supports the decarbonisation of other sectors of the economy through electrification.

Under our business as usual **Current trends** trajectory, the NEM's electricity sector is projected to reduce its emissions 93% by 2050. To facilitate the **Deep decarbonisation** of our economy, we hit 100% renewable energy by 2035, as shown in Figure 25.

> **"A decarbonised power sector, dominated by renewable sources, is at the core of the transition to a sustainable energy future"**
>
> *IRENA, 2018, Global Energy Transformation: A roadmap to 2050*

> **"To achieve net zero emissions globally by 2050, unabated natural gas-fired generation peaks by 2030 and is 90% lower by 2040"**
>
> *International Energy Agency, 2021, Net Zero by 2050*

Figure 25: Australia's emissions projections and breakdown into the NEM and rest of the economy [1]



- Emissions from the NEM's electricity sector are projected to fall by 93% to 2050 in **Current trends**, while emissions from the rest of Australia's economy only falls by 7% over the same period
- It takes less than 15 years to eliminate emissions from the NEM's electricity sector (by 2035) and takes almost 30 years (to 2050) to reduce 87% of emissions from the rest of the economy in **Deep decarbonisation**
- Under a 2°C trajectory in **Clean energy superpower**, by 2050, half of all of Australia's emissions reductions are achieved by the NEM's electricity sector

1. Note: results exclude land-based sequestration offsets, which are necessary to achieve net zero emissions by 2050 in **Clean energy superpower** and **Prosumer power** and net zero emissions by 2035 in **Deep decarbonisation** and then net negative emissions beyond.

Deep decarbonisation

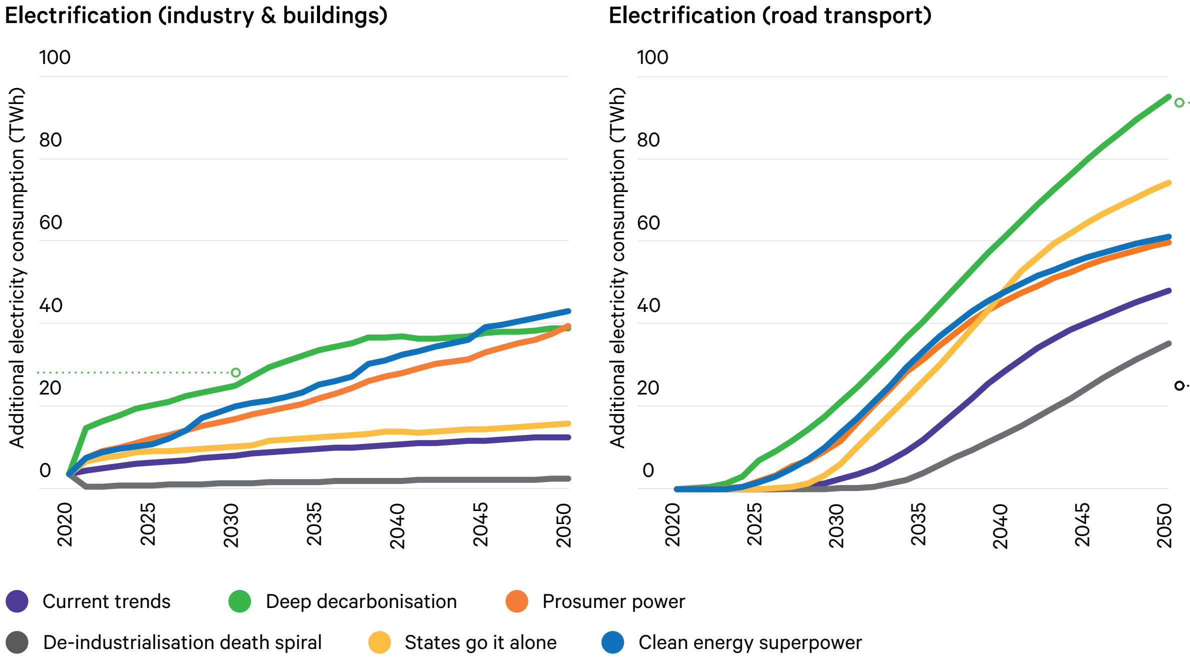
Pillar three: electrification and fuel switching

Spreading the use of electricity into more parts of the economy is the single largest contributor to reaching net zero emissions[an]. Electrification offers the cheapest route to decarbonise sectors such as light-duty transport (replacing liquid fuels), cooking, space and water heating (replacing gas) and many industrial and manufacturing processes (replacing gas, oil and coal)[ao].

Weaning the heavy transport sector off oil will be much harder. Yet to achieve a **Deep decarbonisation** of the economy, oil must be phased out and switched with other fuel sources, such as bioenergy or hydrogen. These sources are projected to play a key role in replacing fuels that are challenging to electrify, such as for heavy vehicles, aviation and shipping.

- Approximately 75% of the increase in energy consumption due to electrification in industry and buildings comes from industry, 20% from residential buildings and 5% from commercial buildings in **Deep decarbonisation**

Figure 26: Projections of increased electricity consumption in the NEM from electrification[1]



- By 2050, all road transport is electrified in **Deep decarbonisation** (23 million electric vehicles), apart from an assumed 50% of articulated trucks being run on hydrogen fuel cells

- The growth in electricity consumption from the transport sector is larger than the decline in electricity consumption due to energy efficiency in **all scenarios**

> **"Spreading the use of electricity into more parts of the economy is the single largest contributor to reaching net-zero emissions"**
>
> *International Energy Agency, 2020, Energy Technology Perspectives*

> **"By 2030, 60% of new car sales should be electric, with no internal combustion cars being sold after 2035"**
>
> *International Energy Agency, 2021, Net Zero by 2050*

1. Figure 26 (left) represents the electrification of existing Australian industries. It does not include the additional growth in green steel and aluminium production envisaged in **Clean energy superpower**.

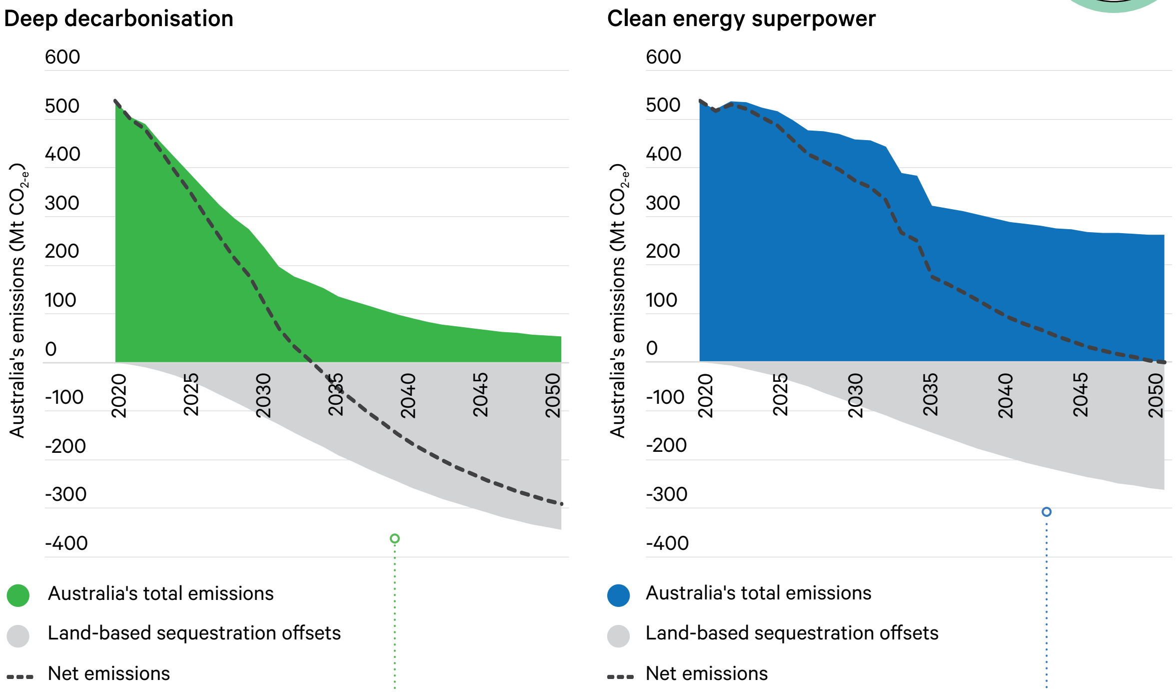
Deep decarbonisation

Pillar four: non-energy emissions reductions and land-based carbon offsets

Non-energy emissions reductions will include emissions from mining fossil fuels, manufacturing heavy metals and materials, and agriculture [ap].

Carbon offsetting is a temporary solution on a pathway to zero emissions [aq]. Land-based sequestration is required to offset hard-to-abate sectors that lack established or cost effective low emissions technology alternatives. Our modelling suggests that ambitious amounts of land-based sequestration will be required to successfully reach net zero emissions by 2035 and net negative beyond in **Deep decarbonisation** and net zero emissions by 2050 in **Prosumer power** and **Clean energy superpower**.

Figure 27: Total Australian emissions and requirements for land-based sequestration offsets



- To keep within **Deep decarbonisation's** 1.5°C emissions budget, 5,562MT CO_{2-e} of land-based sequestration are required by 2050
- Due to significantly fewer emissions reductions achieved across the economy, keeping within **Clean energy superpower's** 2°C emissions budget requires 4,250MT CO_{2-e} of land-based sequestration by 2050

Land-based sequestration is required to offset hard-to-abate sectors that lack established or cost effective low emissions technology alternatives

Our vision

Clean energy superpower

This is a future where we harness Australia's abundant renewable energy resources, large landmass, significant mineral ores and access to Asian markets to revitalise our industries, grow our economy and create new jobs.

Hydrogen offers an exciting opportunity to decarbonise hard-to-abate sectors of the global economy, such as heavy transport, as a fuel and feedstock for industrial processes, such as steel making, and for electricity peaking generation. BloombergNEF suggests that renewable hydrogen will be cheapest to produce in countries with the lowest-cost electricity, such as India, Brazil, Australia and Scandinavia [ar]. Australia's hydrogen exports could supply countries that don't have enough suitable land or renewable resources to meet their own domestic hydrogen needs.

Australia is the world's largest producer and exporter of iron ore, accounting for 67% of global exports. Yet only 1% of Australia's iron ore goes to domestic steelmaking, producing only 0.3% of the world's steel [as]. In a zero-carbon world, Ross Garnaut suggests there will be no economic sense in any aluminium or iron smelting in Japan or Korea, not much in Indonesia, and enough to cover only a modest part of domestic demand in China and India [at].

Noting the high cost of hydrogen transport and Australia's abundant renewable energy and iron ore resources, the domestic production of zero emissions green steel could become globally competitive, enabling us to grow our export revenues, create local jobs and help reduce global emissions.

> "Use of clean hydrogen can help address the toughest third of global greenhouse gas emissions by 2050, but only if net-zero emission goals and policies are set"
>
> *BloombergNEF, 2020, Hydrogen Economy Outlook – key messages*

> "Converting one quarter of Australian iron oxide and half of aluminium oxide exports to metal would add more value and jobs than current coal and gas combined"
>
> *Ross Garnaut, 2019, Australia could fall apart under climate change. But there's a way to avoid it, The Conversation*

Hydrogen and green steel

As the cost of producing hydrogen from electrolysis falls, zero emission electricity becomes the dominant energy source for hydrogen production, with green hydrogen representing 94% of total hydrogen production by 2050

Broadly in line with the Federal Government's National Hydrogen Strategy high scenario, our analysis assumes that in **Clean energy superpower**, 1.1MT of hydrogen is produced annually in Australia by 2030 and 19.2MT by 2050. Of that total, our analysis assumes 11.7MT of hydrogen is exported, 4.3MT is used domestically to produce and export green steel and the remaining 3.2MT is used domestically for heavy transport, electricity generation and other industrial processes, as shown in Figure 28.

Our modelling optimises for the least cost hydrogen production pathway. Results for **Clean energy superpower** suggest that, as the cost of producing hydrogen from electrolysis falls, zero emission electricity becomes the dominant energy source for hydrogen production, with green hydrogen representing 94% of total hydrogen production by 2050 (18MT), as shown in Figure 29.

Figure 28: Hydrogen production assumptions, Australia-wide

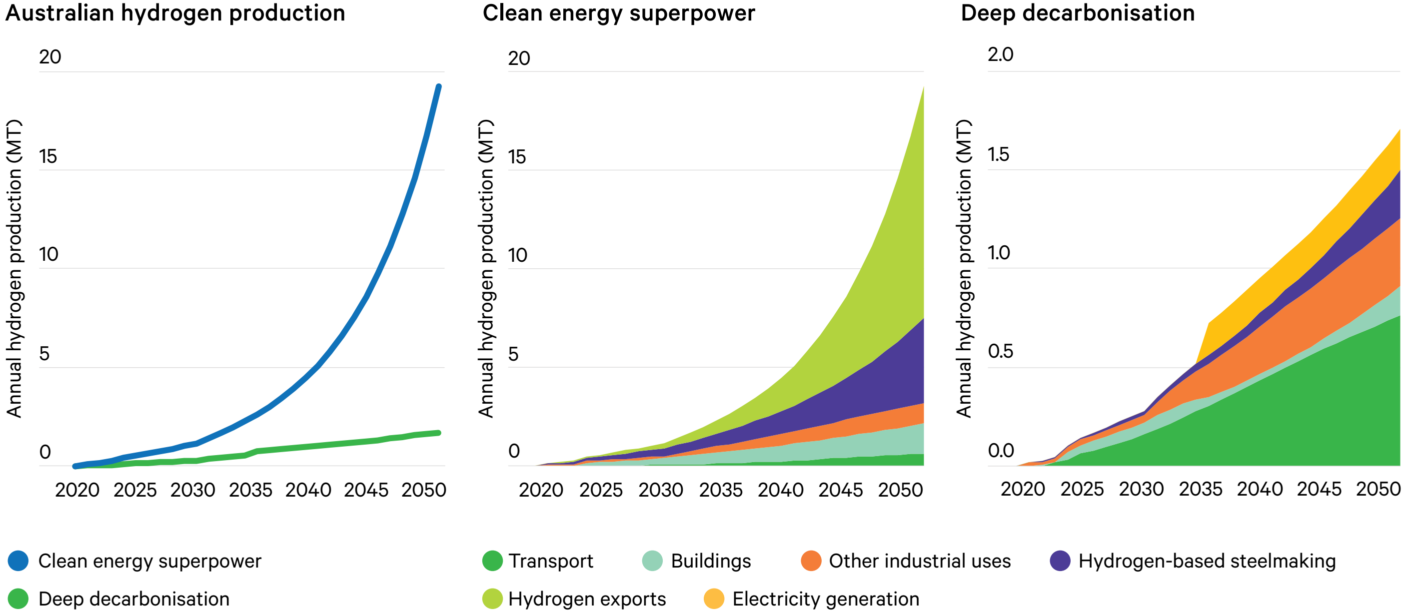
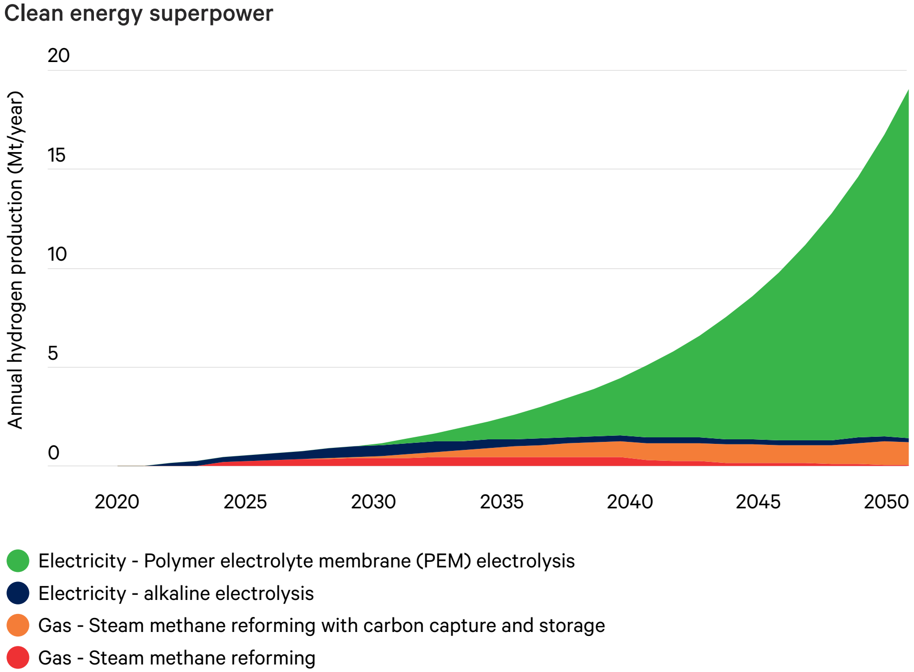


Figure 29: Hydrogen production in Australia, split by production pathway



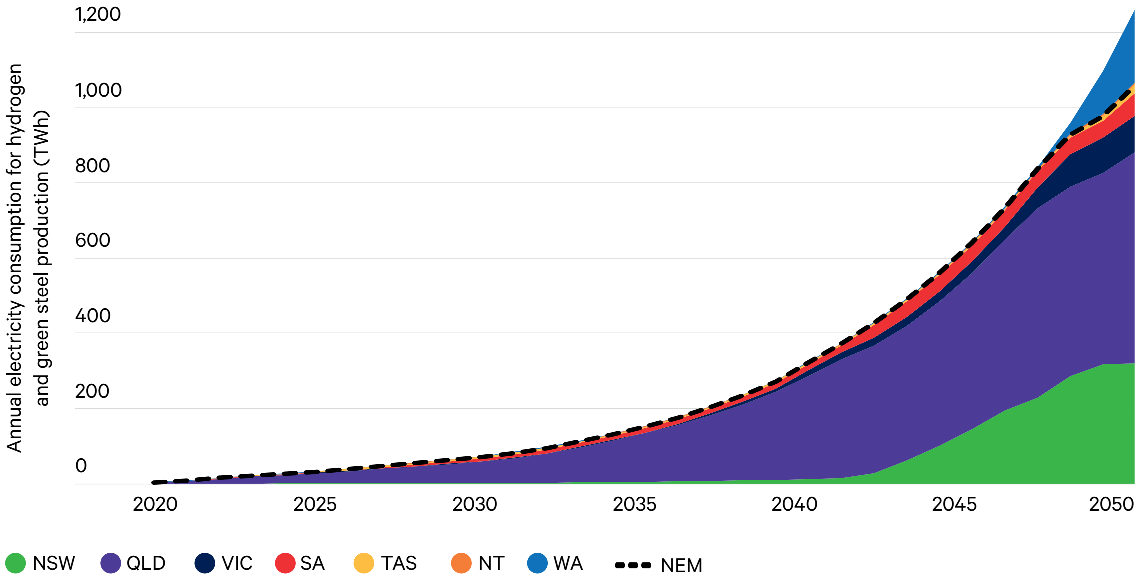
Hydrogen and green steel

Our analysis optimises for the least cost location and cost of hydrogen production (Australia-wide). Projections suggest that the levelised cost of green hydrogen in **Clean energy superpower** will fall below $2/kg in the early 2030s, reaching $1/kg by 2050 at major hydrogen producing locations on the south and east coast of Australia. Hydrogen production costs include capital and operating expenditures, but exclude hydrogen transportation and hydrogen storage costs.

Clean energy superpower assumes that, by 2050, Australia retains 18% of its iron ore output for conversion to steel via a hydrogen Direct Reduction, electric arc furnace and hot rolling production route to produce 100MT per year of steel [au].

Our analysis optimises for the least cost location and cost of green steel production (Australia-wide), constrained by port capacities and the availability of a skilled workforce. Production costs include construction and operation costs, including the domestic transport of iron ore and electricity and green hydrogen inputs.

Figure 30: Electricity consumption for hydrogen and green steel production across Australia in **Clean energy superpower**



Optimised for both hydrogen and green steel production, results indicate that QLD dominates in the 2030s, followed by NSW and WA in the 2040s, as shown in Figure 30. Exploring these results:

- QLD is dominant due to the quantum of low-cost renewable energy resources, the large skilled workforce and available port capacity
- NSW's hydrogen and green steel production grows in the 2040s, particularly in the Hunter Valley, as the demand for hydrogen and green steel increases, making use of the large workforce available
- WA, while home to the majority of Australia's iron ore resources, is projected to have a smaller share of hydrogen and green steel production by 2050, primarily due to higher labour and construction costs and a smaller available workforce. These higher costs offset the cost of transporting iron ore to the east coast of Australia.

Producing 19.2MT/year of green hydrogen and 100MT/year of green steel would require more than 1,200TWh of electricity Australia-wide by 2050.

Our analysis assumes this quantity of hydrogen production is grid connected, with electricity brought in from renewable energy zones via electricity transmission to industrial hubs located at major ports. This assumption ensures we can stress test the implications of a large hydrogen industry on the NEM. In practise, the supply chain configuration will vary depending on the economics of specific projects, with likely options being grid-connected and located near end users (with electricity tranported from renewable energy zones via transmission) and off-grid or edge-of-grid, where hydrogen is produced near renewable energy zones and is transported via dedicated pipelines or trucks to end users.

The levelised cost of green hydrogen in **Clean energy superpower** is projected to fall below $2/kg in the early 2030s, reaching $1/kg by 2050 at major hydrogen producing locations on the south and east coast of Australia.

Supporting global decarbonisation

Efforts to support global decarbonisation could strengthen Australia's economic growth, boost exports and build local jobs

Additional export opportunities

Clean energy superpower assumes a significant growth in domestic aluminium production (to 10MT/year of aluminium), requiring eight additional large aluminium smelters in the NEM by 2050 [av].

In addition, the decarbonisation of the global economy will create a surge in demand for minerals. Australia is uniquely placed to take advantage of this opportunity. By 2040, demand for lithium could grow 42 times, 25 times for graphite, 21 times for cobalt, 19 times for nickel and 7 times for rare earth metals [aw].

Australia possess some of the world's largest recoverable resources of lithium (currently we are the world's largest producer), nickel, titanium and cobalt, and has the world's sixth largest rare-earth resource base [ax].

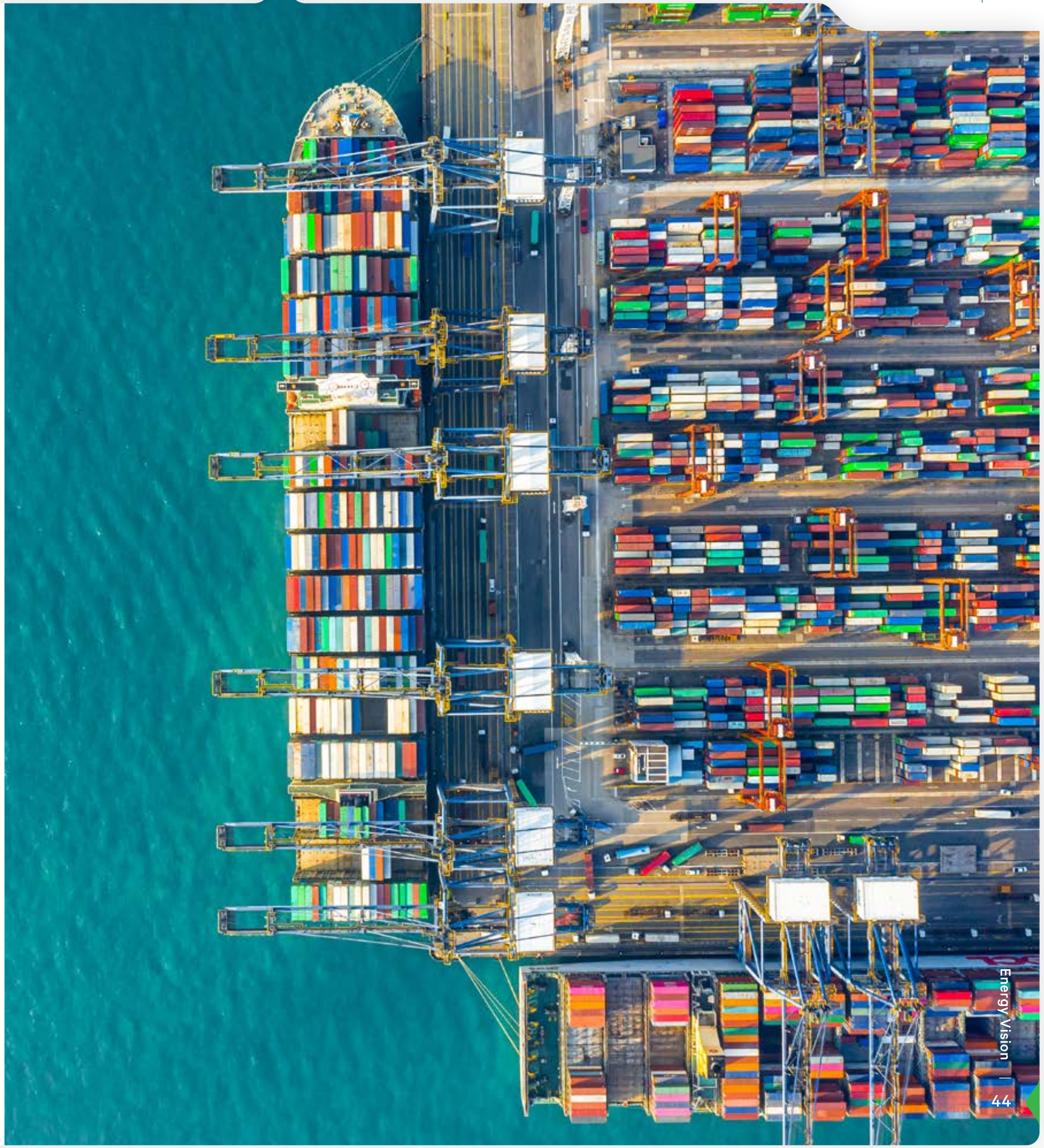
The export of electricity via undersea cables to our South East Asian neighbours is also envisaged in the narrative of **Clean energy superpower**, but not modelled as these links are unlikely to interact with the NEM.

> "Australia has the potential to grow a new green export mix worth $333 billion per annum, almost triple the value of existing fossil fuel exports"
>
> *Beyond Zero Emissions, 2021,*
> *Export Powerhouse:Australia's $333 billion opportunity*

Additional jobs and export revenue beyond the electricity sector

Actual job creation in a **Clean energy superpower** future would be signficantly greater than our modelling shows because the analysis only considers jobs in the electricity sector. Other analysis suggests significant GDP and job growth in downstream industries:

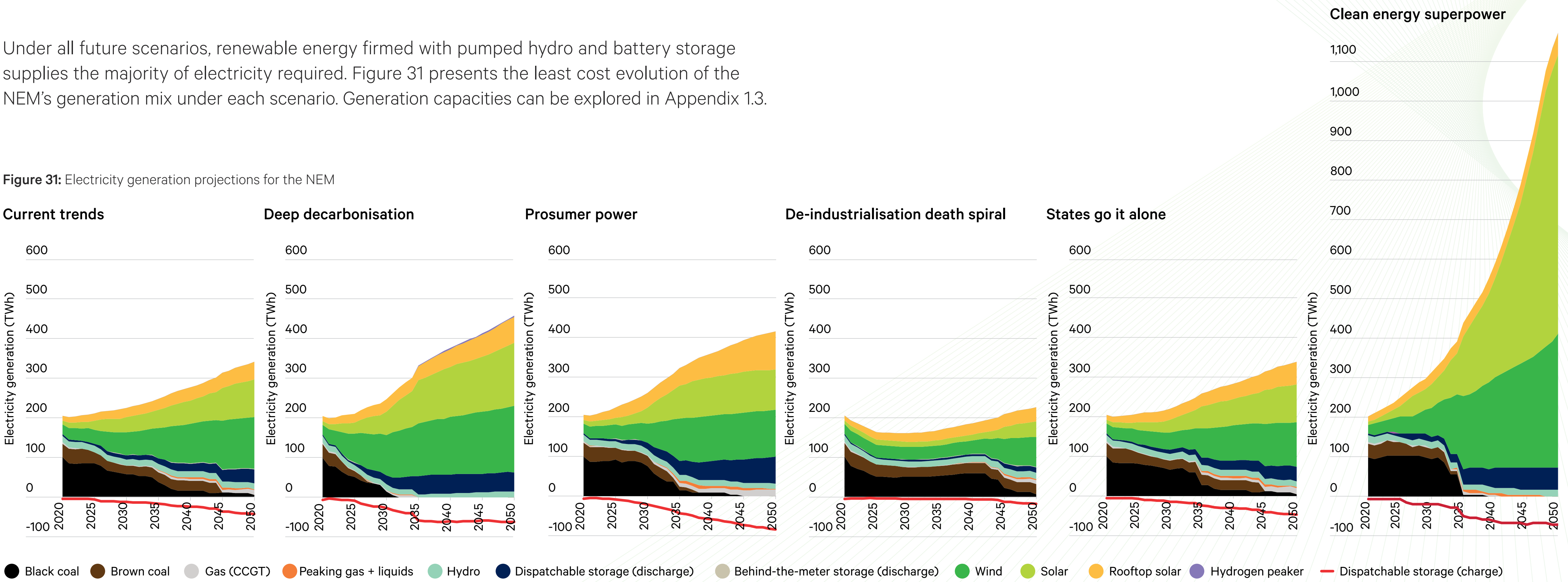
- Deloitte's analysis for the National Hydrogen Strategy suggests 19,600 additional jobs could be created and an extra $26 billion could be added to Australia's GDP by 2050 (under a similar hydrogen growth trajectory to **Clean energy superpower**) [ay].
- The Grattan Institute found that the export of green steel (equivalent to the export quantity in **Clean energy superpower**) could create 25,000 ongoing jobs and an annual export value of $65 billion by 2050 [az]. This analysis identified Central Queensland and the Hunter Valley in NSW as the lowest cost locations for the production of green steel in Australia.
- The Energy Transition Hub's analysis of Australia's opportunity to grow our zero emissions aluminium production found that GDP could be increased by $15 billion and 15,000 ongoing jobs could be created (equivalent to the aluminium sector growth assumed in **Clean energy superpower**) [ba].
- Beyond Zero Emissions and ACIL Allen found that establishing Renewable Energy Industrial Precincts in Gladstone and the Hunter Valley could support 45,000 new ongoing jobs and $13 billion in annual revenue [bb].



Power system implications

Under all future scenarios, renewable energy firmed with pumped hydro and battery storage supplies the majority of electricity required. Figure 31 presents the least cost evolution of the NEM's generation mix under each scenario. Generation capacities can be explored in Appendix 1.3.

Figure 31: Electricity generation projections for the NEM



A changing generation mix

The NEM's generation mix reflects the growing penetration of variable renewable energy (VRE) and a growth in dispatchable storage, as described in Table 1.

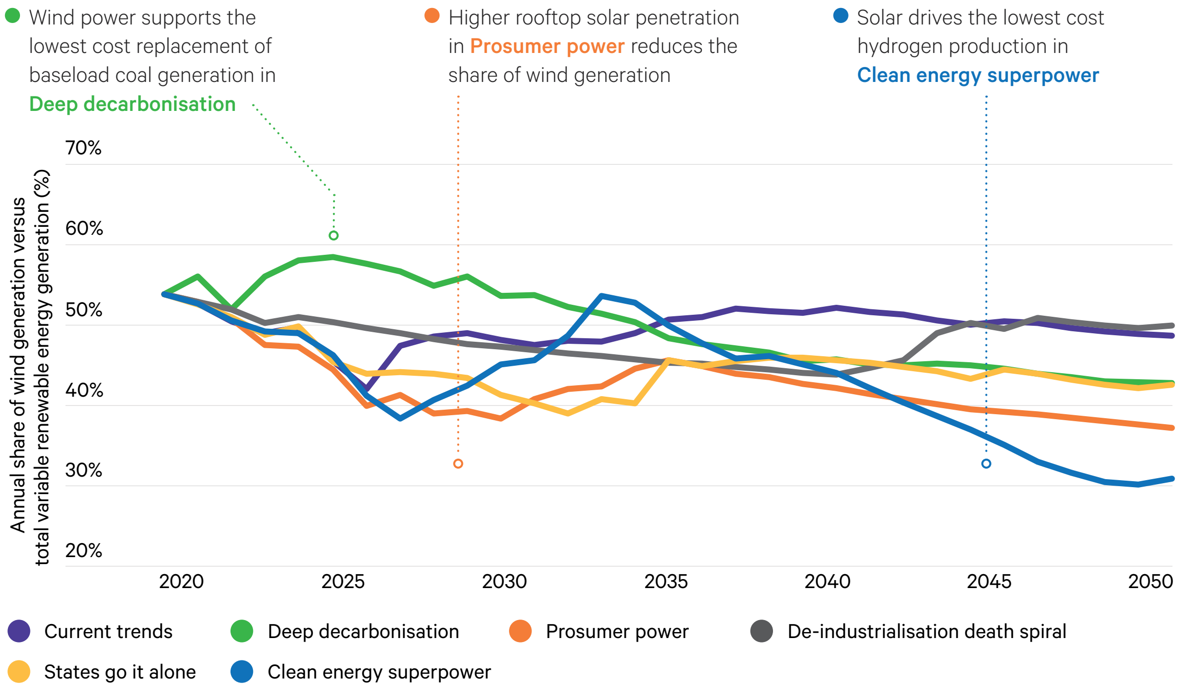
Table 1: VRE capacity and generation share, including largescale wind[1], solar PV and rooftop solar (therefore excludes hydro and biomass). Dispatchable storage capacity includes large scale battery storage, pumped hydro, Virtual Power Plant batteries and electric vehicles batteries with Vehicle-to-Grid technology.

NEM	2030			2050		
	VRE capacity (GW)	VRE share of total generation (Annual, %)	Dispatchable storage capacity (GW)	VRE capacity (GW)	VRE share of total generation (Annual, %)	Dispatchable storage capacity (GW)
Current trends	51	55%	5	108	88%	18
Deep decarbonisation	76	85%	12	159	96%	33
Prosumer power	57	51%	13	155	90%	45
De-industrialisation death spiral	32	42%	3	63	71%	10
States go it alone	46	49%	7	115	87%	23
Clean energy superpower	64	53%	8	417	98%	38

159GW of variable renewable energy capacity and 33GW of dispatchable storage is required across the NEM by 2050 in Deep decarbonisation

Our modelling determines the optimal split of wind and solar capacity to achieve the lowest system cost, shown in Figure 32.

Figure 32: Split of wind generation to total variable renewable energy generation in the NEM, including rooftop solar



1. Note: wind generation refers to onshore wind. Offshore wind was not modelled, though the potential for offshore wind along the coast of Australia is recognised (for example a notional 40GW resource limit is included within AEMO's 2021 Inputs, Assumptions and Scenarios Report).

Exponential demand for storage

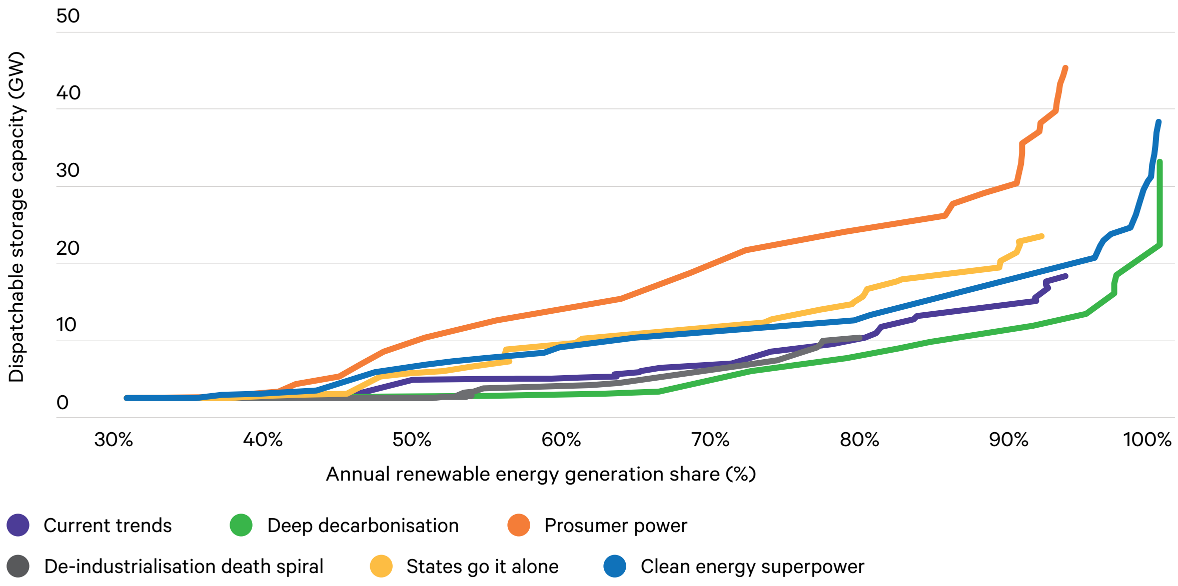
As market value shifts from bulk generation to flexibility and dispatchability, firming technologies will be critical to enable a high penetration of variable renewable energy into the electricity system. The requirement for storage (and storage duration) increases non-linearly with increasing annual renewable energy share, especially above 90%, roughly equivalent to an 85% variable renewable energy share.

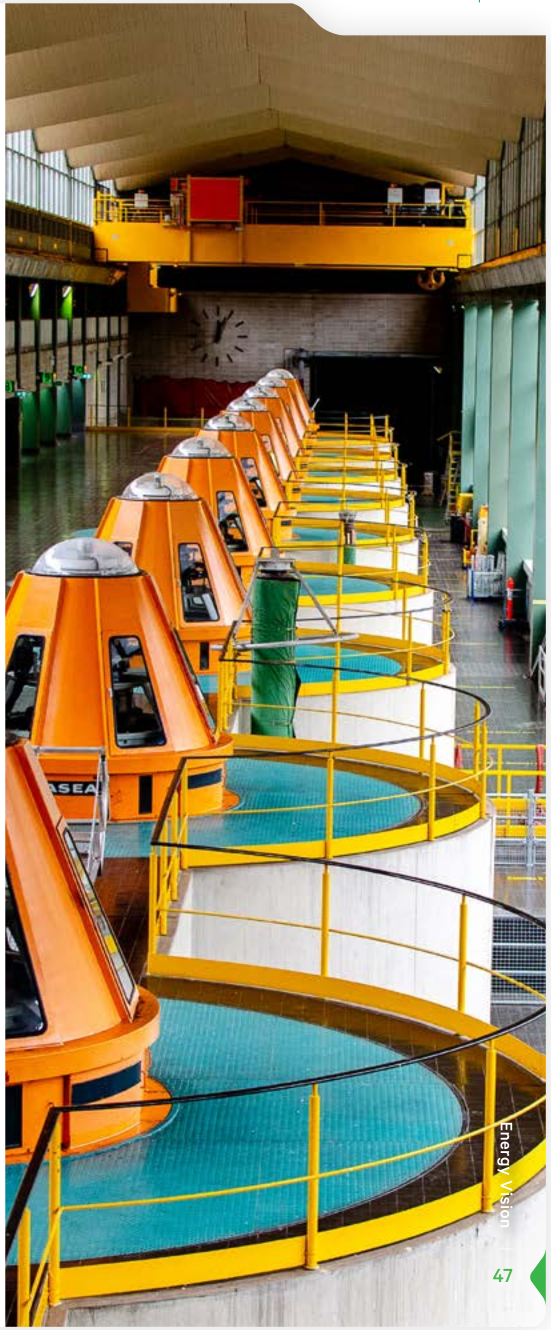
The spread of storage requirements shown in Figure 33 vary between scenarios because:

- Each scenario has very different electricity requirements, and higher levels of electricity consumption typically require more storage capacity to manage higher generation volumes (with the exception of **Clean energy superpower**)
- The flexibility of hydrogen electrolysers in **Clean energy superpower** means that hydrogen production can closely track renewable production, turning down or off where necessary, reducing storage requirements for the NEM as a whole
- Generally, scenarios with higher proportions of solar power require more storage to shift power from day to night (such as in **Prosumer power**).
- **Prosumer power** has higher dispatchable storage because of the availability of consumer storage within Virtual Power Plants and from electric vehicles with Vehicle-to-Grid technology, providing low-cost dispatchability to the energy system.

The requirement for storage (and storage duration) increases non-linearly with increasing annual renewable energy share

Figure 33: Dispatchable storage capacity against the renewable energy generation share in the NEM





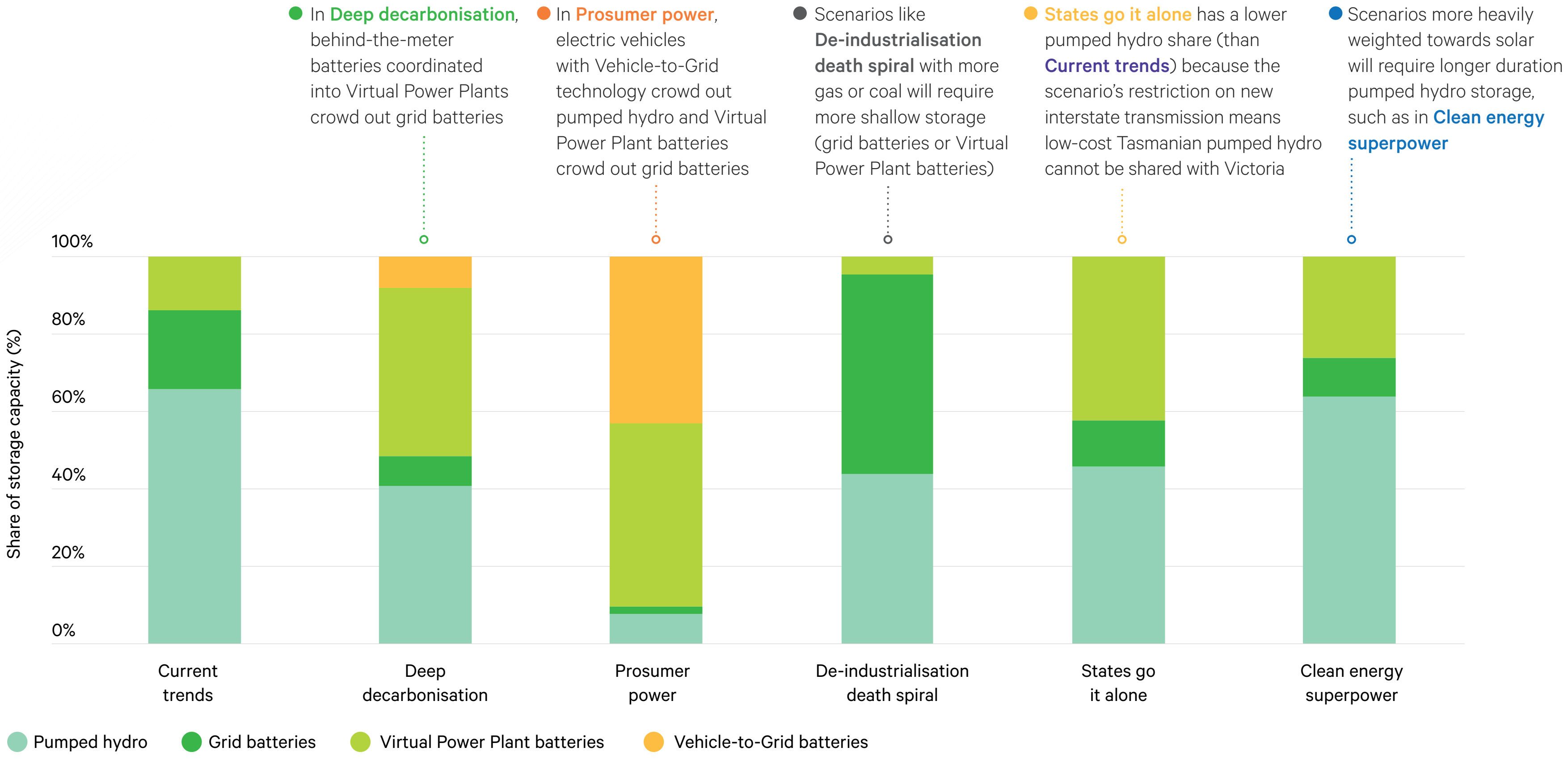
Varying storage depths

Vehicle-to-Grid technology has the potential to dramatically alter the energy storage landscape and significantly benefit the energy system.

Analysis by BloombergNEF for Germany suggests that, by 2040, if all the country's electric vehicles were equipped with Vehicle-to-Grid capabilities and were all (theoretically) available to the grid, they could provide three times more power than the system's peak electricity demand [bc].

The differences in storage technologies vary between scenarios, primarily influenced by required storage depths, as shown in Figure 34.

Figure 34: Share of storage capacity in the NEM in 2050 by type of storage



Spotlight

Power system implications

Demand side flexibility

Hydrogen electrolysers are extremely flexible. They can turn down, off or even up near instantaneously (including up to 200% of capacity for 10-30 minutes), enabling them to closely track renewable production, and to provide demand response and grid balancing services [bd].

If hydrogen electrolysers are grid connected, this flexibility translates into lower storage requirements for the energy system as a whole and lower costs for all consumers. Normalised for annual electricity consumption, in 2050 **Clean energy superpower** requires almost three times less storage capacity than **Deep decarbonisation**.

Hydrogen is not the only industry able to operate flexibly. Metal refineries and other large users are already varying their demand in response to the price of electricity. Germany's largest producer of aluminium, Trimet, is trialling techniques to make its facility more demand responsive, enabling one production line to turn up or down by 25% for several hours [be]. And it's not just industry either – individual households are increasingly varying their demand in response to signals from energy market participants.

As the NEM transforms to a two-way electricity system, all consumers will have a role to play.

The role of dispatchable generation

Dispatchable generation will continue to play an important firming role in our future energy system – injecting electricity during long stretches without plentiful solar and wind generation, in effect, avoiding the need for more costly long-duration storage.

With the exception of **Deep decarbonisation** and **Clean energy superpower**, gas generation increases as the annual share of variable renewable energy generation surpasses 60%, with gas generation sitting at around 6% of total annual electricity generation by 2050. Yet modelling suggests that gas generation capacity in the NEM has already peaked and will fall over time, in all scenarios modelled.

Our analysis shows that a zero emissions form of dispatchable generation is required in **Deep decarbonisation**, to maintain affordable energy prices. Yet it only operates with a maximum capacity factor of 5% and produces less than 1% of the NEM's annual electricity generation. Hydrogen reciprocating engines were modelled in **Deep decarbonisation**, but any form of zero emissions fuel, such as biogas or biodiesel, would work equally well.

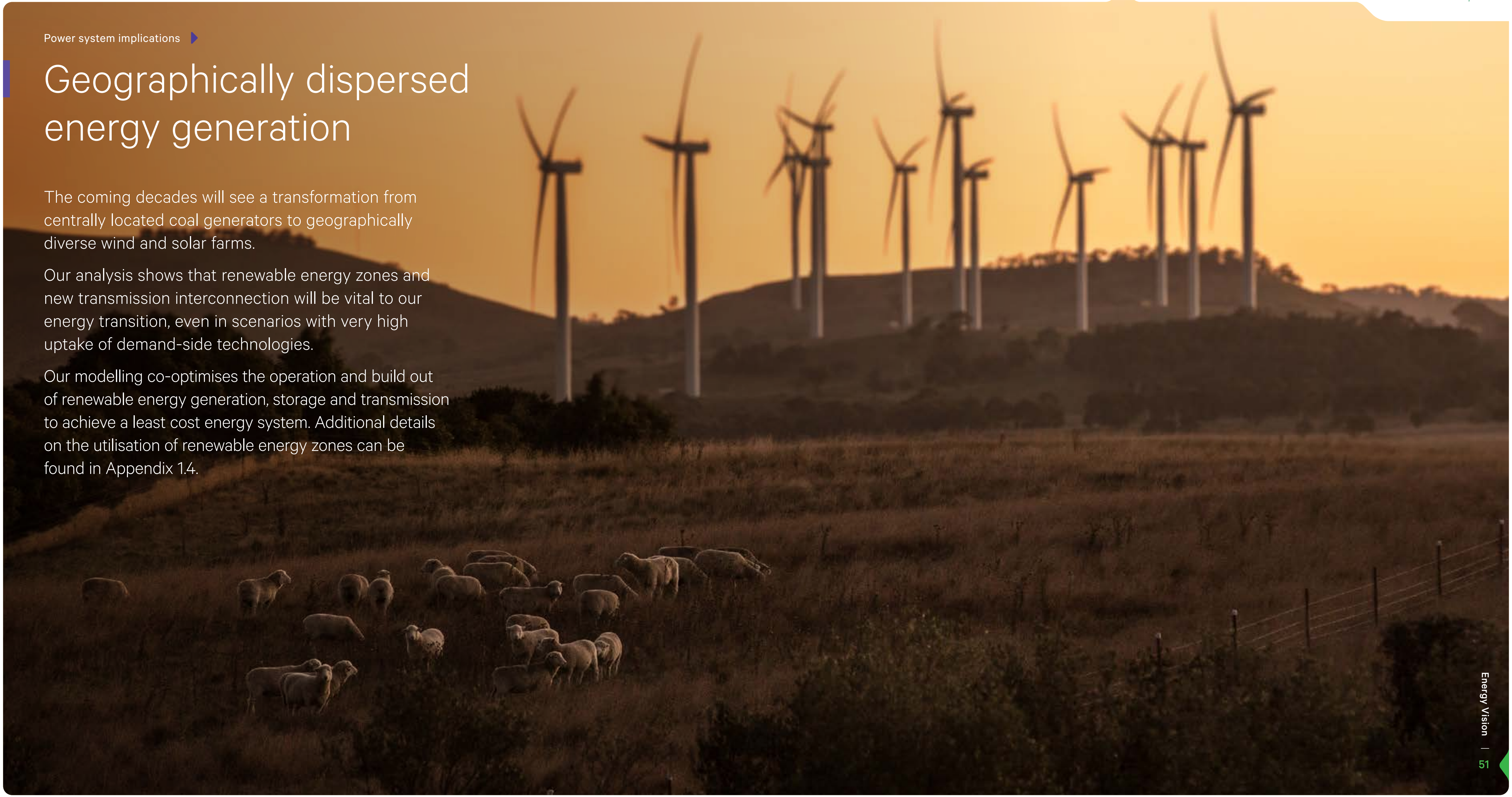
As hydrogen electrolysers become more widespread in the mid-2030s in **Clean energy superpower**, their flexibility offsets the need for dispatchable gas generation, which falls close to zero by 2050.

Geographically dispersed energy generation

The coming decades will see a transformation from centrally located coal generators to geographically diverse wind and solar farms.

Our analysis shows that renewable energy zones and new transmission interconnection will be vital to our energy transition, even in scenarios with very high uptake of demand-side technologies.

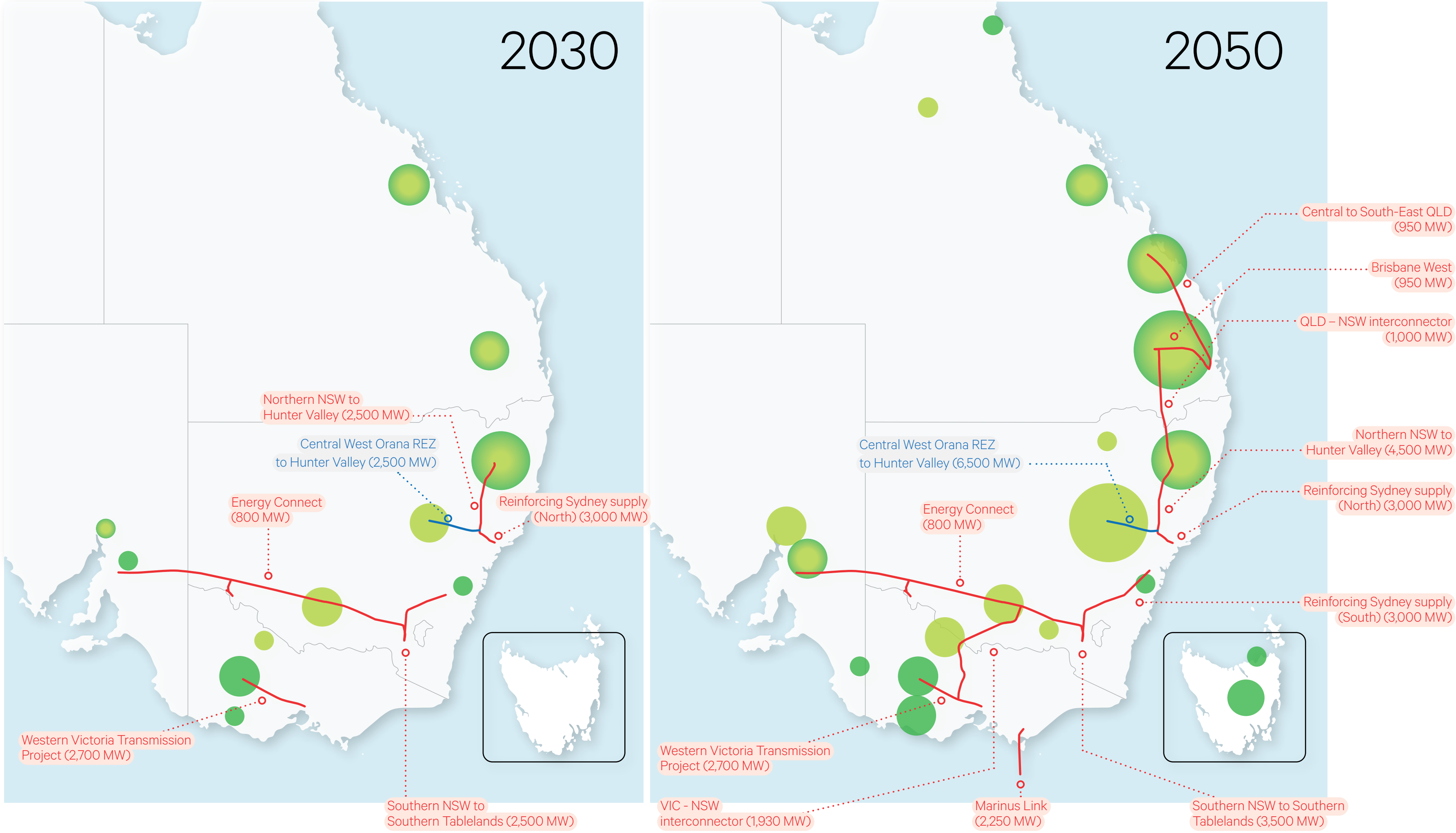
Our modelling co-optimises the operation and build out of renewable energy generation, storage and transmission to achieve a least cost energy system. Additional details on the utilisation of renewable energy zones can be found in Appendix 1.4.

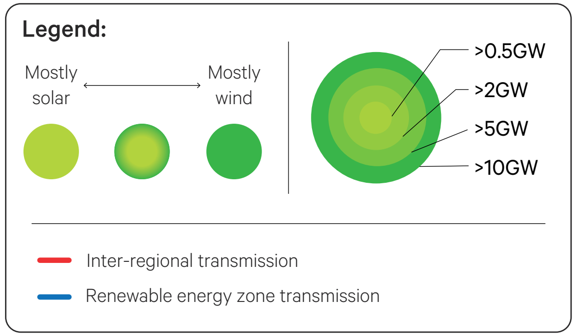


Current trends

By 2050, renewable energy zones in the NEM are projected to support 65GW of new largescale wind and solar PV capacity. This generation will be connected to the transmission backbone via 46GW of new renewable energy zone transmission and shared across the NEM through 25GW of new inter-regional transmission connection.

Figure 35: Renewable energy zone and transmission maps for **Current trends**



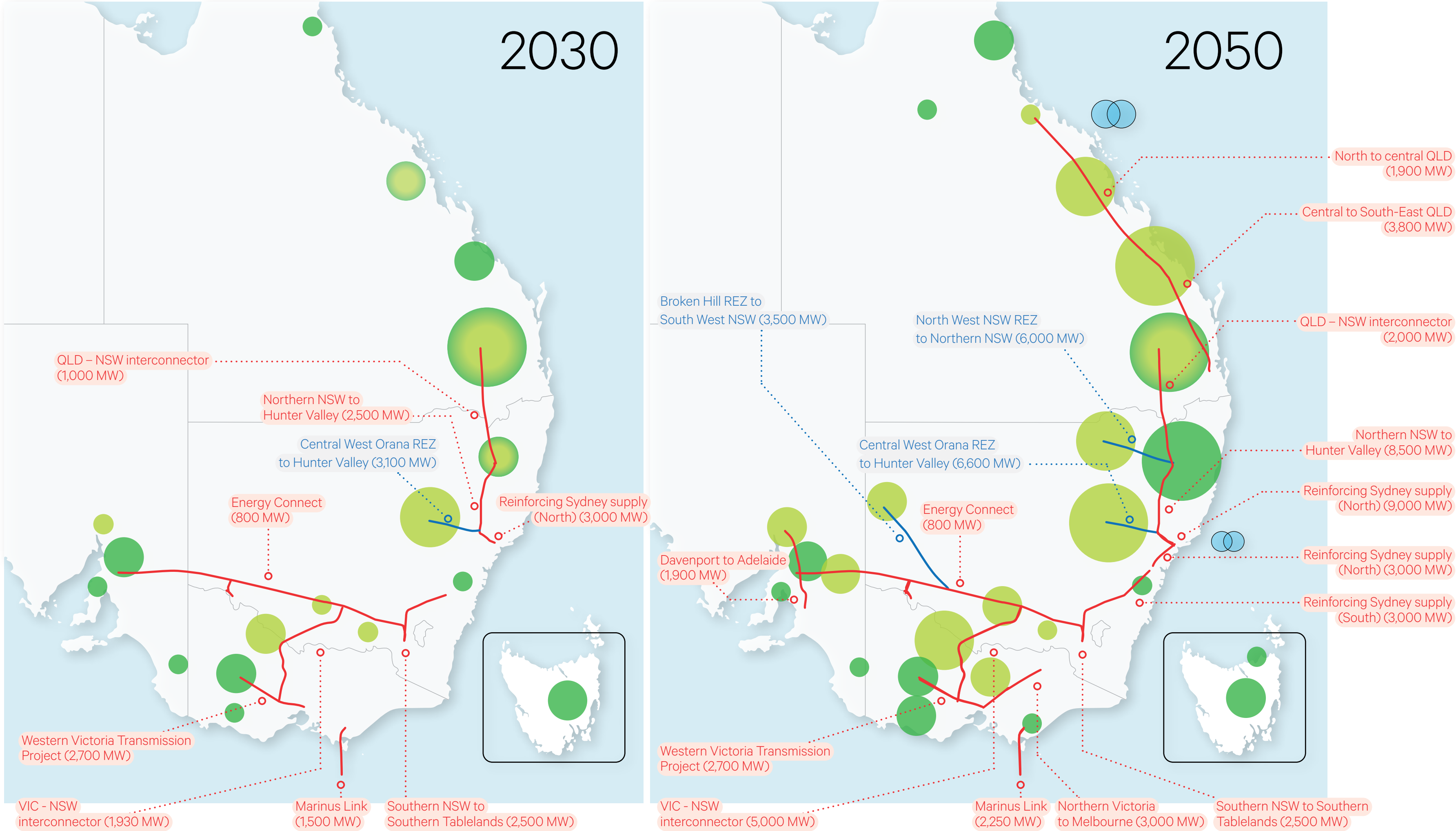


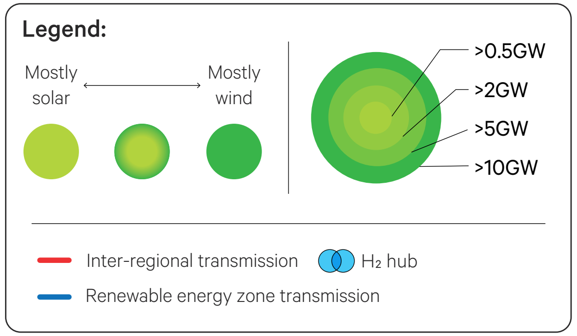
Deep decarbonisation

In **Deep decarbonisation**, the NEM requires a more significant growth in renewable generation capacity to achieve a zero emissions power system by 2035 and to support electrification in other sectors.

By 2050, 98GW of new wind and solar PV capacity is deployed within renewable energy zones, connected to the transmission backbone via 75GW of renewable energy zone transmission and shared by 47GW of inter-regional transmission.

Figure 36: Renewable energy zone and transmission maps for **Deep decarbonisation**



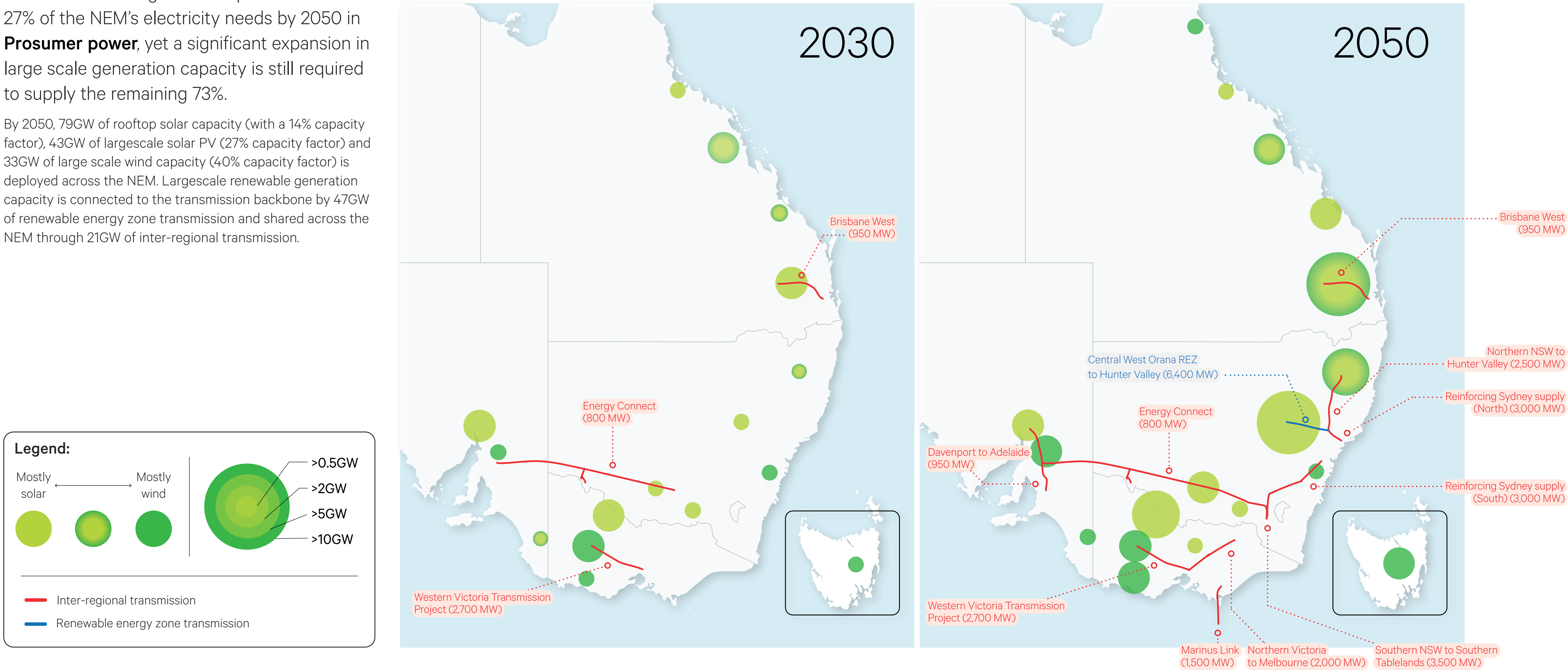


Prosumer power

Behind-the-meter generation provides 27% of the NEM's electricity needs by 2050 in **Prosumer power**, yet a significant expansion in large scale generation capacity is still required to supply the remaining 73%.

By 2050, 79GW of rooftop solar capacity (with a 14% capacity factor), 43GW of largescale solar PV (27% capacity factor) and 33GW of large scale wind capacity (40% capacity factor) is deployed across the NEM. Largescale renewable generation capacity is connected to the transmission backbone by 47GW of renewable energy zone transmission and shared across the NEM through 21GW of inter-regional transmission.

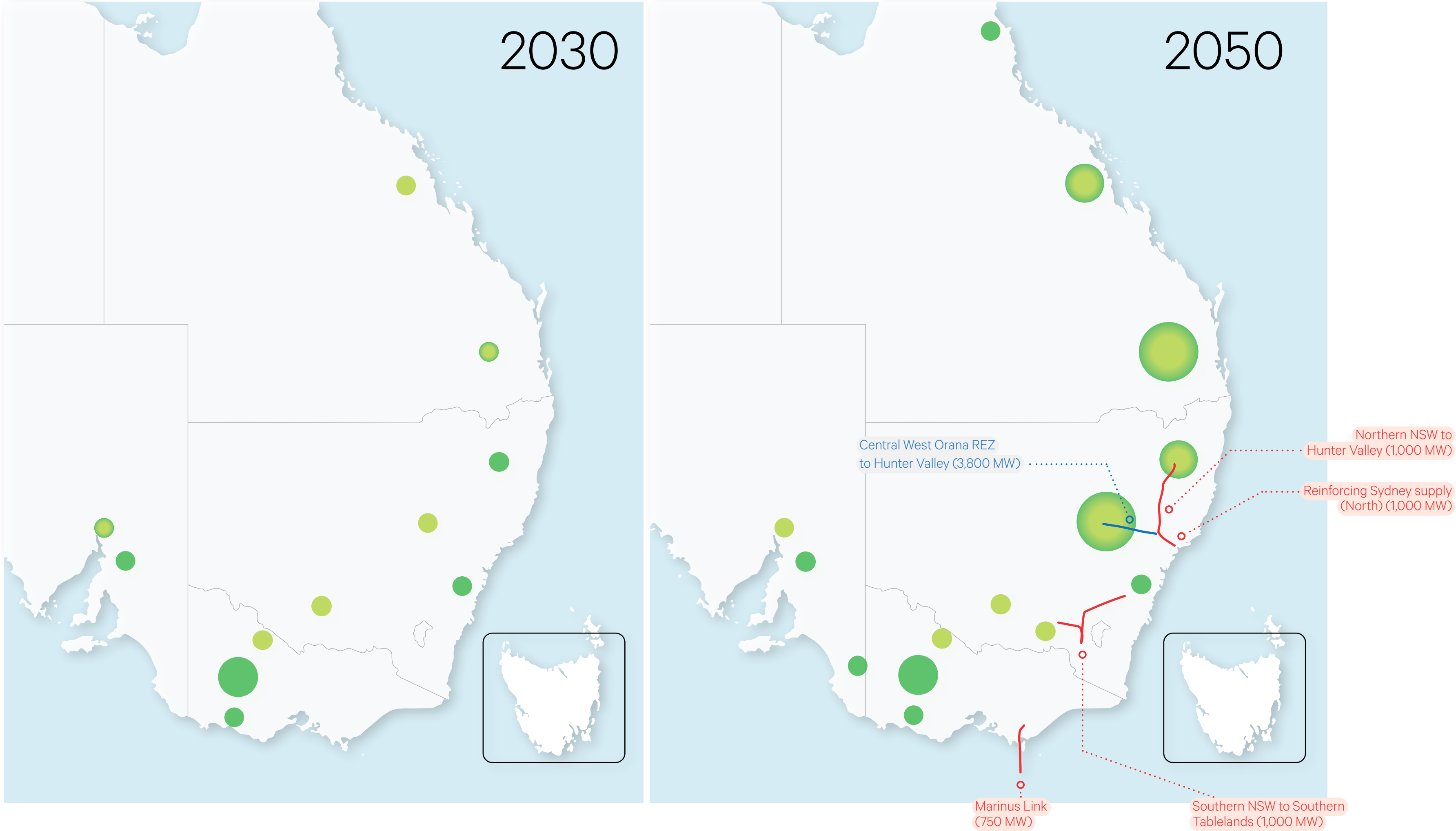
Figure 37: Renewable energy zone and transmission maps for **Prosumer power**

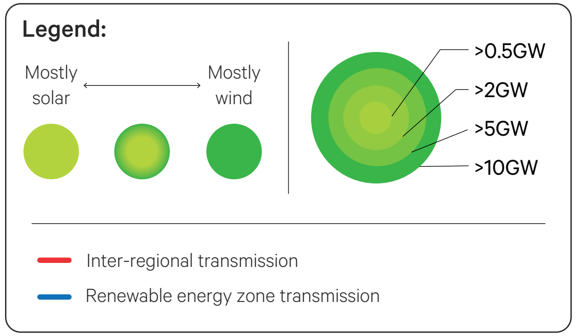


De-industrialisation death spiral

Despite a delayed growth in the demand for electricity, 26GW of new largescale wind and solar PV capacity is developed in renewable energy zones by 2050. These renewables are connected to the transmission backbone by 16GW of new renewable energy transmission and shared across the NEM by 4GW of new inter-regional transmission.

Figure 38: Renewable energy zone and transmission maps for **De-industrialisation death spiral**

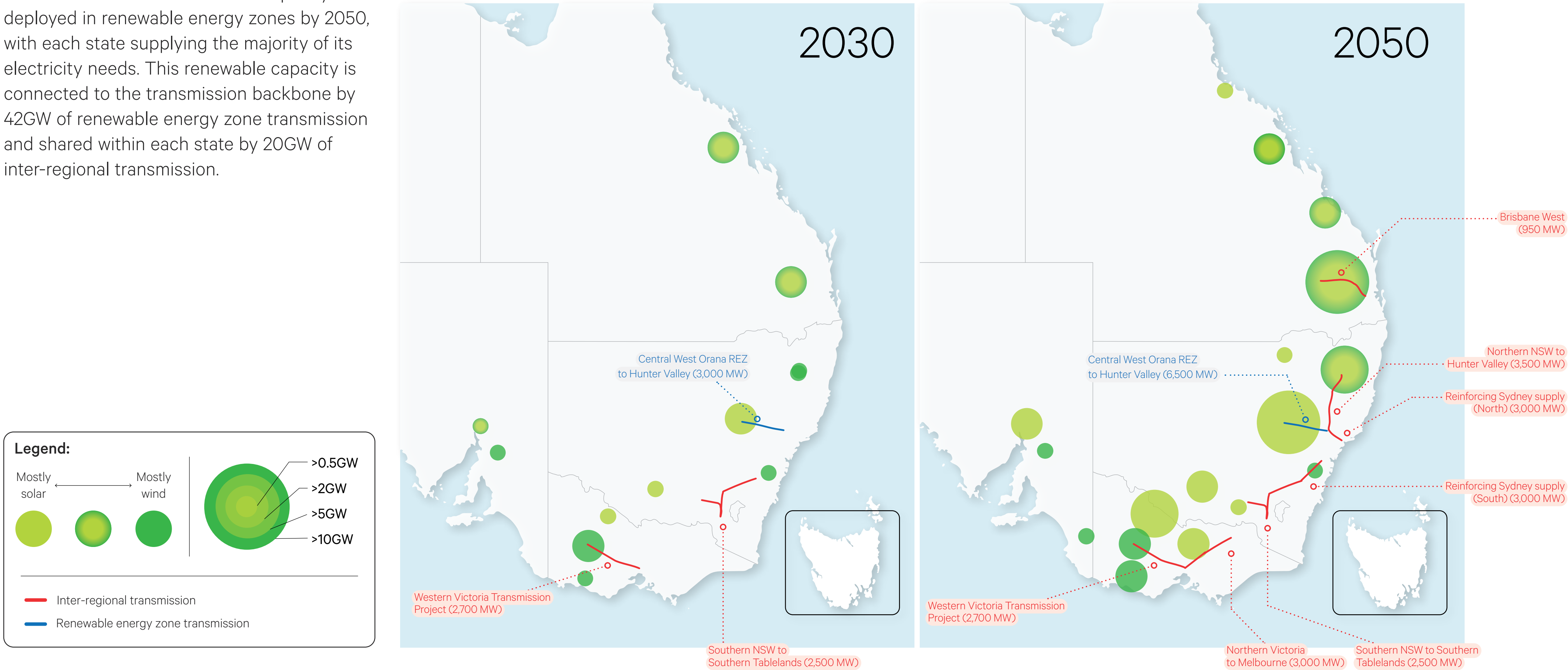




States go it alone

61GW of new wind and solar PV capacity is deployed in renewable energy zones by 2050, with each state supplying the majority of its electricity needs. This renewable capacity is connected to the transmission backbone by 42GW of renewable energy zone transmission and shared within each state by 20GW of inter-regional transmission.

Figure 39: Renewable energy zone and transmission maps for **States go it alone**



Clean energy superpower

A six-fold increase in electricity consumption by 2050 in **Clean energy superpower** is supplied by 43GW of rooftop solar, 97GW of largescale wind and 277GW of largescale solar PV.

Largescale generation is connected to the transmission backbone or directly to industrial hubs via 266GW of renewable energy zone transmission. 72GW of inter-regional transmission shares power between regions.

The required generation capacity is beyond the resource availability in AEMO-identified[1] renewable energy zones. Our analysis assumes additional mega-renewable energy zones are developed in far-north west NSW, far-north west QLD and far-south west QLD. For example, our modelling suggests 62GW of new renewable generation is required in a far-north west NSW zone and 42GW in a far-south west QLD zone in the period 2043-50.

To scale and cost-effectively transfer this huge quantity of electricity required from these more remote zones, we envisage increasingly sophisticated transmission technology will be used, such as ultra-high voltage alternating current or high voltage direct current technology.

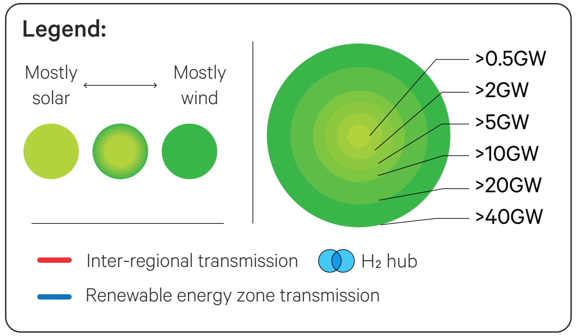
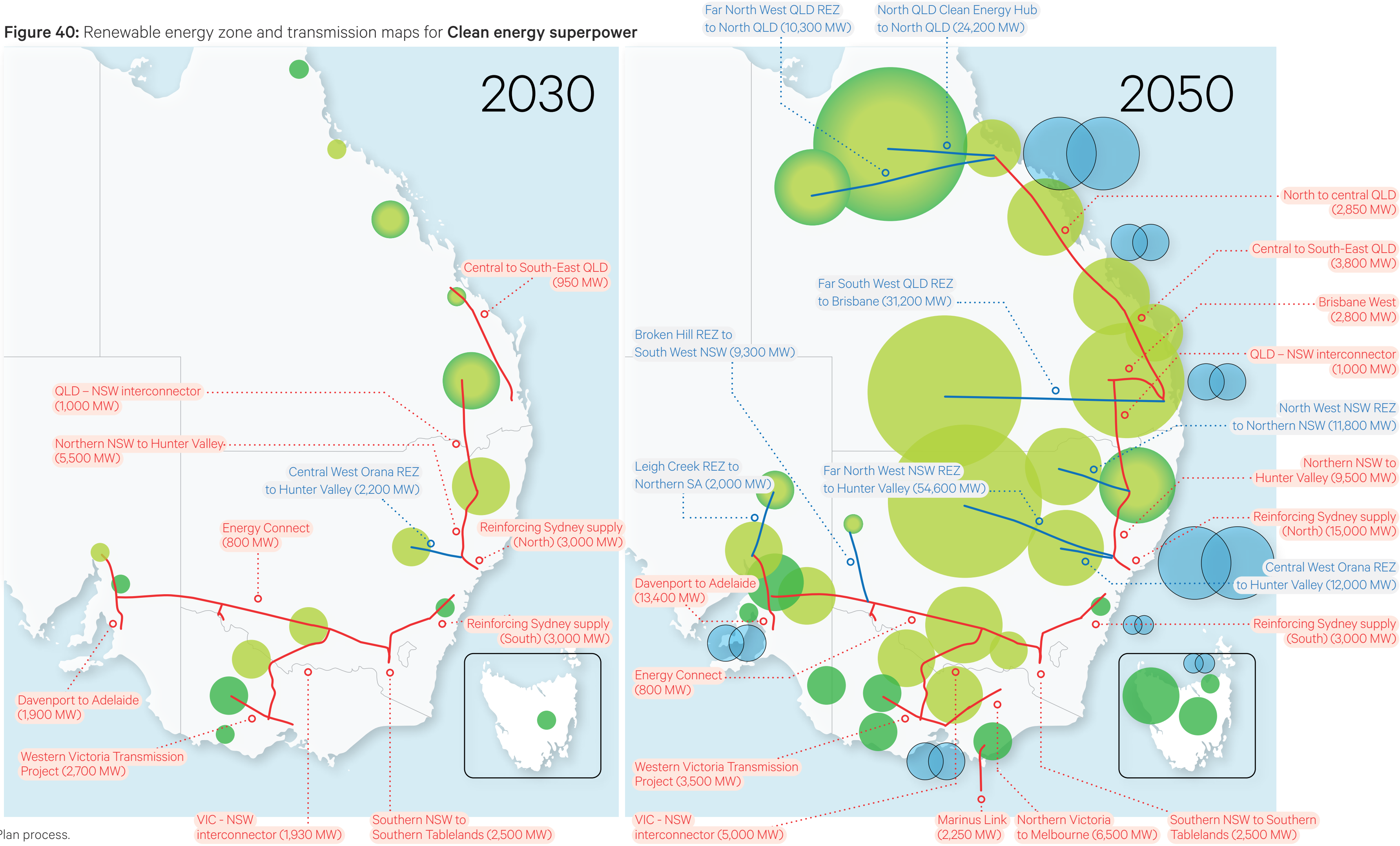


Figure 40: Renewable energy zone and transmission maps for **Clean energy superpower**



1. Renewable energy zones identified through the AEMO 2020 Integrated System Plan process.

Spotlight

Power system implications

Embedding social license into Australia's energy transformation

Our energy transformation will bring new technologies and infrastructure into our homes, our cities and into regional Australia.

To produce sufficient quantities of clean energy, a large number of renewable energy generation and storage projects must be located in regional Australia, with transmission infrastructure connecting generation to population and demand centres.

The benefits and impacts of the energy transformation will be felt differently by different communities.

Strongly embedding social licence into the planning and rollout of clean energy infrastructure will help ensure the energy transition improves social and economic outcomes in regional Australia. Early, collaborative engagement and investment in local industry, employment, education and training is key.

An expanded transmission backbone

Transmission is a critical facilitator of our energy transformation.

The backbone of the NEM's transmission system was built to bring power from coal-fired power stations located near coal fields to load centres, with weak interconnections between states and to regional population centres. As our generation sources evolve and more geographically dispersed renewable energy enters the system, the NEM's transmission system must also evolve.

Greater interconnection enables:

- The best and lowest cost energy resources to be accessed, fostering wholesale market competition and lowering prices
- Access to geographically dispersed renewable energy to offset higher emissions fossil fuel electricity
- Sharing of uncorrelated renewable energy generation between regions, reducing the requirements for energy storage and dispatchable generation, lowering system costs[1]
- The connection of location-specific deep storage so these firming resources can be shared between regions
- An increase in diversity of supply options, improving system security and system resilience

Interstate electricity transmission saves $20 billion to 2050 by connecting and sharing the lowest cost electricity between states

States go it alone provides a useful counterfactual to **Current trends** to assess the benefit of interstate transmission. A comparison of the total system costs shows that new interstate transmission provides $20 billion in cumulative savings to the energy system by 2050 (real, 2021 dollars).

Ensuring that transmission developments are robust across a range of possible future scenarios is critical. Table 2 presents the operational dates (financial year) of new inter-regional transmission within and from NSW, as optimised within the least cost modelling. It can be seen that these transmission developments are robust across the vast majority of future scenarios. Subsequent expansions of these links may be required. Table 3 identifies the cumulative requirements for inter-regional transmission by 2050, within and from NSW.

Transmission is a critical facilitator of our energy transformation, transferring 73-95% of the electricity produced in the NEM to customers, even in scenarios with extremely high distributed energy resource uptake

Table 2: Inter-regional transmission developments within or from NSW; timing of the first financial year of operation

Timing of the first financial year of operation[2]	QLD – NSW interconnector	Northern NSW to Hunter Valley	Reinforcing Sydney supply (North)	Reinforcing Sydney supply (South)	Southern NSW to Southern Tablelands	VIC - NSW interconnector	Energy Connect[3]
Current trends	2035	2027	2027	2035	2026	2040	2025
Deep decarbonisation	2027	2026	2026	2031	2026	2028	2025
Prosumer power	-	2031	2034	2035	2031	-	2025
De-industrialisation death spiral	-	2045	2045	-	2043	-	-
States go it alone	*	2033	2033	2035	2026	*	*
Clean energy superpower	2029	2027	2027	2030	2026	2028	2025

Table 3: Capacity of inter-regional transmission expansion within or from NSW required by 2050. The shaded cells represent transmission links which are expanded on more than one occasion.

Cumulative transmission requirements by 2050[2]	QLD – NSW interconnector	Northern NSW to Hunter Valley	Reinforcing Sydney supply (North)	Reinforcing Sydney supply (South)	Southern NSW to Southern Tablelands	VIC - NSW interconnector	Energy Connect[3]
Current Trends	1,000MW	4,500MW	3,000MW	3,000MW	3,500MW	2,000MW	800MW
Deep Decarbonisation	2,000MW	8,500MW	9,000MW	3,000MW	2,500MW	5,000MW	800MW
Prosumer Power	-	2,500MW	3,000MW	3,000MW	3,500MW	-	800MW
De-industrialisation Death Spiral	-	1,000MW	1,000MW	-	1,000MW	-	-
States Go it Alone	*	3,500MW	3,000MW	3,000MW	3,500MW	*	*
Clean Energy Superpower	1,000MW	9,500MW	15,000MW	3,000MW	2,500MW	5,000MW	800MW

1. In a recent report for Boston University's Institute of Sustainable Energy, analysts from The Brattle Group and National Grid found that when real-time uncertainties of renewable generation and loads relative to their day-ahead forecasts are taken into consideration, the benefit of geographic diversification through the transmission grid are 2 to 20 times higher than benefits typically quantified based only on 'perfect forecasts'.
2. Both tables exclude the ongoing QNI minor and VNI minor projects.
3. Energy Connect represents the recently approved interconnector between South Australia, New South Wales and Victoria (not additional capacity beyond this).

* Additional interstate transmission links were restricted in **States go it alone** due to the scenario narrative

Spotlight

Power system implications

Transmission as insurance against the early closure of coal generators

The early withdrawal of coal generation is becoming increasingly likely – yet the timing is far from certain.

To manage this risk, the early development of specific renewable energy zones and corresponding transmission links can provide strategic insurance value against early coal closure.

Our modelling has found that the NSW renewable energy zones of Central West Orana and New England are vital. By 2027, the two zones supply 36% of NSW's total in front-of-the-meter generation in **Current trends**, and 45% in **Deep decarbonisation**, and 75% and 70% respectively of the state's largescale wind and solar PV generation. Ensuring that electricity from these two zones can reach Sydney prior to the closure of NSW's next coal generator is critical (after Liddell in FY2022-23).

New electricity transmission is required to facilitate the flow of this electricity to Sydney, specifically new transmission interconnection between Northern NSW and the Hunter Valley and to reinforce Sydney's supply (north). Our modelling suggests that both links must be operational in financial year 2026 in **Deep decarbonisation** and 2027 in **Current trends**. With a typical design and construction duration of 4-6 years for transmission, fast-tracking these links is essential to provide insurance against the possible early closure of NSW coal generators.

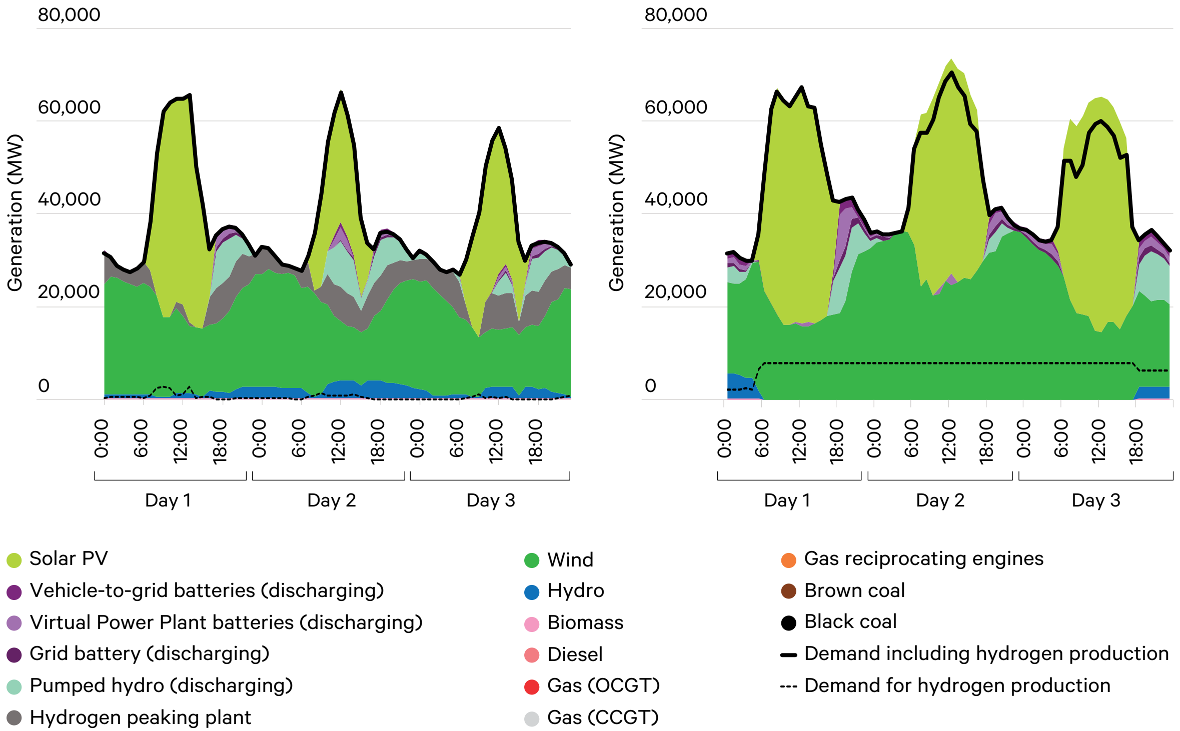
Power system implications

An increasingly variable energy system

As the share of renewable energy increases, our electricity system is becoming more variable and more complicated to manage. Weather conditions will drive distinct periods of energy over- and under-supply, as shown for **Deep decarbonisation** in Figure 41.

Figure 41: Deep decarbonisation, low and high renewable generation days in winter and summer for the NEM in 2050

Low renewable generation in winter (NEM, 2050) **High renewable generation in summer (NEM, 2050)**



Transgrid

The importance of highly coordinated distributed resources

The coordinated charging and discharging of electric vehicles and behind-the-meter batteries will become critical to future power system operation, requiring sufficient charging infrastructure, intelligent controls and appropriate financial incentives to promote consumer behaviour change. Demand profiles for an average day in 2050 show the implications of these technologies in Figure 42.

As distributed energy resources proliferate, consumers will seek a new suite of behind-the-meter energy services to help them optimise and manage their own energy supply and demand to reflect their preferences for sustainability, control and affordability. These services will need to:

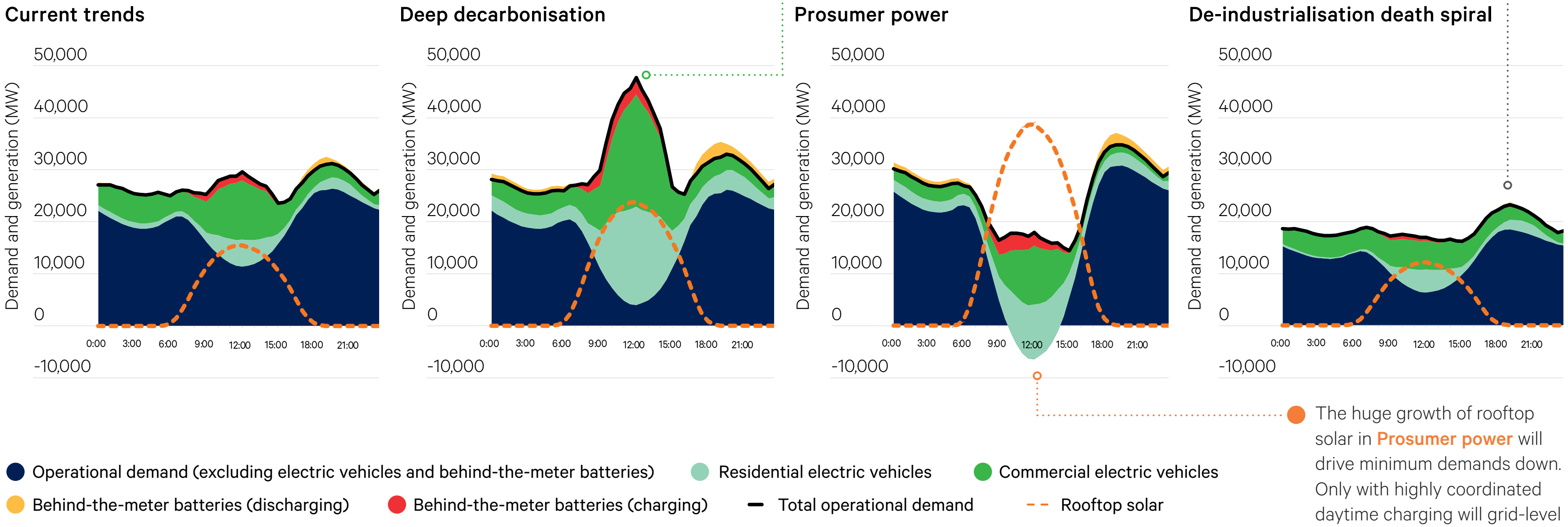
- Improve convenience and simplify the customer experience
- Provide energy security and ensure the consumer has access to energy when they need it most
- Manage complex interactions with energy markets and system operators to maximise customer value

Novel software platforms and new business models are emerging, as demonstrated by the growth in Virtual Power Plant offerings. Over time, these offerings will become smarter and more autonomous with improved artificial intelligence, machine learning and internet of things capabilities. They will also grow in their breadth of control to include hot water heating, electric vehicles and consumer devices. These platforms will enable consumers within individual homes, buildings or microgrid precincts to form geographic or virtual energy communities that can share and trade electricity.

If aggregated to a meaningful scale, distributed energy resources have the potential to provide valuable services along the energy supply chain. This includes demand-side flexibility that can respond to wholesale market conditions and alleviate congestion in distribution and transmission networks.

The electricity sector must evolve to meet changing consumer expectations and to leverage new distributed energy resource capabilities, to support the ongoing stability of the electricity system.

Figure 42: NEM-wide demand profiles for an average demand day in 2050 under various scenarios



The electrification of all passenger vehicles in **Deep decarbonisation** creates a significant additional load on the electricity system. With appropriate price signals, the lowest cost time to charge batteries will be during the day, acting as a solar sponge

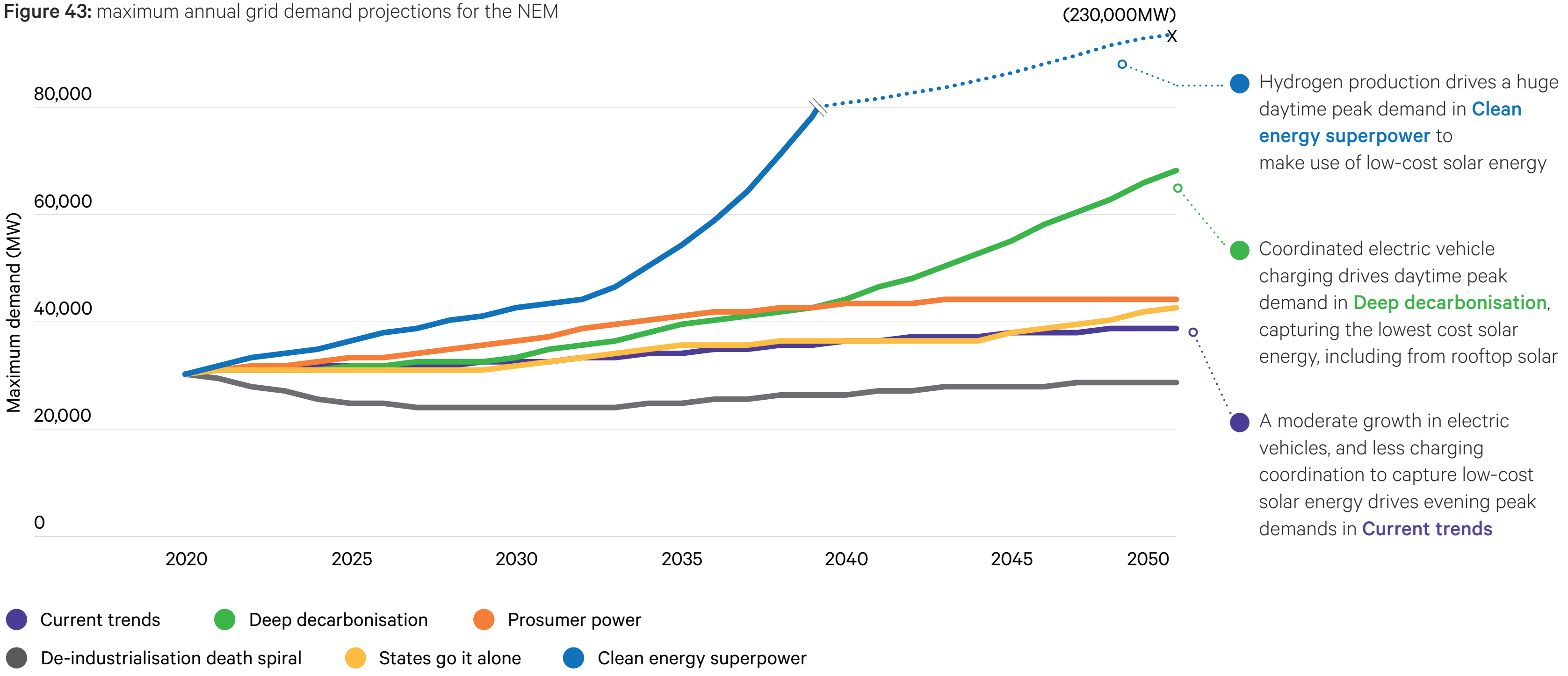
Less coordination of electric vehicle charging increases the evening peak demand in **De-industrialisation death spiral**

The huge growth of rooftop solar in **Prosumer power** will drive minimum demands down. Only with highly coordinated daytime charging will grid-level demand be kept from falling below zero (theoretically)

The changing patterns of maximum demand

The scale and timing of peak electricity demand will evolve as consumer behaviours change, technologies become more efficient and electric vehicles become more widespread, as noted in Figure 43.

Figure 43: maximum annual grid demand projections for the NEM

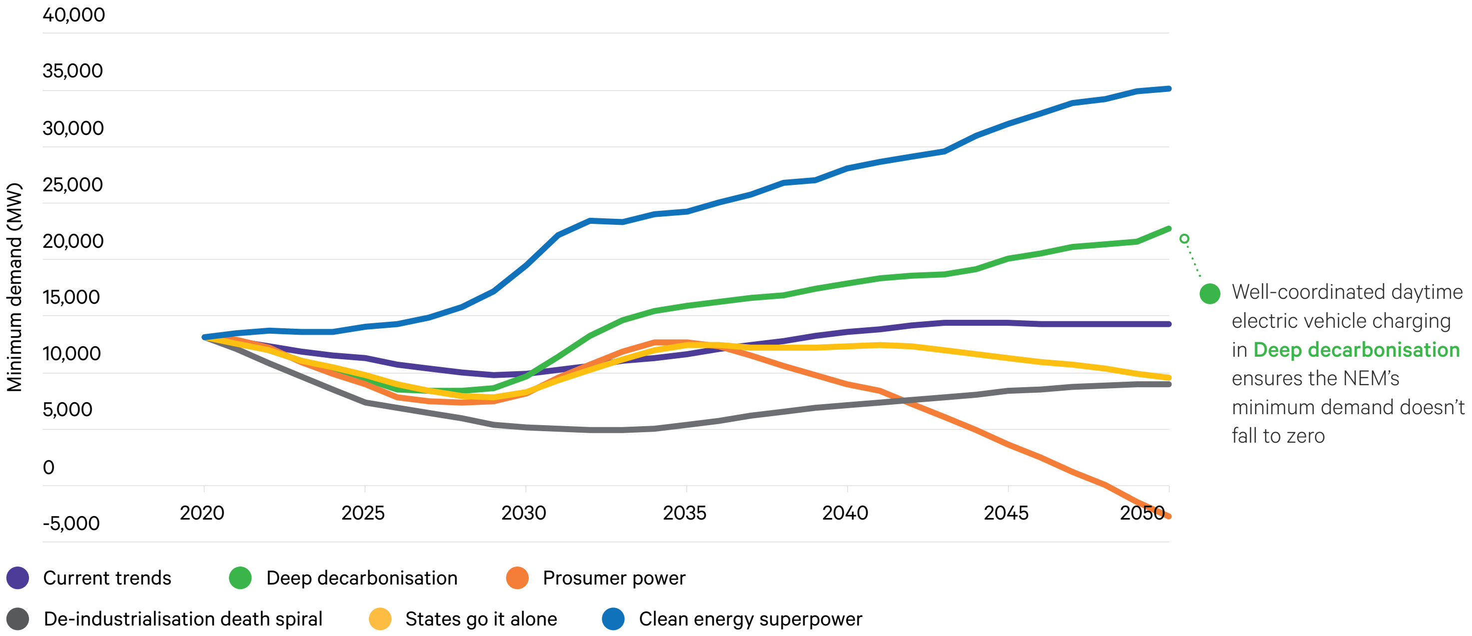


Declining minimum demands

The growth in rooftop solar is driving down daytime electricity demand on the distribution and transmission system, increasingly challenging system stability.

With continued rooftop solar uptake, the NEM as a whole is projected to see negative minimum demands (theoretically[1]) in the late 2040s in **Prosumer power,** as shown in Figure 44. Daytime electric vehicle charging to soak up rooftop solar generation is essential to avoid theoretical minimum demands in **Deep decarbonisation** and **States go it alone**.

Figure 44: Minimum demand projections for the NEM



1. Note that these are theoretical minimum demands, without any supply/demand price response. In reality, generators would likely respond to negative prices by decreasing supply or being curtailed, and sophisticated industrial users would likely respond to negative prices by increasing demand.

Maintaining system security

Managing system security will become increasingly complex as synchronous generators retire. Historically, inertia and fault current have been abundant in the NEM, a by-product of synchronous generation. As the penetration of inverter-based renewables increase and synchronous generators retire, new solutions and technologies will be required to ensure the energy system remains secure.

Based on existing rules and regulations, Figure 45 shows inertia in NSW will drop below what is currently considered an acceptable level between 2031-33, and possibly as early as 2030 in **Deep decarbonisation**.

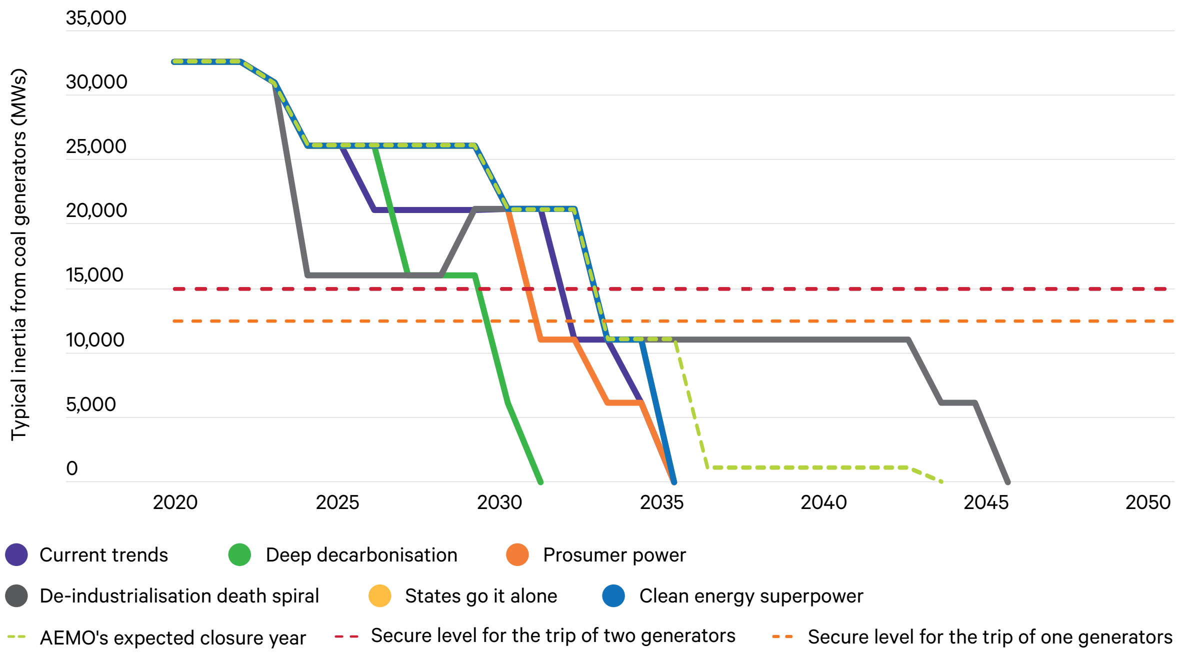
Our modelling co-optimises the operation and build out of the NEM's power system with its secure operation, as defined by *existing* inertia and system strength[1] requirements. We model the role of synchronous condensers and renewables and batteries with grid forming inverters to provide inertia and system strength ancillary services.

Our analysis suggests that each state's inertia requirements will generally be met as a by-product of meeting system strength requirements. This is primarily because system strength services are locationally dependent – system strength remediation in one area of the grid will have diminishing value for locations electrically further away. Whereas inertia services provided by that same equipment will benefit the entire NEM.

Our modelling suggests that the inertia and system strength ancillary services required to ensure a secure electricity system will represent between 1-3% of total system cost. This is a small cost to maintain a safe and reliable energy system into the future.

Moving beyond existing rules and regulations, technological advancements could transform the management of our energy system. Ultimately, we envisage a 100% renewable energy grid, secured by power electronics alone.

Figure 45: Typical inertia from coal generators in NSW as they retire



1. System strength relates to the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance. A location with 'weak' system strength is one further from synchronous generating systems and with less transmission interconnection, typically found in more remote parts of the grid. Source: AEMO, 2020, System Strength in the NEM explained, https://aemo.com.au/-/media/files/electricity/nem/system-strength-explained.pdf

Batteries and grid forming inverters

New technologies, skills and services will be required to manage the electricity system of the future.

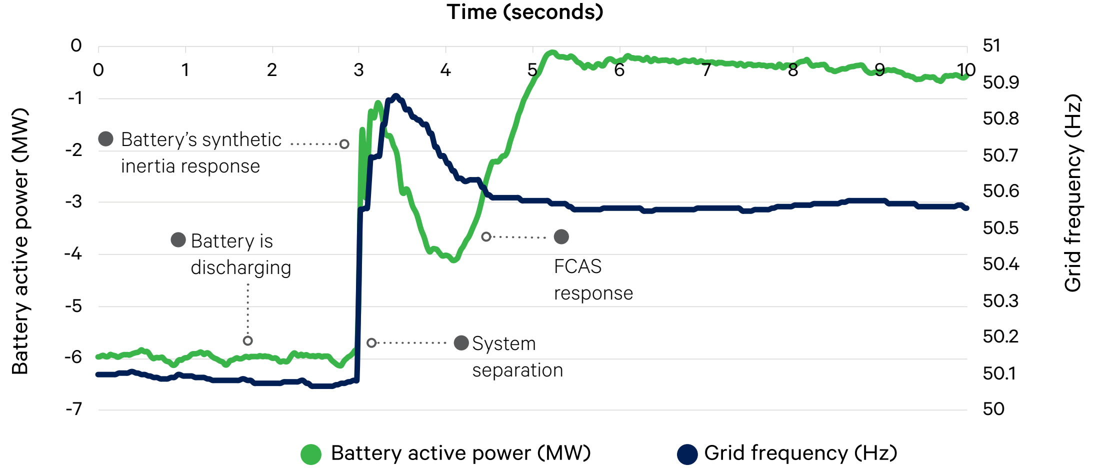
Continued innovations in grid forming inverters could reshape how the electricity system is controlled and operated. Systems including ElectraNet's ESCRI battery [bf], Neoen's Hornsdale battery [bg] and (soon) Transgrid's Wallgrove battery [bh] are already operating with synthetic inertia capabilities. Research is also demonstrating that batteries with grid forming inverters can actively improve system strength in weak areas of the grid [bi].

Grid forming inverters are likely to play a critical role across a full range of grid applications, including:

- Supporting the connection of renewable energy generators in weaker areas of the grid
- Supporting grid operation during faults (for example, through synthetic inertia and fault current)
- Enabling islanding and black start capabilities

It is essential that we develop the technologies, rules and regulations to support the operation of the grid with low or no synchronous generation.

Figure 46: Dalrymple ESCRI-SA Battery providing synthetic inertia and FCAS following the separation of South Australia on the 16th November 2019 [1]



1. ElectraNet, https://www.electranet.com.au/electranets-battery-storage-project/

Appendix

Appendix

1.1 Our partners

Our partners in analysing the evolution of Australia's energy system are the independent experts: CSIRO, ClimateWorks Australia and The Brattle Group.

The Brattle Group facilitated the development of our future energy scenarios through a series of workshops with Transgrid senior managers with input from Transgrid and Australian subject-matter experts. Key trends, drivers and future uncertainties were identified for Australia's energy system. A suite of scenario narratives were then developed, selected and refined to cover a diverse range of plausible futures. Finally, assumptions were quantitatively defined to be carried through to detailed system modelling.

CSIRO and ClimateWorks Australia facilitated the development of detailed demand and supply side assumptions and undertook quantitative market and system modelling. CSIRO and ClimateWorks Australia's approach integrated multiple system models to analyse the least cost development and operation of the NEM's energy system to 2050.

This included the:

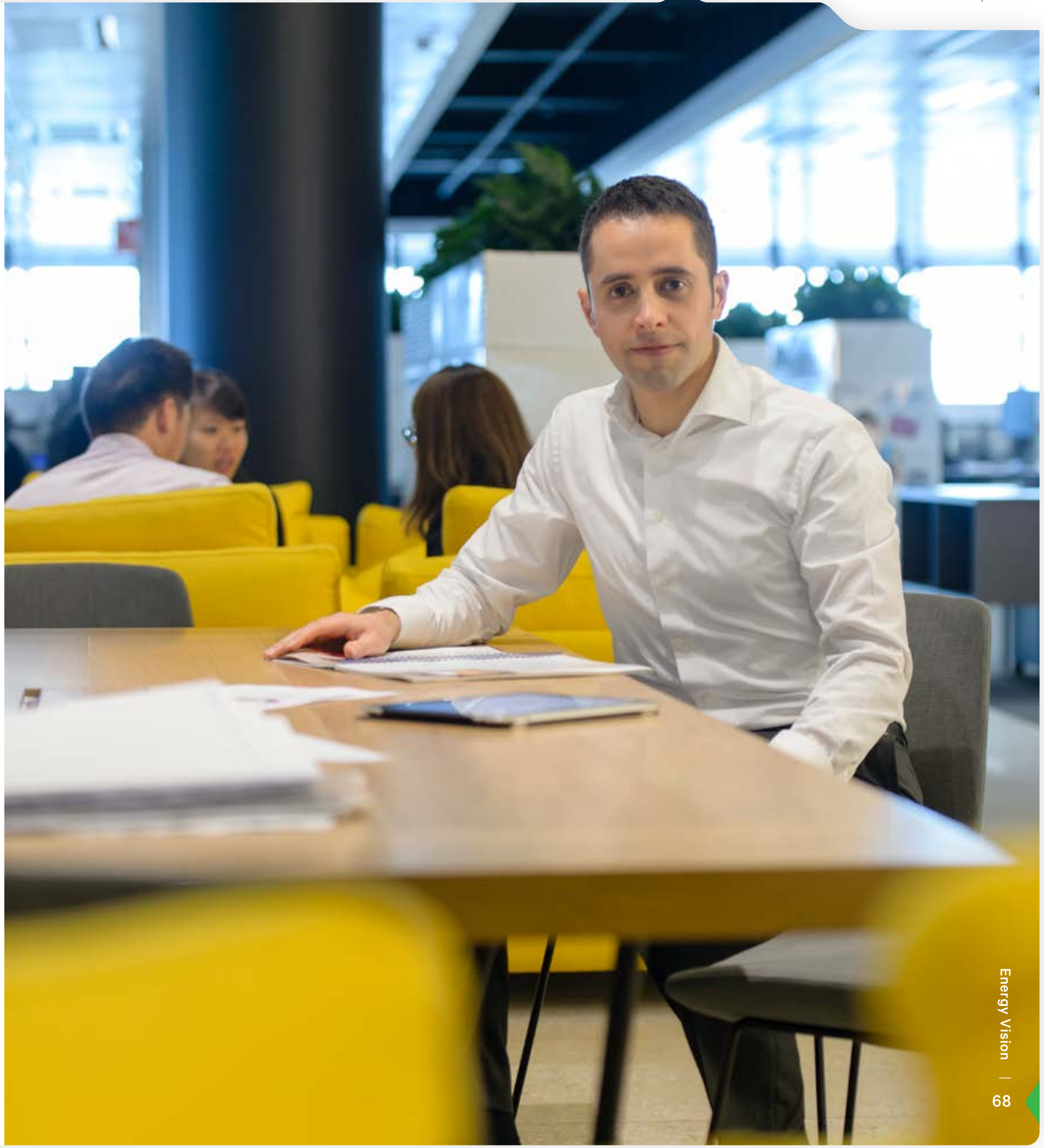
Projected growth of distributed energy resources, electric vehicles, Vehicle-to-Grid technology and consumer participation in Virtual Power Plants

- Projections of energy consumption, demand, energy efficiency and electrification
- Least cost modelling of generation and storage investment, generation retirement, transmission expansion, system security and hydrogen production
- Projections of the implications of each scenario on the cost of electricity and residential electricity expenditure

Throughout the modelling process, Transgrid engaged with key stakeholders via the Transgrid Advisory Council to stress-test assumptions and results and ensure insights were useful for the broader industry.

Note: all dates presented within our analysis are in Financial Years.

CSIRO | ClimateWorks AUSTRALIA | Brattle



1.2 Summary of assumptions

Key policy and supply side assumptions reflected in the modelling are provided below.

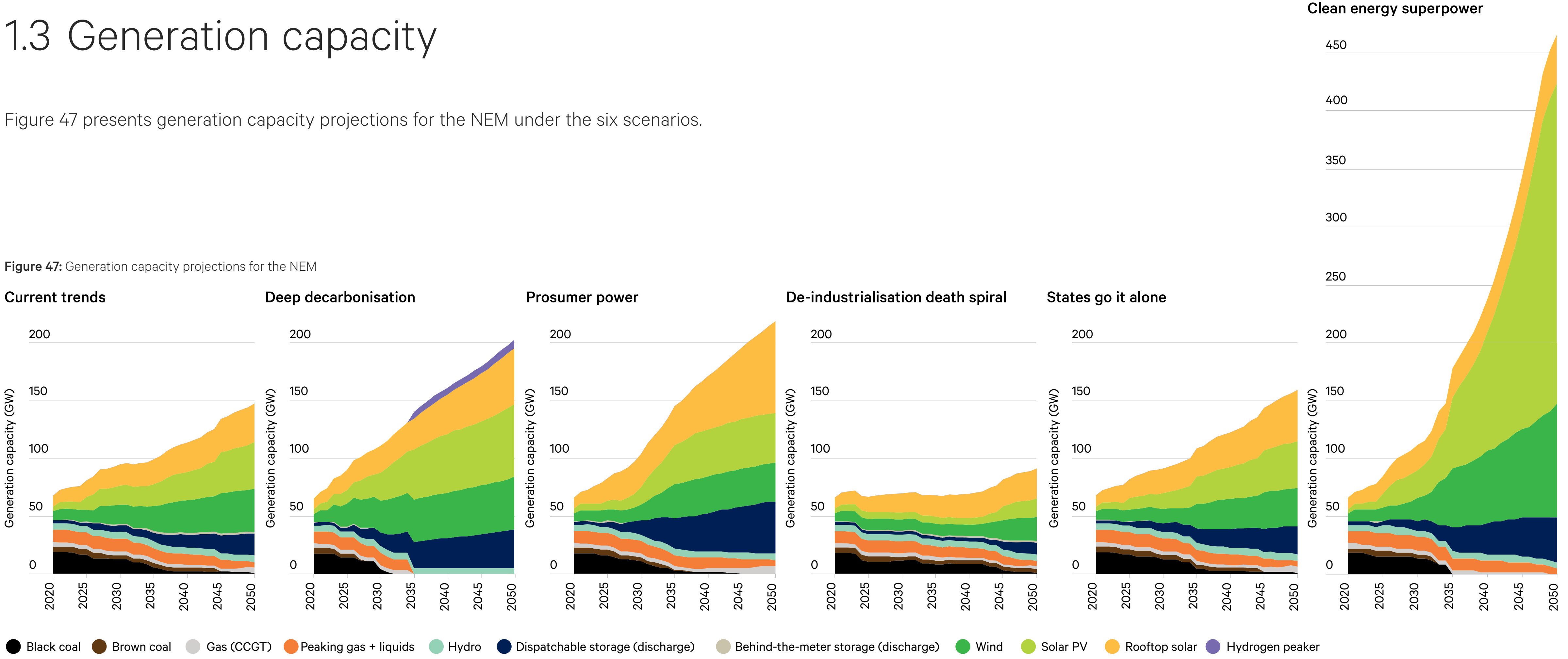
Key assumption	Current Trends	Deep Decarbonisation	Prosumer Power	De-industrialisation Death Spiral	States Go it Alone	Clean Energy Superpower
Coal generator retirements	Economic retirement before or at expected closure year	Economic or decarbonisation-driven retirement before or at expected closure year	Economic retirement before or at expected closure year	Retirement before, at or after expected closure year, with a 10 year life extension possible	Economic retirement before or at expected closure year	Economic retirement before or at expected closure year
Decarbonisation: average temperature rise by 2100, Representative Concentration Pathway (RCP), Date of net zero emissions	4°C RCP 7.0	>67% chance of holding temperatures to 1.5°C (with overshoot), or, >50% chance of holding temperatures to 1.5°C (with no overshoot)[1] RCP 1.9 Net zero emissions economy by 2035 then net negative emissions to 2050	>67% chance of holding temperatures to 2°C RCP 2.6 Net zero emissions economy by 2050	>4°C RCP 8.5	4°C RCP 7.0	>67% chance of holding temperatures to 2°C RCP 2.6 Net zero emissions economy by 2050
VRET (40% by 2025; 50% by 2030)	✓	✓	✓	✗	✓	✓
QRET (50% by 2030)	✓	✓	✓	✗	✓	✓
TRET (100% by 2022, 200% by 2040)[2]	✓ for 100%, ✗ for 200%	✓	✓ for 100%, ✗ for 200%	✗	✓ for 100%, ✗ for 200%	✓
NSW Electricity Infrastructure Roadmap (12GW additional largescale wind and solar PV by 2030)[3]	✓	Central West Orana REZ only (3GW by 2025)	✗	✗	Central West Orana REZ only (3GW by 2025)	✓
Federal Government's 26-28% target	✓	✓	✓	✓	✓	✓
Snowy 2.0[4]	✓	✓	✗	✗	✓	✓
Hydrogen production	✗	Broadly aligned with 'BAU' from Australia's National Hydrogen Strategy	✗	✗	✗	Broadly aligned with 'Energy of the Future' from Australia's National Hydrogen Strategy
New plant costs	GenCost 2020, Central	GenCost 2020, High VRE	GenCost 2020, High VRE	GenCost 2020, Diverse technology	GenCost 2020, Central	GenCost 2020, High VRE (with lower solar costs)
Coal prices	WoodMackenzie 2019, Neutral	WoodMackenzie 2019, Fast	WoodMackenzie 2019, Neutral	WoodMackenzie 2019, Slow	WoodMackenzie 2019, Neutral	WoodMackenzie 2019, Fast
Gas prices	Core Energy 2019, Neutral	Core Energy 2019, Fast	Core Energy 2019, Neutral	Core Energy 2019, Slow	Core Energy 2019, Neutral	Core Energy 2019, Fast

1. Overshoot is where warming increases past the 1.5°C mark and then cools back down. Approach based on carbon budget calculations by Meinshausen (2019, Deriving a global 2013-2050 emission budget to stay below 1.5°C based on the IPCC Special Report on 1.5°C) that takes into consideration the latest scientific advice from the IPCC's special report on 1.5°C. Based on a 'contraction and convergence' approach from the Garnaut Review (2008, http://www.garnautreview.org.au/2008-review.html), this asserts that Australia's emissions must not exceed more than 0.97% of the global carbon budget.
2. A 200% TRET requirement was not implemented as the model was left to optimise for the NEM-wide least cost of distribution of generation, transmission and hydrogen production.
3. The requirement for an addition 12GW of largescale wind and solar capacity has only been committed into the modelling for **Current trends** and **Clean energy superpower**. 3GW of generation capacity is committed in the Central West Orana renewable energy zone, 8GW in the New England renewable energy zone and 1GW of additional capacity from another NSW renewable energy zone. The NSW Roadmap was not committed in **Deep decarbonisation**, to test the optimised build out of NSW renewable energy capacity under a strong decarbonisation trajectory. It was not committed in **Prosumer power** as we wanted to maintain the divergence in the build out of NSW generation capacity.
4. Snowy 2.0 was not committed in **Prosumer power**, to test whether the energy system requires this level of deep storage in a scenario with a very high penetration of distributed energy resources. Snowy 2.0 was not committed in **De-industrialisation death spiral** to test whether the reduction in demand might negate the need for this development.

1.3 Generation capacity

Figure 47 presents generation capacity projections for the NEM under the six scenarios.

Figure 47: Generation capacity projections for the NEM



Appendix

1.4 Renewable energy zone utilisation

The utilisation of renewable energy zone capacity depends on the least cost optimisation of generation and transmission capital costs and the technical characteristics of the renewable energy zones, such as resource availability and quality.

Table 4 describes the utilisation of each renewable energy zone in 2050 for the six scenarios (compared with total available capacity[1]). Renewable energy zones with high utilisation across multiple scenarios are considered robust against different future outcomes; for example, New England and Central West Orana, followed by Wagga Wagga and South-West NSW within NSW.

Table 4: Utilised renewable energy zone capacity in the NEM, for zones with over 1GW of available capacity.

State	Renewable energy zone	Current trends	Deep Decarbonisation	Prosumer power	De-industrialisation death spiral	States go it alone	Clean energy superpower[2]
NSW	North-West NSW	15%	100%	5%	5%	15%	100%
	New England	85%	100%	75%	30%	80%	100%
	Central West Orana	100%	100%	100%	65%	100%	100%
	Broken Hill	5%	30%	5%	5%	5%	5%
	South-West NSW	55%	55%	55%	15%	45%	100%
	Wagga Wagga	50%	50%	50%	50%	50%	100%
QLD	Far North QLD	45%	75%	30%	40%	35%	100%
	North QLD Clean Energy Hub	0%	10%	0%	0%	0%	100%
	Northern QLD	15%	15%	15%	15%	15%	100%
	Isaac	30%	60%	45%	20%	40%	100%
	Barcaldine	0%	0%	0%	0%	0%	0%
	Fitzroy	50%	100%	35%	15%	25%	100%
	Wide Bay	5%	10%	5%	5%	5%	100%
	Darling Downs	100%	100%	100%	55%	100%	100%
	Far North West QLD	0%	0%	0%	0%	0%	5%
SA	South-East SA	50%	40%	55%	20%	45%	65%
	Riverland	0%	40%	0%	0%	0%	100%
	Mid-North SA	60%	80%	50%	15%	20%	100%
	Yorke Peninsula	35%	35%	35%	35%	35%	100%
	Northern SA	65%	100%	100%	35%	95%	100%
	Leigh Creek	0%	0%	0%	0%	0%	45%
TAS	North-East Tasmania	45%	55%	15%	15%	15%	100%
	North-West Tasmania	5%	5%	5%	5%	5%	100%
	Tasmania Midlands	100%	100%	95%	15%	20%	100%
VIC	Murray River	90%	100%	100%	15%	100%	100%
	Western Victoria	100%	100%	100%	80%	100%	100%
	South-West Victoria	85%	100%	85%	50%	100%	100%
	Gippsland	5%	100%	10%	5%	10%	100%
	Central-North Vic	5%	60%	55%	5%	65%	100%

1. Available capacity has been sourced from AEMO's 2020 Integrated System Plan
2. In **Clean energy Superpower**, solar build limits within AEMO-identified renewable energy zones have been doubled (and tripled for the zones Broken Hill (NSW), North QLD Clean Energy Hub, Barcaldine (QLD), Leigh Creek (SA), Roxby Downs (SA)) to provide additional renewable energy resource availability. The utilisation percentages represent the utilisation against the original AEMO-identified renewable energy zone capacity.

   In addition, new inland renewable energy zones have been created to provide additional resource availability **Clean energy Superpower**, including three inland zones in QLD, two in NSW and one in SA (not included in Table 4).

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