Aim High, Go Fast:
Why Emissions Need to Plummet this Decade.
Limiting global warming to 1.5 °C.

Sectoral pathways & Key Performance Indicators for Net-Zero Target Setting
Infrastructure Requirements for the National Electricity Market (NEM), Western Australian and the Northern Territory

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The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government, and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human wellbeing, and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organizations in a collaborative process that emphasizes strategic decision-making.

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EXECUTIVE SUMMARY

There is a substantial gap between what the science says is necessary for decarbonization and the plans that are underway or proposed for Australia. The Climate Council's foundational report *Aim High, Go Fast: Why Emissions Need to Plummet this Decade* and the update report *Mission Zero: How Today's Climate Choices Will Reshape Australia* underpin the Climate Council's science-based vision for what Australia's effort should look like: a 75% reduction from 2005 levels by 2030, reaching net zero by 2035.

Achieving this level of deep emissions reduction will not be straightforward. As part of building further momentum and ratcheting up strong climate action, we must identify and socialize the 'next wave' of effective climate action that will allow Australia to cut its emissions steeply in this decade (and beyond).

The Climate Council has commissioned the *Institute of Sustainable Futures* at the *University of Technology Sydney* to model how far emissions reductions can be accelerated by 2030 and 2035. ISF has already modelled a pathway by which Australia can achieve real zero energy-related emissions by 2050. This project involves the further assessment of how much key technologies and solutions must be accelerated to achieve emissions reductions at a science-aligned scale.

The research questions are:

- To what extent can energy-related emissions reductions be accelerated by 2030 and 2035 in Australia—with a view to finding a pathway by which Australia can reduce its emissions overall by 75% by 2030 and to net zero by 2035? What is the earliest date by which real zero energy-related emissions can be achieved?
- What level of emissions reductions is technologically possible by 2030 and 2035 in each sector and industry (listed below), given the right level of policy support and investment?
- What technologies and solutions will drive these emissions reductions in each of the analysed sectors and industries?
- What is the overall abatement potential and assumed uptake, with a focus on energy supply?

The sectors and industries included are: aluminium, chemicals, cement, steel, textiles and leather, agriculture and food processing, forestry and wood products, construction and real estate/buildings, power utilities, gas, water utilities, and transport.

The overall goal of this project was to craft a pathway by which Australia can reduce its emissions to 75% below 2005 levels by 2030 and to net zero by 2035.

Methodology: Energy Scenario Development

This analysis is based on the advanced version of the One Earth Climate Model (OECM 2.0). The OECM is an integrated energy assessment model that was originally developed in an interdisciplinary research project between the University of Technology Sydney, the German Aerospace Centre (DLR), and the University of Melbourne between 2017 and 2019. It consists of three independent modules:

1. Energy System Model (EM): a mathematical accounting system for the energy sector.
2. Transport scenario model (TRAnsport Energy Model, TRAEM), with high technical resolution.
3. Power system analysis model [R]E 24/7, which simulates the electricity system on an hourly basis and at geographic resolution to assess the requirements for infrastructure, such as the grid connections between different regions and electricity storage types, depending on the demand profiles and power-generation characteristics of the system.

Based on the OECM, the Institute for Sustainable Futures, University of Technology Sydney (UTS/ISF), in close co-operation with the UN-convened Net Zero Asset Owners Alliance, updated the OECM 1.0 model. The advanced OECM (OECM 2.0) merges the energy system model *EM*, the transport model *TRAEM*, and the power system model *[R]E 24/7*' into one MATLAB-based energy system module. The OECM has now been applied to 19 countries and the EU27 region, which formed the G20 in 2023, to produce energy scenarios and fair carbon budgets for each country, together with detailed carbon budgets for key industries within each country.

The Global Industry Classification System (GICS) is used in OECM 2.0 to allow the design of energy and emissions pathways for clearly defined industry sectors (sectorial pathways). Finding pathways to reduce emissions for industry sectors requires very high technical resolution in the calculation and projection of the future energy demands and the supply of electricity, (process) heat, and fuels that are required by, for example, the steel and chemical industries. An energy model with high technical resolution must be able to calculate the energy demand based on either sector-specific gross domestic product (GDP) projections or market forecasts of material flows, such as the demand for steel, aluminium, or cement, in tonnes per year.

Power Sector Analysis

After the energy demand has been calculated, the supply of electricity, heat, and fuels is calculated on an annual basis. The supply does not differentiate between demand sectors. Therefore, the electricity demand for all sectors—residential, industry, and transport—is aggregated and is provided as a total value. Consequently, no specific electric generation mix for the transport sector, for example, is considered. These annual values are used in conjunction with calibrated proportions of the supply technology to provide a breakdown of energy shares across the different supply technologies. After this modelling step is completed in OECM, an additional power sector analysis is computed separtely in MATLAB using an equillibrium energy balance methodology to assess the electrcity supply for Australia, given the electricty configuration of the National Electricity Market (NEM) and the islanded grids of WA and NT.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, allows a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services.

Analysis of Solar and Wind Energy Potential

GIS mapping was used to ascertain Australia's solar and wind energy resources. It was also used in the regional analysis of geographic and demographic parameters and the available infrastructure that can be leveraged in developing the scenarios. Mapping was performed with the software ESRI ArcGIS 10.6.1, which allows a spatial analysis and maps the results. It was used to allocate solar and onshore wind resources and for the demand projections for the 11 modelling regions. Population density, access to electricity infrastructure, and economic development projections are key input parameters in the region-specific analysis of Australia's future energy situation, to clarify the requirements for additional power grid capacities and/or micro-grids.

The [R]E Space methodology is part of the OECM methodology, and is used to map the solar energy potential and onshore energy potential. Open-source data and maps from various sources were collected and processed to visualize the country, its regions, and districts. Further demographic data related to the population and poverty were plotted onto the maps, together with transmission networks and power plants.

The land areas available for potential solar and onshore wind power generation were calculated and visualized at national and state levels with ArcGIS. A land-cover map, elevation (Digital Elevation Model, DEM), the World Database on Protected Areas, solar irradiation (direct normal irradiation, DNI), and wind speed data were obtained from the ETH Zuerich renewabler.ninja website as raster data, and were all converted into binary maps (0 = not suitable as a potential area, 1 = suitable as a potential area) against a set of assumption about land-use restrictions, and then combined into one binary map by overlaying all the raster data. This map integrates all the criteria cited above in one map, with a value of 1 (land included in the potential area) or 0 (land not included in the potential area).

Data on transmission lines and protected areas exist as vector data. All protected areas were excluded from the above value 1 areas in the integrated raster data using a mask layer generated from the 'erase' function. For a second scenario buffer layers were generated from transmission line (10 km) data, and then the raster data without protected areas were clipped by these buffer layers to generate potential area maps under Scenario 2. This input was fed into the calculations for the [R]E 24/7 model, as described below.

The mapping procedure for offshore wind potential involved gridded bathymetry data (GEBCO_2023) for ocean depth, the World Database on Protected Areas for marine and coastal protected areas, and wind speed data (≥ 6 m). Similar to the [R]E Space methodology, all the data were converted into binary maps (0 = not suitable as a potential area, 1 = suitable as a potential area) against all assumptions and then combined into one binary map by overlaying all the raster data. The latest data from the Digital Atlas Australia were used to map the locations of ports and the 50 km radii around them.

The calculated solar, onshore wind, and offshore wind potentials under Scenario 2 are significant:

- Solar: 11,905 GW
- Onshore wind: 2,006 GW
- Offshore wind: 5,318 GW

Scenario Definitions

Modelling the energy system to assess its impact on climate change involves a variety of methodological requirements. These pose specific challenges when addressed on the national level: the quantitative projection of developments in (future) technologies and potential markets; a consistent database of renewable energy potentials and their temporal and spatial distributions; reliable data on the current situations in all regions; an assessment of energy flows and emissions across all energy sub-sectors, such as industry, transport, residential, etc.; and a comprehensive assessment of all CO_2 emissions. Finally, analysing and assessing the energy transition require a long-term perspective on future developments.

Changes to energy markets require long-term decisions to be made because infrastructure changes are potentially required and they are therefore independent of short-term market developments. The energy market cannot function optimally without long-term infrastructure planning. Grid modifications and the roll-out of a smart metering infrastructure, for example, require several years to implement. These technologies form the basis of the energy market and allow energy trading. Therefore, the time required for infrastructure planning and other substantial transformation processes must be considered in the scenario-building approach. In this analysis, three different scenarios have been calculated.

The *BASE AMBITION* PATHWAY (*BA*)

The *Base Ambition* pathway (BA) is based on the OECM 1.5 °C pathways for G20 countries and takes international and national market and policy developments into account. Although the goal of the decarbonization pathway is ambitious the main focus in this scenario is on the power sector. The demand development in the transport sector is assumed to remain relatively stable, with moderate reductions in overall passenger–kilometres and accelerated electrification rates in road transport. Decarbonization of the industry and building sectors follows the international best practice pathways developed in the OECM research project between 2017 and 2022, which is documented in the scientific literature.

The *NECESSARY AMBITION* PATHWAY (*NP*)

The *Necessary Ambition* pathway (*NP*) is based on the *BA* pathway but goes further, aiming to achieve an energy-related CO_2 reduction of 75% relative to 2005 by 2030. The main differences from the *BA* pathway are:

- Accelerated implementation of solar photovoltaic, onshore, and offshore wind installation
- Accelerated phase-out of oil and gas for residential and industrial process heating
- Accelerated mode shift towards public transport and an increase in active transport modes, such as walking and cycling, in urban areas to reduce passenger transport, especially vehicles with internal combustion engines (ICEs).

The *NECESSARY AMBITION PATHWAY PLUS RENEWABLE ENERGY EXPORT* (*NPX*)

The *Necessary Ambition Pathway Plus Renewable Energy Export* (*NPX*) is based on the *NP* scenario with the development of additional renewable energy exports for the steel and aluminium value chains. Whereas the development in the domestic energy demand between 2020 and 2050 is identical to those in the *NP* scenario, the iron ore and bauxite mining industries are assumed to transition to the exportation of hot briquette iron (HBI) and alumina, respectively. The additional industrial processes will require a significant amount of additional electricity from 2035 onwards.

Socio-economic Assumptions

The population growth until 2050 is based on the Australian Government's projection of an average of 1.05% per year. The long-term GDP development is based on Government's projection of 2% per year on average until 2045.

Scenario Narratives

Scenario studies cannot predict the future, but they can describe what is needed for a successful pathway in terms of technology implementation and investment. Scenarios also help us to explore the possible effects of transition processes, such as supply costs and emissions. However, to develop a long-term energy scenario for Australia requires a shared vision.

The energy demand and supply scenarios in this study are based on information about current energy structures and today's knowledge of energy resources and the costs involved in deploying them.

Key Results

The key results for the three calculated energy pathways for Australia compare the demand and supply trajectories of the *BA* and *NP* pathways, both with and without renewable energy export development (*NPX*). Where the results for the *NP* and *NPX* are similar, the acronym *NP(X)* is used.

Final Energy Demand

The final energy demand for Australia decreases under the *BA* and *NP* scenarios until the end of the modelling period in 2050 (this is mostly due to the increased efficiencies associated with electrification). The *BA* energy demand decreases by around 1.5% per year until 2030 and by approximately 3% between 2031 and 2050. The *NP* scenario accelerates the efficiency measures across all sectors—mainly by faster electrification of the transport sector in combination with behavioural changes—leading to annual reduction rates of 3.5%–4% between 2030 and 2050.

The *NPX* pathway leads to an increase in the final energy demand—mainly electricity—after 2030 due to the increased renewable electricity required for the onshore manufacture of HDI and alumina. The *NPX* energy demand will increase by 4% annually between 2030 and 2040 and by 10% between 2041 and 2050. Australia will export energy equivalent to 85% of the domestic energy demand by 2050 in the form of these goods manufactured with zero emissions.

As a result of the electrification of all sectors to phase-out the use of fossil fuels, the electricity demand will increase constantly from the first year of projection (2024), with a significant jump under the *NPX* scenario. By 2050, Australia will export around 75% of the domestically generated electricity in the form of manufactured goods. The overall electricity demand under the *BA* and *NP* scenarios will grow by a factor of around 2.5 between 2025 and 2050.

Transport Demand

The final energy demand for transport will decrease under the *BA* and the *NP(X)* scenarios between 2025 and 2050 by 2% and 3% respectively as an annual average. Passenger transport modes will shift from private vehicles towards public transport (bus and rail) and—in urban areas—to active transport (walking and cycling). The overall final energy demand will decrease significantly by 65% (*BA*) or 70% (*NP(X)*), due to a combination of this mode shift and the replacement of inefficient ICEs with highly efficient electric drivetrains.

Fossil fuels—almost exclusively oil for ICEs—will be replaced by renewable electricity as the main energy source. Biofuels will be used mainly for shipping and aviation. Synthetic aviation fuels (SAF), produced with green hydrogen, will be introduced after 2040.

The overall passenger–kilometres in domestic aviation will decrease across all scenarios by 1.7% per year between 2020 and 2050. Although land-based travel—rail and road combined—will remain stable under all three scenarios, the transport modes will develop differently. The *BA* scenario projects a shift from road to rail of around 1% per year on average between 2025 and 2050; the *NP(X)* scenario, in contrast, is more ambitious, with an annual rate of 2%. Furthermore, the use of public transport buses will grow at the expense of individual passenger cars, from 5% (2020) to 20% (2050).

The reduction in the demand of the transport sector is not only based on technical measures, but also on behavioural changes, e.g., commuters in urban areas will not only shift from private vehicles to public transport, but also to active forms of transport, such as walking and cycling.

The freight transport demand will increases in line with economic growth. The *NP(X)* pathway assumes a slight reduction in freight transport, from trucks to cargo bicycles. However, this reduction is difficult to quantify because the development towards transport bikes, which mainly began in European cities, is yet to be determined. The additional demand for freight transport will shift mainly to railways under all scenarios.

Power Sector

The decarbonization of the power sector is vital under all three scenario narratives. New renewable power generation—mainly solar photovoltaic, onshore and offshore wind—will not only replace existing coal and gas power plant capacities, but must also meet the increasing electricity demand as transport, buildings, and industry are increasingly electrified. Sector coupling—the connection of the transport and heating sectors with the power sector via increased electrification—and new power system management are essential. By 2025, over 40% of Australia's power generation will be from renewable electricity—increasing to over 80% by around 2030. By 2035, Australia's entire electricity demand will be generated from renewables under all three scenarios.

The renewable energy generation capacity will increase significantly until 2050 under all scenarios. The increase in capacity is due to the higher electricity demand and the lower capacity factors of solar and wind power plants compared with those of coal and gas power plants. Investment in the higher capacity required comes with additional requirements for storage capacity, but an almost complete phase-out of (fossil) fuel costs.

The Australian solar photovoltaic industry must increase its annual capacity—including the required supply chains—from an installation rate of around 5 GW per year to around 10 GW per year under the *BA* scenario. Under both the *NP* and *NPX* scenarios, solar and wind capacities will ramp up faster between 2025 and 2030, leading to 30%–50% higher annual installation rates.

Although under the ‘NP’, these will remain at 2030 levels for the coming two decades, under *NPX*, annual capacities will continues to increase, such that they are four times higher than in 2023 for solar photovoltaic and 2–3 times higher for the wind industry.

The onshore wind market will increase from around 1.5 GW per year to about 4 GW, whereas the offshore wind industry is assumed to ramp up between 2023 and 2030, with its first installation just before 2030 and a long-term annual capacity of 1.5–2 GW per year.

The overall development of the solar and wind industries will increase from the current ~8 GW per year to 15 GW under the *BA* scenario and to over 20 GW under the *NP(X)* scenario around 2030. Although the *NP* pathway will remains at around 20 GW of new solar and wind capacities per year, approximately 10 GW of additional new solar and wind power plants must be built to supply the increased demand for clean exports.

The new installed capacity required annually for solar photovoltaics and onshore and offshore wind under the three scenarios for 2040, 2045, and 2050 include repowering capacities—to replace generators after 20–25-year lifetimes. This has been assumed based on the annual market sizes in 2020, 2025, and 2030. To avoid boom and bust cycles, the repowering capacities of generators built before 2020 are distributed across 2030 and 2035 because the technical lifetimes for solar and wind turbines have proven to be 5–10 years longer than the assumed 20 years. Solar photovoltaic is projected to remain the technology with the highest capacity in Australia across the modelling period, followed by onshore wind and then offshore wind.

Heating Sector

The heat demand in Australia is assumed to increase only slightly over time due to the increase in building stock, but increased efficiency measures, electrification, and increased economic activity are expected to keep demand almost stable. The domestic heat demand for residential buildings, and especially industrial process heat, will increase by only 15% in total between 2020 and 2050—while over the same period, GDP will increase by around 2% per year and population by 1% annually. Electric heating systems—especially heat pumps, but also electric arc furnaces (EAF) for the steel and chemical industries—will increase the overall electricity share in Australia’s heating supply from 2% currently to over 35% by 2035 and 50% in 2050.

Primary Energy Demand

Finally, the primary energy demand for Australia will decrease by 0.6% per year due to high-level electrification under the *BA* scenario and by 1.9% per year under the *NP* scenario between 2020 and 2050. The *NPX* scenario will lead to an increase in Australia’s primary energy demand of 35% within the same time frame, an increase of around 1.2% per year.

Energy-related CO_2 Emissions

As a result of the phase-out of fossil fuel across all three scenarios and the significant increases in the renewable energy supply, the 2030 emissions will decrease by 61% under the *BA* scenario and by 75% under the *NP(X)* scenario relative to Australia’s energy-related CO_2 emissions in 2005. The *BA* scenario will lead to an 84% reduction from 2005 levels by 2035; the *NP* scenario will lead to an 88% reduction; and the *NPX* scenario to an 87% reduction. All three scenarios will lead to complete decarbonization by 2050. Importantly, this demonstrates a ‘real zero’ approach to the energy sector, where CO_2 emissions are fully eliminated—rather than relying on carbon offsets, carbon capture and storage, or other proposed alternatives to achieve notional emissions reductions.

Australia’s CO_2 emissions: Historical data (2005–2022 AGEIS) and projections (2023–2050) based on One Earth Climate Model 1.5 °C

[Mt CO_2/a]	2005			2021			2025			2030			2035			2040			2050		
	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX
Electricity	197	197	197	164	164	164	113	107	108	34	13	13	3	0	1	0	0	0	0	0	0
Stationary energy	82	82	82	99	99	99	67	66	68	38	31	32	28	23	24	16	12	13	0	0	0
Transport	82	82	82	92	92	92	73	66	66	57	38	39	30	20	20	18	11	11	0	0	0
Total energy-related CO_2	361	361	361	355	355	355	253	239	242	129	82	84	61	43	45	34	23	24	0	0	0
Reduction relative to 2005	0%	0%	0%	2%	2%	2%	30%	34%	33%	64%	75%	73%	84%	88%	88%	91%	94%	93%	100%	100%	100%

Australia and the National Electricity Market (NEM): Power Sector Analysis

The power sector analysis focuses on of the *NP* scenario and aims to provide insight into the electricity supply and demand balance and possible requirements in additional infrastructure, such as power grid and storage technologies, by 2030.

The underlying assumptions about generation capacity do not change across the generation scenarios (figure below)—only the proportion of roof-top solar varies. In the centralised generation scenario, utility-scale solar reaches its 2030 potential according to AEMO's *Green Energy Export* scenario[1] and thus roof-top photovoltaic is ~50% of total solar, whereas in the distributed generation scenarios, roof-top photovoltaic retains its current proportion of ~62% of total solar and thus the total distributed photovoltaic aligns with the value expected in 2035 under the *Step Change* scenario[2]. The values for storage vary in line with the scenario being tested, as described in the table below. The aim of this analysis is to evaluate whether centralised or decentralised generation and storage is more favourable for the power system, or if a combination of centralised and decentralised capacities offer benefits.

		Distribution of power generation	
		Greater decentralised generation	Greater centralised generation
Distribution of storage	Greater decentralised storage	**Decentralised power generation, decentralised storage (DP DP)** ● Most of the shortfall in supply between what is planned and what is needed to meet the generation target is met with residential and commercial roof-top solar. ●Co-ordinated and uncoordinated distributed storage makes a strong contribution to meeting our storage needs. ● No more additional pumped hydro will be required in Australia by 2030 beyond what is already planned. ● Participation in demand-side management and electric vehicle battery charging schemes	**Centralised power generation, decentralised storage (CP DS)** • The bulk of renewable energy generation is supplied by utility-scale solar, onshore wind, and offshore wind in locations that guarantee the highest capacity factors. • Co-ordinated and uncoordinated distributed storage makes a strong contribution to storage needs. • No more additional pumped hydro will be required in Australia by 2030 beyond what is already planned.
	Greater centralised storage	**Decentralised power generation, centralised storage (DP CS)** • Most of the shortfall in supply between what is planned and what is needed to meet our generation target is met with residential and commercial roof-top solar. • Storage needs are primarily met with a combination of pumped hydro, and utility-scale batteries, with smaller contributions from co-ordinated and uncoordinated distributed storage. • Pumped hydro is implemented as scheduled, with potentially more built if required.	**Centralised power generation, centralised storage (CP CS)** • The bulk of renewable energy generation is supplied by utility-scale solar, onshore wind, and offshore wind in locations that guarantee the highest capacity factors. • New medium-scale pumped hydro contributes strongly to meeting storage needs, alongside utility-scale batteries. • Decentralised storage system will not grow fast enough to take over significant power-system-relevant storage services.

Storage assumptions for centralised and decentralised scenarios

Storage Type	Centralised Scenario [GW]	Decentralised Scenario [GW]
Distributed Batteries	11.60[3]	25.49[4]
Utility-scale Batteries	26.83[5]	16.84[6]
Pumped Hydro	8.44[7]	4.28[8]
Total	46.87	46.61

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[1] https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/a3-renewable-energy-zones.pdf

[2] 2023 IASR Workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

[3] In line with the forecasted value for 2030 under 'Step Change', 2023 IASR workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

[4] In line with 2035 'Step Change', 2023 IASR Workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

[5] 2030 Forecast + Announced *and* Proposed projects from Renew Economy Map, https://reneweconomy.com.au/big-battery-storage-map-of-australia/

[6] 2030 Forecast + Announced projects from Renew Economy Map, https://reneweconomy.com.au/big-battery-storage-map-of-australia/

[7] 2030 Forecast + Battery of the Nation + NSW projects which could be supported through policy/storage target, https://www.energy.nsw.gov.au/nsw-plans-and-progress/major-state-projects/shift-renewables/emerging-energy-program

[8] 2030 Forecast value, 2023 IASR workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

Interconnector limits

The power-carrying capacity of a power line varies over time and is dependent on several parameters, including the outside temperature, the utilisation of the line, the frequency, the physical characteristics of the line, the length of the line, and the power generation capacity connected to the line.

Because the modelling year was set to 2030 across the power sector analysis scenarios, a methodology was developed for linking the *NP* generation capacities to the regional interconnection limits, such that the interconnection limits would be appropriate under all scenarios when the input parameters were changed—while leaving sufficient flexibility in the model to easily allow for different transmission scenarios to be established if required. The following steps were used to model the regional interconnection limits:

1. A table of predicted 2030 interconnection limits was developed, according to Australian Energy Market Operator (AEMO) documentation.[9]
2. Tables of the predicted regional breakdown of generation capacity under the *NP* scenario were developed.
3. Steps 1 and 2 were used to calculate the percentages of interconnection relative to the regional generation capacities.

Using these three steps, the percentages for differing scenarios can be modified easily if required and used for the analysis of different years, as required. The calculations made for different scenarios indicated a relatively constant percentage value based on the underlying assumptions. Therefore, the percentages were held relatively constant across the 2020–2030 period.

In our analysis, an increase in the necessary inter-regional exchange of capacity, in addition to the increase in grid capacity within the regions as demand increases, will start between 2025 and 2030. This will be particularly true of those regions with a high population density, high demand, and high solar and wind generation potential. Three regions are particularly important for the transfer of power supply and the appropriate interconnections must increase and/or be established between 2025 and 2030:

1. Victoria–South New South Wales: increase from 400 MW to 2069 MW
2. Victoria–Tasmania: increase from 462MW to 1212 MW
3. Southern New South Wales–Central South Australia: new connection with 800 MW capacity

Development of power plant capacities

Under the NP scenario, the solar photovoltaic capacity will grow fastest, from 36 GW in 2023 to 79 GW in 2030. The second largest total capacity will come from onshore wind, which will increase from 10 GW in 2023 to 69 GW in 2030. Moreover, offshore wind is expected to enter the Australian power grid just before 2030 as a new form of renewable generation, with high 'base-load-like' capacity factors. Hydro power and bio-energy are projected to grow only moderately and according to the current project development pipeline, with an additional 2 GW of hydro power and 1 GW of bio- energy until 2030.

Solar photovoltaic is the key renewable energy technology for Australia, but diversity is required to keep the storage demand low and the security of supply high. All renewable power technologies—on- and offshore wind, geothermal power, and concentrated solar power plants—are important for the successful decarbonization of Australia's power sector.

Development of load, generation, and residual load

Based on the recalculated historical load and generation, the maximum load (= demand), power generation, and residual load have been calculated for 2025 and 2030 with the projected electricity demand and supply development under the *NP* scenario. The calculated maximum loads under both scenarios (*BA* and *NP*) lead to identical results. The actual power demand is not influenced by the different distributions of generation.

However, the calculated values for maximum generation show minor differences between the decentralised and centralised generation scenarios–even though identical total installed capacities are assumed. This difference can be explained by regional variations in solar and wind power generation shares and the available interconnections and storage capacities, which influence the curtailment rate—or the forced shut-down of generation capacity when there is no local demand and the surplus electricity can neither be stored nor transported to sites of demand.

'Residual load' describes the difference between the required load (= demand) and the available supply. The higher the share of decentralised power generation—roof-top photovoltaic—the lower will be the residual load. Solar photovoltaic supplies the residential power demand close to the point of demand. However, the differences are relatively small and additional research

[9] https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-transmission-expansion-options-report.pdf

is required that includes different voltage levels. It is worth noting that no differences in the maximum residual load could be calculated in the two regions that were not connected to the NEM (WA and NT).

Peak load and peak generation events do not appear at the same time, so the values cannot simply be added. Moreover, peak loads can vary across all regions and appear at different times. Therefore, to sum all the regional peak loads will only provide an indication of the peak load for the whole power system. The maximum residual load[10] shows the maximum undersupply in a region and indicates the maximum load imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. Optimizing the interconnection for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be supplied by the following options:

- imports from other regions through interconnections;
- charged storage facilities providing additional load;
- available back-up capacities, such as gas peaking plants;
- load- and demand-side management.

In practice, security of supply will be achieved with a combination of several measures, and will require an in-depth analysis of the regional technical possibilities, e.g., whether a cable connection is possible.

Storage requirements

In the *NP* scenario, the share of variable generation will exceed 30% by 2025 in all 11 Australian regions. In this analysis, we assume that a curtailment rate of 5% of the annual generation (in GWh/a) for solar photovoltaics and onshore and offshore wind will be economically viable by 2030. Curtailment rates over 10% indicate that additional grid integration measures are required to increase the economic performance of the overall power system.

However, economic curtailment rates are dependent on the available grid capacities and can vary significantly, even within Australia. Curtailment will be economic when the power generated by a wind turbine or photovoltaic power plant exceeds the demand for only a few hours per day and this event occurs rarely across the year. Therefore, grid expansion will not be justifiable. Decentralised storage scenarios achieve slightly lower utilisation rates than centralised storage scenarios—even though the overall installed storage capacity in GW is identical in all four scenarios. By the 2030, the overall storage capacities will be:

- NEM: 45 GW
- Australia (NEM + WA + NT): 47 GW

The combination of decentralised generation and centralised storage will achieve the highest utilisation rates. This is attributable to the chosen dispatch order—decentralised storage is charged first with roof-top photovoltaic generation, whereas centralised storage also has access to surplus wind power generation, but is constrained by transport capacities and the interconnections power grid between the geographical position of generation and demand..

Curtailment and security of supply

In the four scenarios, combinations of centralised and decentralised storage technologies have been calculated with solar and wind data for the year 2012 to make them comparable to the Integrated System Plan (ISP), which uses that year. Our analysis for the year 2030 at hourly resolution (8760 hours per year) showed that the chosen electricity generation mix generated 17%–22% more electricity than required. However, the chosen storage capacities were not sufficient to absorb this surplus electricity generated. The times of over- and undersupply were several months apart, so the surplus electricity stored in batteries was no longer available at the time of undersupply. The following options can fill this supply gap:

- supply with gas generation;
- increased interconnection;
- increased demand-side management.

Based on the current projections for increased interconnections and storage projects, gas back-up was the selected option in all four scenarios.

[10] Residual load is the load remaining after the local generation within the analysed region is exhausted. A shortage of load supply could be due to the operation and maintenance of a coal power plant or reduced output from wind or solar power plants.

Key take-away messages: Power sector analysis

All four scenarios lead to a secure power supply for the NEM and Australia. This in itself is a significant finding, because it demonstrates that with sufficiently ambitious policy support for the energy transition, it will be possible to decarbonize Australia's electricity production faster than is currently predicted. In an example of this, AEMO's *Step Change* scenario in the 2022 ISP utilises a total of ~7GW across the NEM in 2030[11], whereas the *NP* scenario assumes the retirement of all coal capacity across the National Electricity Market (NEM) of the east-coast and Western Australian *South West Interconnected System* (SWIS) grids—without expansion of the gas capacity beyond current levels. The supply of all regions is secure under all four scenarios and the results of this analysis do not indicate any technical barriers to the *NP* scenario and the assumed power generation mix.

Due to the modelling methodology and scenario assumptions used, negligible differences were observed between the centralised and decentralised generation parameters. When a modelling method with higher resolution was used, further differences were observed when the proportion of distributed to utility-scale solar was altered, e.g., distributed network hosting capacity limits, other network constraints and export limits, etc. (this is beyond the scope of this report). Thus, our modelling supports the need for the continued uptake of both roof-top solar and utility-scale projects, together with storage, to accelerate the decarbonization of electricity production in Australia. It should be noted that the scenarios also require an expansion of wind generation (onshore and offshore) beyond current forecasts, to ensure sufficient supply outside solar hours.

Both the decentralised and centralised storage scenarios produced similar results, although curtailment was lower in the centralised storage scenarios than in the decentralised storage scenarios. This is because centralised storage scenarios have a higher GWh because the duration of storage is greater for pumped hydro and utility-scale batteries than for decentralised batteries. Furthermore, utility-scale storage has the added ability to store and dispatch power to neighbouring regions, further reducing the curtailment of surplus renewables.

Although this effect is slight, it can be said that neither an entirely centralised power generation and storage system nor an entirely decentralised generation and storage system is preferable. Ultimately, a combination of renewable generation and different storage types is required to achieve the *NP*, with a noticeable increase in uptake across both centralised and decentralised technologies relative to the current forecasts required, if the *NP* scenario is to be achieved.

These results suggest that a high supply share with decentralised roof-top solar systems in combination with decentralised storage for the residential sector and centralised utility-scale solar combined with onshore wind, offshore wind, and utility-scale storage, which are connected to the high-voltage lines that serve industrial consumers, will lead to the highest security of supply with the lowest curtailment rates.

Conclusion

The aim of this research was to develop a vision for an ambitious energy transition concept to bridge the substantial gap between what the climate science says is necessary for decarbonization and the plans that are underway or proposed in Australia. This report *Aim High, Go Fast: Why Emissions Need to Plummet this Decade*, underpins the Climate Council's science-based vision for what Australia's effort should look like: a 75% reduction from 2005 levels by 2030, reaching net zero by 2045.

[11] https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf

Key answers to the research questions are:

1. Australia can reduce its energy-related CO_2 emissions by 75% relative to 2005 levels by 2030. The *Necessary Ambition* scenario will lead to energy-related CO_2 emissions of 82 $MtCO_2$ in 2030 and 43 $MtCO_2$ in 2035.
   The energy sector will be entirely decarbonized just before 2050.
2. The overall carbon budget for Australia until full decarbonization is calculated to be 3 $GtCO_2$ between 2020 and 2050. In this analysis, we developed a sector-specific carbon budgets for 15 sectors (see Table 37). The research indicates that there are no technical barriers to achieving full decarbonization in all the sectors analysed.
3. To achieve these ambitious decarbonization pathways, a wide spectrum of technologies is required and policies to implement those pathways must be comprehensive and long-term.

a. For the power sector, solar photovoltaic is the key renewable energy technology for Australia, but diversity is required to keep the storage demand low and the security of supply high. All renewable power technologies—on- and offshore wind, geothermal power, and concentrated solar power plants—are important for the successful decarbonization of Australia's power sector.
b. For the industry sector, the generation of electrical process heat and thermal process heat based on hydrogen and synthetic fuels is among the most important new technological developments.
c. For the transport sector, the electrification of road and rail transport vehicles, increased active transport, such as cycling and walking, and consistent policies are the key measures and among the most challenging for Australia, given the geography of the country.
d. For the building sector, significant improvements in building efficiency in terms of the building envelope and double glazing are key.

To conclude, Australia can decarbonize its economy with existing technologies, but not with existing policies.

Necessary Pathway—energy-related CO_2 emissions (in $MtCO_2$/year)

Necessary Pathway—energy-related CO_2 emissions (in $MtCO_2$/year)						Cumulative energy-related CO_2 emissions [$MtCO_2$]. Significant improvement in efficiency			Share of Carbon Budget
Sector	Industry	2020	2030	2035	2050	2020–2030	2031–2050	2020–2050	
Cement	Industry	6	3	2	0	51	25	76	2%
Steel	Industry	6	3	2	0	46	32	80	3%
Chemical Industry	Industry	6	2	1	0	46	13	59	2%
Textile & Leather	Industry	0	0	0	0	5	2	6	0%
Aluminium	Industry	30	6	4	0	188	44	232	8%
Buildings—commercial, residential, & construction	Services	148	14	12	0	1,012	144	1,156	38%
Agriculture & Food Processing	Services	18	1	1	0	104	10	115	4%
Forestry & Wood	Services	6	0	0	0	41	4	45	1%
Water Utilities	Services	0	0	0	0	2	0	2	0%
Aviation—Transport Services	Transport	9	7	3	0	91	31	122	4%
Aviation Industry—direct	Transport	0	0	0	0	2	0	2	0%
Navigation Transport Services	Transport	2	2	2	0	20	15	36	1%
Navigation Industry—direct	Transport	0	0	0	0	2	0	2	0%
Road Transport—Transport Services	Transport	64	27	14	0	506	175	680	22%
Road Transport Industry—direct	Transport	4	1	0	0	20	0	20	1%
All other sectors	Other	60	12	3	0	412	34	443	14%
Sum		360	79	43	0	2,547	530	3,077	100%

1 INTRODUCTION & SCOPE OF THE RESEARCH

1.1 CONTEXT OF THIS RESEARCH

There is a substantial gap between what the science says is necessary for decarbonization, and the plans that are underway or proposed in Australia. The Climate Council's foundational report *Aim High, Go Fast: Why Emissions Need to Plummet this Decade* and the updated report *Mission Zero: How Today's Climate Choices Will Reshape Australia* underpin the Climate Council's science-based vision for what Australia's effort should look like: a 75% reduction from 2005 levels by 2030, reaching net zero by 2035.

Getting to this level of deep emissions reductions will not be straightforward. As part of building further momentum and ratcheting up strong climate action, we must identify and socialize what the 'next wave' of effective climate action is that can see Australia cut emissions steeply in this decade (and beyond).

The Climate Council has commissioned the Institute of Sustainable Futures (University of Technology Sydney) to model how far emissions reductions can be accelerated by 2030 and 2035. ISF has already modelled a pathway for Australia to achieve real zero energy-related emissions by 2050. This project involved further assessment of how much key technologies and solutions must be accelerated to achieve emissions reduction at a science-aligned scale."

1.1.1 RESEARCH QUESTIONS

The research questions are:

- To what extent can energy-related emissions reductions be accelerated by 2030 and 2035 in Australia—with a view to finding a pathway for Australia to reduce its emissions overall by 75% by 2030 and to net zero by 2035? What is the earliest date by which real zero energy-related emissions can be achieved?
- What level of emissions reductions is technologically possible by 2030 and 2035 in each sector and industry (listed below), given the right level of policy support and investment?
- What technologies and solutions will drive these emissions reductions in each sector and industry listed (with as much granularity as possible)?
- What is the overall abatement potential and assumed technological uptake, with a focus on energy supply?

The sectors and industries included are: aluminium, chemicals, cement, steel, textiles and leather, agriculture and food processing, forestry and wood products, construction and real estate/buildings, power utilities, gas, water utilities, and transport.

The overall goal of this project was to craft a pathway for Australia to reduce its emissions by 75% below 2005 levels by 2030 and to net zero by 2035.

1.2 ROLE OF THE EXPERT ADVISORY GROUP

After a series of consultations with leading experts and a literature review to inform the scope of the project, the Climate Council established an Expert Advisory Group—consisting of experts in economy-wide decarbonization, energy systems, transport, the built environment, the economy, and industry—to advise this research. The role of the Expert Advisory Group is to:

- Contribute to the assumptions to ensure they are as ambitious as possible (but robust), including advising where barriers could be shifted by implementing enablers (e.g., institutional or financial), to accelerate emissions reductions;
- Provide input during the project if there are specific issues that require specific guidance;
- Review the draft results.

2 ONE EARTH CLIMATE MODEL—METHODOLOGICAL OVERVIEW

This analysis is based on the advanced version of the One Earth Climate Model, 'OECM 2.0'.

The OECM is an integrated energy assessment model. It was originally developed in an interdisciplinary research project undertaken collaboratively by the University of Technology Sydney, the German Aerospace Centre (DLR), and the University of Melbourne in 2017–2019. The task was to develop a detailed energy-related greenhouse gas (GHG) emissions trajectory towards 1.5 °C for 10 world regions. OECM 1.0 was developed on the basis of established DLR and UTS energy models, and consisted of three independent modules:

1. Energy System Model (EM), a mathematical accounting system for the energy sector[12].
2. Transport scenario model (TRAnsport Energy Model, TRAEM), with high technical resolution[13].
3. Power system analysis model [R]E 24/7, which simulates the electricity system on an hourly basis and at geographic resolution to assess the requirements for infrastructure, such as grid connections, between different regions and electricity storage types, depending on the demand profiles and power-generation characteristics of the system[14].

Based on the OECM,[15] the Institute for Sustainable Futures (ISF), University of Technology Sydney (UTS), in close co-operation with the UN-convened Net Zero Asset Owners Alliance, updated the OECM 1.0 model. OECM 2.0 merges the energy system model EM, the transport model TRAEM, and the power system model [R]E 24/7 into one MATLAB-based energy system module. OECM has now been applied to 19 countries plus the EU27 region, which formed the G20 in 2023, to produce energy scenarios and fair carbon budgets for each country, as well as detailed carbon budgets for the key industries in each country.

The Global Industry Classification System (GICS) was used in OECM 2.0 to allow the design of energy and emissions pathways for clearly defined industry sectors (sectorial pathways). Finding pathways to reduce emissions for industry sectors requires very high technical resolution for the calculation and projection of future energy demands and the supply of electricity, (process) heat, and fuels, which are necessary for, for example, the steel and chemical industries. An energy model with high technical resolution must be able to calculate the energy demand based on either the sector-specific GDP projections or market forecasts of material flows, such as the demand for steel, aluminium, or cement, in tonnes per year.

This methodology chapter outlines five fundamental elements of the modelling process:

- (i) databases and model calibration;
- (ii) sector and sub-sector definitions;
- (iii) cost calculations;
- (iv) a demand module; and
- (v) a supply module.

2.1 DATABASES AND MODEL CALIBRATION

The OECM uses several databases for the energy statistics, energy intensities, technology market shares, and other market or socio-economic parameters. The calculation of the energy balance for the base year is based on the International Energy Agency (IEA) Advanced World Energy Balances[16] and additional sector and nation-specific databases.

The energy statistics for an analysed country and/or region are uploaded via an interface module. The data for each year from 2005 onwards until the last year for which data are available, are used to calibrate the model. This process is based on the Energy System Model (EM), which was developed by the German Aerospace Centre DLR. The market shares are calculated based on the IEA statistics and a technical database for energy intensities for various appliances and applications across all sectors. These data are inputs, and the calibration process is performed with a standardised Excel tool. The calibration method is briefly outlined below using the transport sector as an example. To calibrate the model, the transport demand of the past decade was recalculated on the basis of the available energy statistics. The IEA's Advanced World Energy Balances provides the total final energy demand by transport mode—aviation, shipping, rail, or road—accordingh to country, region, or globally. However, it

[12] Simon S, Naegler T, Gils HC. Transformation Towards a Renewable Energy System in Brazil and Mexico—Technological and Structural Options for Latin America. Energies 2018;11:907.

[13] Pagenkopf J, van den Adel B, Deniz Ö, Schmid S. Transport transition concepts. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +15 °C and +2 °C. 2019, 131–59.

[14] Teske S. Bridging the Gap between Energy and Grid Models. Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies. Chapter 2. 2015.

[15] Teske S, Pregger T, Naegler T, Simon S, Pagenkopf J, van den Adel B, et al. Energy scenario results. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C. 2019, 175–401.

[16] IEA. IEA World Energy Statistics and Balances. IEA. 2021. https://doi.org/https://doi.org/10.1787/enestats-data-en

provides no further specification of the energy use within each of the transport modes. Therefore, a further division into passenger and freight transport is calculated from their percentage shares. These proportions are determined with literature research, together with the average energy intensity for each of the transport modes for passenger and freight vehicles.

The annual transport demand in passenger–kilometres per year (pkm/yr) and tonne–kilometres per year (tkm/yr) is calculated as the annual energy demand divided by the average energy intensity by mode. In this work for Australia, these results were compared with statistics from the Bureau of Infrastructure and Transport Research Economic (BITRE),[17] which provide both parameters (pkm/yr and tkm/yr). Calibrating the model on the basis of historical data ensures that the basis of the scenario projection for the coming years and decades are correctly mapped, and ensures that the changes are calculated most realistically. For the forward projection of the transport demand, the calculation method is reversed: the transport demand for each transport mode is calculated on the basis of the annual change, as a percentage. The calculated total annual passenger–kilometres and tonne–kilometres are the inputs for the energy demand calculation.

Table 1: Calibration for calculating the transport demand

Calculation Concept	Process	Until 2019	Unit	Comment
Transport Demand				
Aviation, Shipping, Rail, and Road **Past to Present**				
Annual Demand	Data	Database	[PJ/yr]	Data: IEA Advanced World Energy Balances
Passenger share	Input	Literature	[%]	Shares of total energy demand from the literature
Freight share	Input	Literature	[%]	Shares of total energy demand from the literature
Average Energy Intensity—passenger transport	Data	Literature	[MJ/pkm]	Literature review—based on current supply mix
Average Energy Intensity—freight transport	Data	Literature	[MJ/tkm]	Literature review—based on current supply mix
Passenger–kilometres	Calculation	= Annual demand/Energy Intensity	[pkm]	Checked against OECD statistics
Tonne–kilometres	Calculation		[tkm]	Checked against OECD statistics
Annual Growth/Reduction—passenger–kilometres	Calculation	= Annual demand previous year/Annual demand calculated year	[%/yr]	Calculated to understand the trend between 2005 and 2020
Annual Growth/Reduction—tonne–kilometres	Calculation		[%/yr]	
Population—indicator of passenger transport development	Data	Database	[million]	Data: UN
GDP per capita—indicator of passenger & freight transport development	Data	Database	[$GDP/capita]	Data: World Bank
GDP—indicator of freight transport development	Data	Database	[$GDP]	Data: World Bank

Table 2: Methodology of OECM 2.0—projection of transport demand based on the changing demand in kilometres

Process	2020–2050	Unit	Comment
Aviation, Navigation, Rail, Road—Projection			
Calculation	= (passenger–km previous year) × (increase/reduction in %/yr)	[pkm]	Starting point: base year 2019
Calculation	= (tonne–km previous year) × (increase/reductyion in %/yr)	[tkm]	Starting point: base year 2019
Input	INPUT in %/yr	[%/yr]	Assumption
Input	INPUT in %/yr	[%/yr]	Assumption
Calculation	INPUT in %/yr	[million]	Assumption based on UN projection
Calculation	= $GDP/population	[$GDP/capita]	
Calculation	INPUT in %/yr	[$GDP]	Assumption based on World Bank projection
Result	Time series 2020–2050: passenger–km per year & region	[pkm/yr]	Input for energy demand calculation
Result	Time series 2020–2050: freight–km per year & region	[tkm/yr]	Input for energy demand calculation

This methodology for calibration and projection is used across all sectors.

[17] The Bureau of Infrastructure and Transport Research Economics (BITRE) provides economic analysis, research and statistics on infrastructure and transport issues to inform Australian Government policy development and wider community understanding. BITRE is part of the Data, Analytics and Policy Division of the Department of Infrastructure, Transport, Regional Development, Communications and the Arts. (https://www.bitre.gov.au/)

2.2 SECTOR BOUNDARIES: SECTORS AND SUB-SECTORS

Table 3: Examples of industry sub-sectors based on the Global Industry Classification Standard (GICS)

Financial Sector	GICS	IEA Statistic Category	Sector Definition
Transportation	203010 Air Freight & Logistics	World Aviation Bunkers	Covers fuels delivered to aircraft of all countries that are engaged in international aviation (*International aviation bunkers*) for the world total aviation bunker demand
	20301010 Air Freight & Logistics 203020 Airlines 20302010 Airlines	Domestic Aviation	Aviation fuels to aircraft for domestic aviation—commercial, private, agricultural use
	203030 Marine	World Marine Bunkers	Fuels delivered to ships of all flags not engaged in international navigation (international marine bunkers) for the whole world marine bunker demand
	20303010 Marine	Domestic Navigation	Fuels delivered to vessels of all flags not engaged in international navigation
	203040 Road & Rail 20304010 Railroads	Road	Fuels used in road vehicles and for agricultural and industrial highway use. Excludes military consumption and the motor gasoline used in stationary engines and the diesel oil used in tractors that are not for highway use
	20304020 Trucking	Rail	Rail traffic, including industrial railways, and rail transport laid in public roads as part of urban or suburban transport systems (trams, metros, etc.)
	203050 Transportation Infrastructure 20305010 Airport Services	Pipeline Transport	Energy used in the support and operation of pipelines transporting gases, liquids, slurries, and other commodities, including the energy used for pumping stations and the maintenance of pipelines
	20305020 Highways & Rail Tracks 20305030 Marine Ports & Services	Transport Equipment (part of Manufacturing)	Manufacture of transportation equipment such as ship building and boat manufacturing, the manufacture of railroad rolling stock and locomotives, aircraft and spacecraft and the manufacture of parts thereof.
Agriculture	3010 Food & Staples Retailing 3020 Food, Beverages, & Tobacco	**Farming** Food Production and Supply	Food and tobacco production, excluding the energy demand for agriculture, as defined under the IEA energy statistic 'other sectors'. Additional statistics from industry partners are required because the IEA statistics only provide the accumulated energy demand for agriculture and forestry.
Forestry	1510 Materials 151050 Paper & Forest Products 15105010 Forest Products 15105020 Paper Products	**Agricultural & Forestry** Paper & Forest Products	Energy demand for all wood and wood products, including pulp & paper and printing. Also includes all energy demands for agricultural services not included in food and tobacco production.
Chemicals	1510 Materials 151010 Chemicals	**Chemical Industry** Chemical Products Petrochemical Products Glass & Ceramics	Energy demand for all chemical, petrochemical, glass, and ceramic products.
Aluminium	151040 Metals & Mining 15104010 Aluminium	**Aluminium**	Energy demand for the production of primary and secondary aluminium, as well as bauxite mining.
Textiles & Leather	2520 Consumer Durables & Apparel 252030 Textiles, Apparel, & Luxury Goods	**Textile & Leather Industry**	This sector covers the energy demand for the textile and leather industry.

The OECM was first developed to calculate energy pathways for geographic regions, as documented by Teske et al. (2019)[18]. The OECM was further developed to meet the requirements of the financial industry and to design energy and emissions pathways for clearly defined industry sectors (sectorial pathways). The finance industry uses different classification systems to describe sub-areas of certain branches of industry. The scenario sector boundaries are based on the Global Industry Classification Standard (GICS). The GIS is an important system[19], but the GICS sub-sectors do not match the IEA statistical breakdown of the energy demands of certain industries. Table 3 shows examples of the finance sector calculated with the OECM, the GICS codes, and the statistical information used. Although the OECM allows all the GICS-coded sub-sectors to be calculated, the availability of statistics limits the resolution of the sectorial pathways. For example, the statistical data for the textile and leather industry are stored in the IEA database, but the database does not separate the two industries further (see also Teske et al. 2022)[20].

2.3 DEMAND MODULE

The demand module uses a bottom-up approach to calculate the energy demand for a process (e.g., steel production) or a consumer (e.g., a household) in a region (e.g., a city or country) or transport services over a period of time. One of the most important elements of this approach is the strict separation of the original need (e.g., to get from home to work), how this need can be satisfied (e.g., with a tram), and the kind of energy required to provide this service (in this case, electricity). This basic logic is the foundation for the energy demand calculations across all sectors: buildings, transport, services, and industry. Furthermore, the energy services required are defined: electricity, heat (broken down into four heat levels: < 100 °C, 100–500 °C, 500–1000 °C, > 1000 °C), and fuels for processes that cannot (yet) be electrified. Synthetic fuels, such as hydrogen, are part of both the demand module, because electricity is required to produce it, and the supply module, because it is an energy source for other processes, such as manufacturing.

The energy requirements are assigned to specific locations. This modular structure allows regions to be defined and, if necessary, the supply from other areas to be calculated.

The demand and supply modules are independent and can be used individually or sequentially. Within the demand module, energy demands can be calculated as either synthetic load profiles[21], which are then summed to annual energy demands, or only as annual consumption, without hourly resolution. Whether or not hourly resolution is selected depends to a large extent on the availability of data. Load profiles, such as those for the chemical industry, are difficult to obtain and are sometimes confidential. In this work for the Climate Council, annual consumption without hourly resolution was used.

2.3.1 INPUT PARAMETERS

As in basic energy models, the main drivers of the energy demand are the development of the population and of economic activity, measured in GDP. Figure 1 shows the basic methodology of the OECM demand module. The tier 1 inputs are population and GDP by region and sector. Whereas 'population' defines the number of individual energy services, which determines the energy required per capita, the economic activity (in GDP) defines the number of services and/or products manufactured and sold. The tier 1 demand parameters are determined by the effect that a specific service requires. For population, the demand parameters are defined by the need for food, shelter (buildings), and mobility and—depending on the economic situation and/or lifestyle of the population—the demand for goods and services.

Economic activity (measured in GDP) is a secondary input, and is directly and indirectly dependent upon the size of the population. However, a large population does not automatically lead to high economic activity. Both population and projected GDP are inputs from external sources, such as the United Nations or the World Bank. The tier 1 input parameters themselves are strictly non-technical. For instance, the need to produce food can be satisfied without electricity or (fossil) fuels. Food production is a service that can be provided by the human workforce.

The tier 2 demand parameters are energy-relevant factors, and describe technical applications, their energy intensities, and the extent to which the application is used. For example, if passenger road transport is required, the technical application 'light duty vehicle (LDV)' can be chosen to satisfy the demand.

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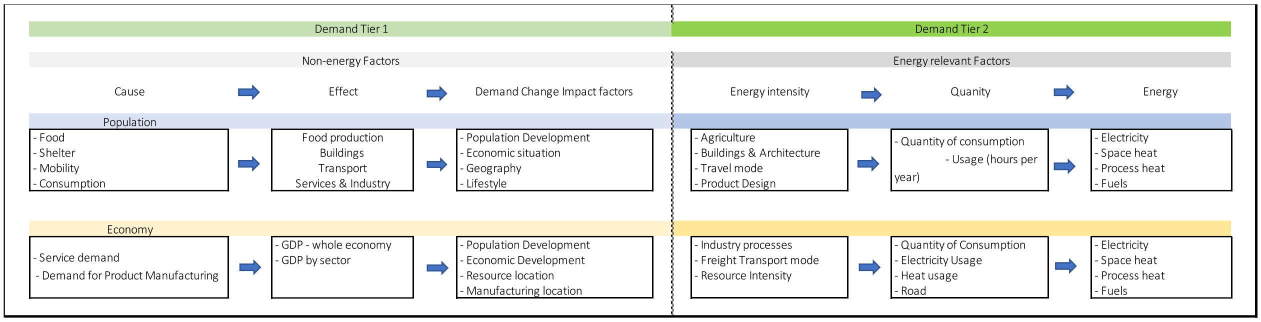
[18] Teske S, Pregger T, Naegler T, Simon S, Pagenkopf J, van den Adel B, et al. Energy scenario results. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5C and +2C. 2019; 175–401.

[19] Morgan Stanley Capital International (MSCI). website, which provides an overview about the Global Industry Classification Standard (GICS). 2021. https://www.msci.com/our-solutions/indexes/gics

[20] Teske, S., Niklas, S., Talwar, S. et al. 1.5 °C pathways for the Global Industry Classification (GICS) sectors chemicals, aluminium, and steel. SN Applied Sciences 4;125:2022. https://doi.org/10.1007/s42452-022-05004-0

[21] Synthetic load profiles are calculated load profiles based on energy demand assumptions for specific consumer groups, usually at hourly resolution over a day, a week or a whole year. Synthetic load profiles are used when measure actual load profiles are not available.

Figure 1. Tier 1 and tier 2 input parameters for the assessment of energy demand



In this example, the energy intensity for an LDV with an internal combustion engine (ICE) is, for example, 1.5 MJ/km. The energy intensity multiplied by the use of the application (vehicle) defines the total energy demand (e.g., if the use is 15,000 km per year, the total energy demand will be 1.5 MJ/km × 15,000 km/yr = 22,500 MJ/yr). The application—in this example, a LDV with ICE—can be replaced with another application, such as an electric vehicle with a reduced energy intensity of 0.5 MJ/km. The transport energy demand decreases, while the transport service (15,000 km) remains stable. In a second step, the actual transport service can be reduced or increased, or shifted to another transport mode altogether (such as light rail) by the modeller.

This very basic and simple principle is used for every application in each of the main sectors: buildings (residential + commercial), industry, and transport. Those sectors are broken down into multiple sub-sectors, such as aviation, shipping, rail, and road for transport, and further into applications, such as vehicle types. The modular programming allows the addition of as many sub-sectors and applications as required.

2.3.2 Structure of the Demand Module

Each of the three sectors, *Residential buildings (R)*, *Industry (I)* and *Transport (T)*, has standardized sub-structures and applications. The residential sector *R* (first layer) has a list of household types (second layer), and each household type has a standard set of services (third layer), such as 'lighting', 'cooling', or 'entertainment'. Finally, the applications for each of the services are defined (fourth layer), such as refrigerator or freezer for 'cooling'. The energy intensity of each application can be altered by the modeller to reflect the status quo in a certain region and/or improvements in energy efficiency. An illustrative example of the residential sector layers is shown in Figure 2.

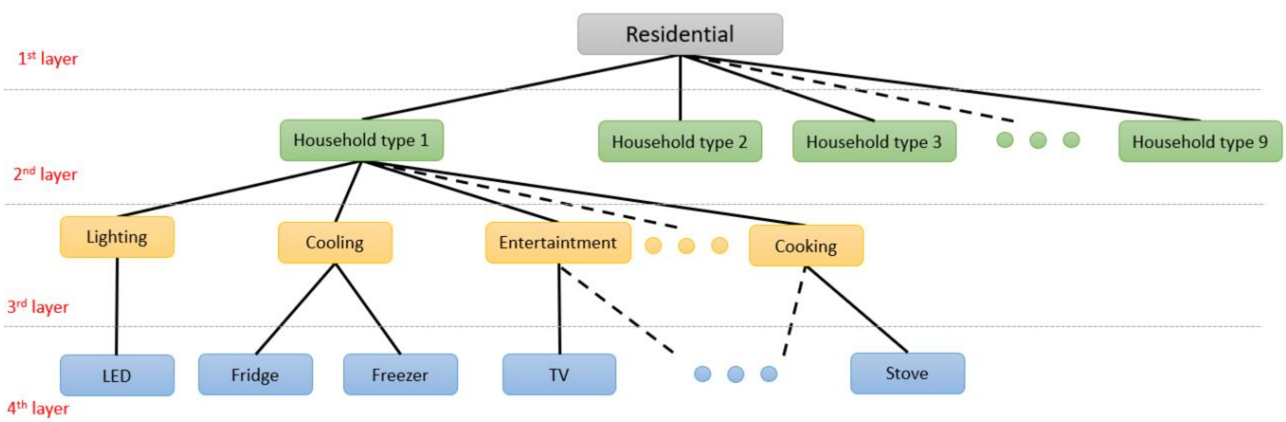


Figure 2. Residential sector sub-structures

Figure 3 shows an example of the model structure of the *Industry* sector. In the second layer are different industries—the OECM 2.0 uses the GICS classification system for industry sub-sectors. The quantity of energy for each sub-sector is driven by either GDP or the projected quantity of product, such as the tonnes of steel produced per year. The market shares of specific manufacturing processes are defined and each process has a specific energy intensity for electricity, (process) heat, and/or fuels.

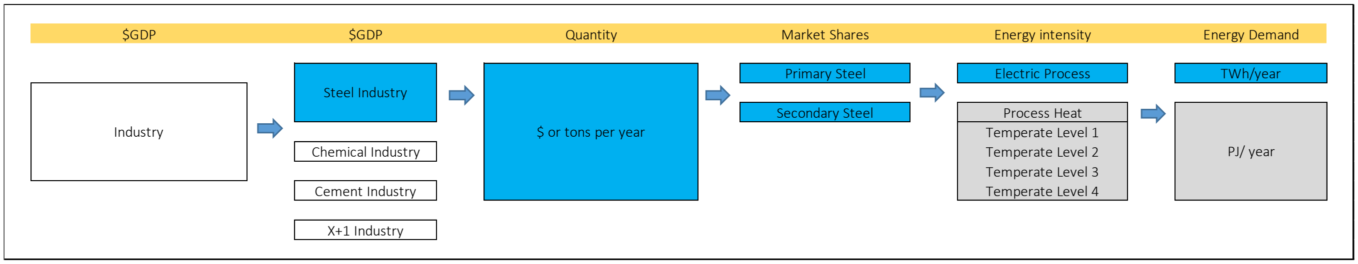


Figure 3. Calculation of *Industry* energy demand

Figure 4 shows the structure for the *Transport* sector. Again, the demand is driven by 'non-energy' factors, such as passenger–kilometres and freight–kilometres, and energy-related factors, such as the transport mode and the energy intensity for the different vehicle options.

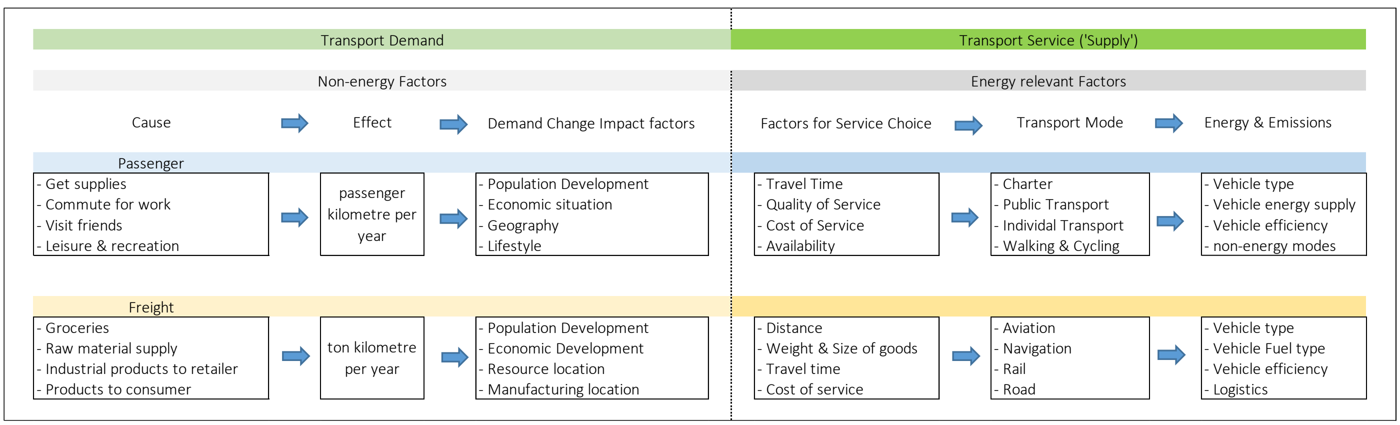


Figure 4. Calculation of *Transport* energy demand

2.4 POWER SECTOR ANALYSIS—METHODOLOGY

After the energy demand has been calculated, the supply of electricity, heat, and fuels is calculated on an annual basis. The supply does not differentiate between demand sectors. Therefore, the electricity demand for all sectors—residential, industry, and transport—is aggregated and provided as a total value. Consequently, no specific electric generation mix for the transport sector, for example, is considered. These annual values are used in concjunction with calibrated propotions of the supply technology to provide a breakdown of energy shares across the different supply technologies. After this modelling step is completed in OECM, an additional power sector analysis step is computed separately in MATLAB, using an equillibrium energy balance methodology to assess the electrcity supply for Australia given the electricty confirguration of the National Electricity Market (NEM) in conjunction with the islanded grids of WA and NT.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, allows a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services.

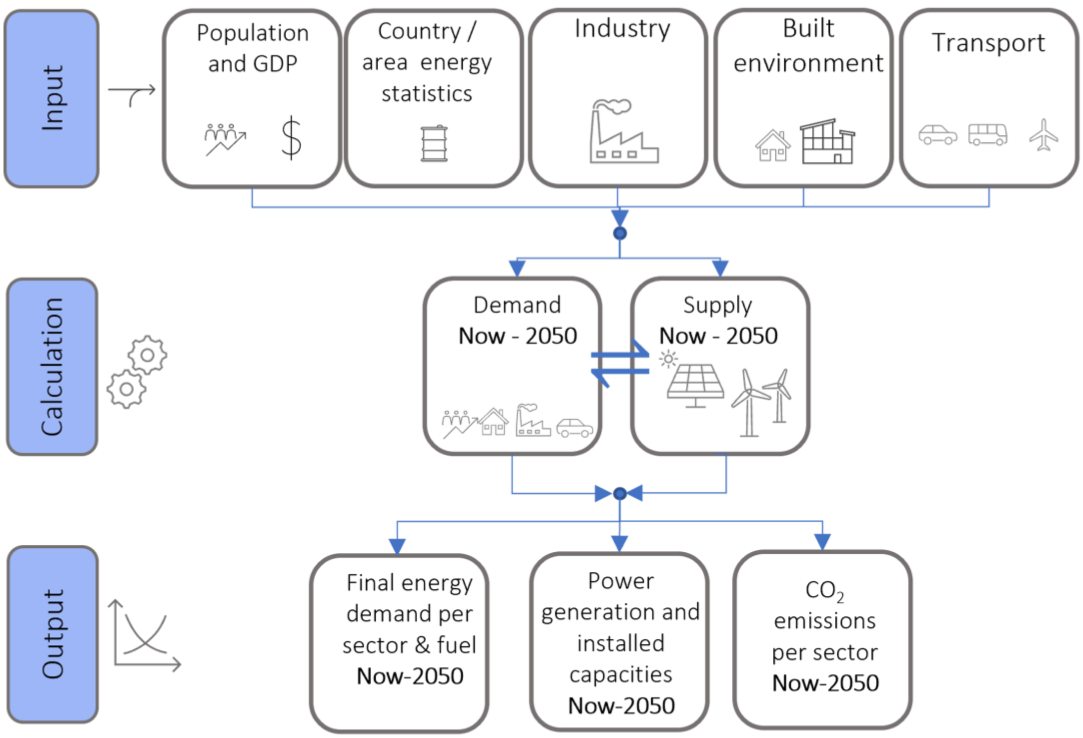


Figure 5. Overview—energy demand and load curve calculation module

2.4.1 METEOROLOGICAL DATA

Variable power generation technologies are dependent on the local solar radiation and wind regimes. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database *renewable.ninja* (RE-N DB 2018)[22], which allows the hourly power output from wind and solar power plants at specific geographic positions throughout the world to be simulated. Weather data, such as temperature, precipitation, and snowfall, for the year 2019 were also available. To utilise climatization technologies for buildings (air-conditioning, electric heating), the demand curves for households and services were connected to the cluster-specific temperature time series. The demand for lighting was connected to the solar time series to accommodate the variability in the lighting demand across the year, especially in northern and southern global regions, which have significantly longer daylight periods in summer and very short daylight periods in winter.

For every region included in the model, hourly output traces are utilised for onshore wind, utility-scale solar, and roof-top solar photovoltaic. Given the number of clusters, the geographic extent of the study, and the uncertainty associated with the prediction of the spatial distribution of future generation systems, a representative site was selected for each of the five generation types.

Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected from the database of Stefan Pfenninger (at ETH Zurich) and Iain Staffell (renewable.ninja; see above). The model methodology used by the Renewables.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[23], and is based on weather data from global re-analysis models and satellite observations (Rienecker and Suarez 2011[24]; Müller and Pfeifroth, 2015[25]).

Given that the optimal solar tilt varies slightly across Australia, a consistent tilt and azimuth were used in the generation of the solar trace files: a tilt of 30 degrees and a north-facing azimuth angle. The onshore wind outputs were calculated at a 110 m hub height to best reflect the scale of wind speed potential up to 2050. This also allows for the fact that the wind speed data for Australia are somewhat conservative—in some cases, producing capacity factors lower than the measured wind speeds or capacity factors of existing wind farms.[26] The Vestas V90 2000 was selected in Renewables.ninja to provide a baseline power curve for the development of a trace file from the wind speed data. The base year for all trace files was 2012, and this selection was made to align our resource assumptions with that used by AEMO in their *Detailed Long-Term Model*[27].

Limitations: Solar and wind resources can differ within one cluster. Therefore, the potential generation output can vary within a cluster and across the model period (2020–2050).

[22] RE-N DB (2018) Renewables.ninja, online database of hourly time series of solar and wind data for a specific geographic position; data viewed and downloaded between September and October 2022, https://www.renewables.ninja/

[23] Pfenninger S, Staffell I (2016a) Long-term patterns of European photovoltaic output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251–1265. doi: 10.1016/j.energy.2016.08.060

Pfenninger S, Staffell I (2016b) Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, 1224–1239. doi: 10.1016/j.energy.2016.08.068

[24] Rienecker M, Suarez MJ (2011) MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

[25] Müller R, Pfeifroth, U (2015) Digging the METEOSAT treasure—3 decades of solar surface radiation. Remote Sensing 7, 8067–8101. doi: 10.3390/rs70608067

[26] Briggs C, Hemer M, Howard P, Langdon R, Marsh P, Teske S, Carrascosa D (2021). Offshore Wind Energy in Australia: Blue Economy Cooperative Research Centre, Launceston, TAS. 92p.

[27] AEMO, 2020 Final ISP Input Data Package And Market Modelling Instructions.

2.4.2 Power Demand Projections and Load Curve Calculations

The OECM power analysis model calculates the development of the future power demands and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- households;
- industry and business; and
- transport.

The industry and transport sectors utilise a fixed load profile, with demand higher during business/daylight hours and returning towards a base-load value outside these hours. These assumptions are consistent with general business and industry load profiles, so that there is a high degree of constant demand for heavy industry operation and increased electricity demand in other business sectors. The regional distribution of the industry load is proportioned according to an approximation of GDP.[28] A simple approach was used to consider the electrical demand related to the transport sector, such that the demand across all transport types is considered in aggregate and load-profile-shaped, using the same logic as industry but proportioned across regions according to population[29].

The household sector load profiles vary with the following parameters:

- electrical applications in use across household types
- the demand pattern of applications across household types (24 h)
- meteorological data:
  - sunrise and sunset, associated with the use of lighting appliances
  - temperature data associated with climatization requirements
- efficiency progress (2020 until 2050, in 5-year steps)
  - possibility that the electricity intensity data for each set of appliances will change, e.g., change from compact fluorescent lamp (CFL) light bulbs to light-emitting diodes (LEDs) as the main technology for lighting.

2.4.3 The [R]E 24/7 Dispatch Module

The [R]E 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour. The first-generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met. In the case of oversupply, the surplus variable renewable electricity can be either moved to storage, moved to other regions, or—if neither option is available—curtailed. Non-variable renewable sources will reduce their output. In the case of undersupply, electricity will be supplied from either available storage capacities, neighbouring clusters, or dispatch power plants. The key objective of modelling is to calculate the load development by region, and modifying the residual load (load minus generation), theoretical storage, and interconnection requirements for each cluster and for the whole survey region. The economic battery capacity is a function of the storage and curtailment costs, as well as the availability of dispatch power plants and their costs.

Figure 6 provides an overview of the dispatch calculation process. A fixed dispatch order is used in this analysis: necessary base-load dispatch, variable renewables, decentralised generation sources, interconnections with other regions to allow exchange of low-cost surplus renewables, utility-scale storage, and finally the remaining additional dispatch generation that is not dispatched as part of the minimum base-load output requirement.

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[28] Bureau of Infrastructure and Transport Research Economics (BITRE), Regional Economic Growth Database

[29] Australian Bureau of Statistics, Regional population, https://www.abs.gov.au/statistics/people/population/regional-population/latest-release#data-downloads

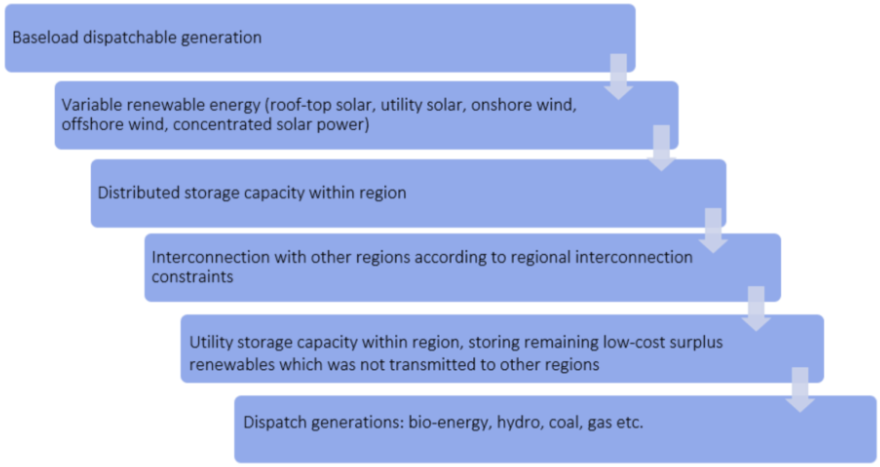


Figure 6. Methodology of dispatch order

The following key parameters are used as input: the generation capacity by type, the demand projection and load curve for each cluster, interconnections with other clusters, and meteorological data, from which solar and wind power generation are calculated with hourly resolution. The installed capacities are derived from the long-term projections described in Section 5, and the resulting annual generation in megawatt hours is calculated based on meteorological data (in the cases of solar and wind power) or dispatch requirements.

Limitations

The calculated loads are not optimized in terms of local storage, the self-consumption of decentralised producers of solar photovoltaic electricity, or demand-side management. The same can be said of electric vehicles. Furthermore, although roof-top photovoltaic is dispatched first in the security supply order, it is considered in a simplified aggregate matter, so the load profile used in the [RE] 24/7 accounts for total demand.

Table 4: Example of generation and storage technologies

Generation		Storage
Power plants	Combined heat and power plants	Electrical
Hard coal	Hard coal	Distributed Batteries
Lignite	Lignite	Utility-scale Battery
Gas	Gas	Pumped Hydro
Oil	Oil	Hydrogen Power Genereation
Diesel	Biomass	
Biomass	Geothermal	
Hydro	Hydrogen	
Wind		
Photovoltaic		
Solar		
Geothermal		
Solar thermal		
Ocean energy		
Hydrogen		

2.5 OECM 2.0: OUTPUT AND AREAS OF USE (INCLUDING ALL SECTORS)

Commodities and/or GDP are the main drivers of the energy demand for industries. The projection of, for example, the global steel demand in tonnes per year over the next decades is discussed with the industry and/or client. OECM 2.0 can calculate either a single specific sector only, or a whole set of sectors. In this work for the Climate Council, various industry projections are combined to estimate both the total energy supply required and the potential energy-related emissions. Therefore, the emissions produced to achieve a specific target or budget can be broken down by specific industries. Table 5 provides an overview of the main parameters that can be used to set specific targets for industries.

Energy intensities are both input data for the base year and a key performance indicator (KPI) for future projections. The effect of a targeted reduction in the energy intensity in a given year and the resulting energy demand and carbon emissions can be calculated, e.g., for the transport service industry.

All sector demands are supplied by the same energy supply structure in terms of electricity, process heat (for each temperature level), and total final energy. Finally, specific carbon intensities, such as CO_2 per tonne–kilometre, CO_2 per tonne of steel or per cubic metre of wastewater treatment, are calculated (and can be used to set industry targets).

Table 5: Example of energy-related key performance indicators (KPIs) for net-zero target setting, calculated for four sectors with OECM 2.0

Sector	Parameter	Units	Base year 2019	Projection 2025, 2030, 2035, 2040, 2045, 2050
		Commodities		
Water Utilities	Water withdrawal	[billion m^3/yr]	Input	Calculated projection with annual growth rates discussed with client
Chemical Industry	Economic development	[$GDP/yr]	Input	
Steel Industry	Product-based market projection	[tonnes steel/yr]	Input	
Aviation	Passenger–kilometres	[million person–km/yr]	Input	
		Energy Intensities		
Water Utilities	Waste-water treatment	[kWh/m^3]	Input	Technical target (KPI) Calculated with annual progress ratio based on technical assessment
Chemical Industry	Industry-specific energy intensity	[MJ/$GDP]	Input	
Steel Industry	Energy intensity	[MJ/tonne steel]	Input	
Aviation	Energy intensity per transport service	[MJ/person–km]	Input	
		Energy Demand		
Water Utilities	Final energy demand	[PJ/yr]	Input	Output—industry-specific scenario(s)
Chemical Industry	Electricity demand	[TWh/yr]	Input	
Steel Industry	Process heat demand by temperature level	[PJ/yr]	Input	
Aviation	Final energy demand	[PJ/yr]	Input	
	Total final energy demand	[PJ/yr]	Input	
		Energy Supply		
Water Utilities	Electricity generation by technology	[TWh/yr]	Input	Output—based on developed scenario supply for all (sub-)sectors.
Chemical Industry	(Process) Heat by technology	[PJ/yr]	Input	
Steel Industry	Fuel supply by fuel type	[PJ/yr]	Input	
Aviation	Fuel supply by fuel type	[PJ/yr]		
	Total final energy supply by fuel type	[PJ/yr]	Input	
		Energy-related Emissions		
	Electricity—specific CO_2 emissions	[gCO_2/kWh]	Calculated	Output—KPI for utilities
	Electricity—total CO_2 emissions	[tCO_2/yr]	Calculated	Output—KPI for utilities
	(Process) Heat-specific CO_2 emissions	[gCO_2/kWh]	Calculated	Output—KPI for industry
	Transport service energy	[gCO_2/km]	Calculated	Output—KPI for industry
	(Process) heat—total CO_2 emissions	[tCO_2/yr]	Calculated	Output—KPI for industry
		Product specific Emission		
Water Utilities	Emissions intensity	[$kgCO_2/m^3$]	Calculated	KPI—water utilities
	Total energy-related CO_2 emissions	[t CO_2]	Calculated	KPI—Water utilities
Chemical Industry	Emissions intensity	[$kgCO_2$/$GDP]	Calculated	KPI—chemical industry
	Total energy-related CO_2 emissions	[tCO_2]	Calculated	KPI—chemical industry
Steel Industry	Emissions intensity	[$kgCO_2$/t steel]	Calculated	KPI—steel industry
	Total energy-related CO_2 emissions	[t CO_2]	Calculated	KPI—steel industry
Aviation	Emission intensity	[$kgCO_2$/passenger–km]	Calculated	KPI—aviation industry
	Total energy-related CO_2 emissions	[t CO_2]	Calculated	KPI—aviation industry

All input and output OECM data are available as MATLAB-based tables or graphs, or as standard Excel-based reports.

2.6 MODEL DYNAMICS

A detailed assessment of the energy demand based on industry products, such as the amount of steel or aluminium used and/or the economic projections (for example, for sub-sectors of the chemical industry)—combined with very high technical resolution—allows the development of the electricity and fuel demands to be comprehensively mapped with steadily increasing sector coupling. A high degree of electrification for heating and transport, replacing fuels, will require an energy scenario to be modelled that includes an electricity system analysis that assesses the infrastructure changes required (i.e., the power grid). OECM 2.0 combines an integrated energy assessment tool with a system analysis module. Net-zero pledges for specific industries lead to more-detailed energy scenarios for specific industry sectors. The steel industry, for example, favours hydrogen-based steel production, which will have a significant impact on the hydrogen demand and the electricity required to produce it. OECM 2.0 takes this development into account and allows the modeller to change from yearly to hourly resolution when developing load curves for industries and/or the entire power system, when simulating an electricity supply with high shares of variable renewable power plants. Another example in which a long-term scenario analysis must be combined with a system analysis occurs in the chemical industry. The switch to electrical process heat will not only significantly increase the power requirement, but also the power load. The decision to use electric or hydrogen-based process heat requires the analysis of the regional infrastructure to ensure the development of a cost-effective solution.

OECM 2.0 is modular and currently includes 20 different industry sectors and sub-sectors. Its expansion to more sectors and sub-sectors is possible without great effort, and thus will increase the accuracy of the analysis of electricity and fuel requirements. This interaction between a technology change in one sector (e.g., moving to electric process heat) and the technical and cost implications for other sectors (e.g., power utilities and grid operators) is a central component of the model dynamics.

2.7 METHODOLOGIES FOR IDENTIFYING AND REPORTING SCOPE 1, 2, AND 3 EMISSIONS

Analysing and reporting GHG emissions is important. The focus is no longer on direct energy-related CO_2 emissions but includes other GHGs emitted by industries. These increasingly include the indirect emissions that occur in supply chains[30]. The Greenhouse Gas Protocol, a global corporate GHG accounting and reporting standard[31], distinguishes between three 'scopes':

- *Scope 1*—direct emissions from owned or controlled sources;
- *Scope 2*—indirect emissions from the generation of purchased energy;
- *Scope 3*—all the indirect emissions (not included in *Scope 2*) that occur in the value chain of the reporting company, including both upstream and downstream emissions.

The United States Environmental Protection Agency (US EPA) defines *Scope 3* emissions as 'the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly impacts in its value chain. They include upstream and downstream of the organization's activities'[32]. According to the US EPA, *Scope 3* emissions include all sources of emissions not within an organization's *Scope 1* and *2* boundaries, and the *Scope 3* emissions of one organization are the *Scope 1* and *2* emissions of another organization. *Scope 3* emissions, also referred to as 'value chain emissions' or indirect emissions, often represent the majority of an organization's total GHG emissions.

Whereas the methodologies of *Scope 1* and *Scope 2* are undisputed, the method of calculating *Scope 3* emissions is an area of ongoing discussion and development[33,34,35]. The main issues discussed are data availability, reporting challenges, and the risk of double counting. Morgan Stanley Capital International (MSCI), for example, avoids double counting by using a 'de-duplication multiplier of approximately 0.205'[36]. This implies that the allocation of emissions based on actual data is not possible. Accounting methodologies for *Scope 3* emissions have been developed for entity-level accounting and reporting[37].

[30] Hertwich EG, Wood R. The growing importance of scope 3 greenhouse gas emissions from industry. Environmental Research Letters 2018;13:104013.
[31] WRI & WBCSD. Greenhouse Gas Protocol. WRI & WBCSD. https://ghgprotocol.org/
[32] EPA. Scope 3 Inventory Guidance.
[33] Baker B. Scope 3 Carbon Emissions: Seeing the Full Picture. MSCI. 2020.
[34] Lombard Odier Debunking 7 misconceptions on scope 3 emissions. Lombard Odier. 2021.
[35] Liebreich M. Climate and Finance—Lessons from a Time Machine | BloombergNEF. 2021. https://about.bnef.com/blog/liebreich-climate-and-finance-lessons-from-a-time-machine/.
[36] MSCI. Global Industry Classification Standard (GICS®) Methodology Guiding Principles and Methodology for GICS. 2020.
[37] WRI & WBCSD. Technical Guidance for Calculating Scope 3 Emissions, Supplement to the Corporate Value Chain (Scope 3) Accounting & Reporting Standard. 2013.

Ducoulombier (2021)[38] found that the reporting of *Scope 3* emissions ('indirect emissions') is incomplete and that reporting standards to support the comparison of companies are lacking. Schulman et al. (2021)[39] found that over 80% of emissions in the food industry are *Scope 3* emissions, and that the data reported by the Customer Data Platform (CDP), a global data service for investors, companies, cities, states, and regions, are incomplete and inconsistent throughout.

In 2009, Huang et al. suggested that 'Protocol organizations should actively make more specific *Scope 3* guidelines available for their constituents by developing sector-specific categorizations for as many sectors as they feasibly can and create broader industry-specific protocols for others'. Therefore, the accounting methodology for *Scope 3* emissions requires significant improvement and has been under discussion for more than a decade. OECM focuses on the development of 1.5 °C net-zero pathways for industry sectors, classified under the GICS, for countries or regions or at the global level. Emissions-calculating methodologies for entity-level *Scope 3* require bottom-up entity-level data to arrive at exact figures. Therefore, data availability and accounting systems for whole industry sectors, on a regional or global level, present significant challenges. The methodology used to calculate *Scope 3* must be simplified for country-, region-, and global-level calculations and to avoid double counting. In the Greenhouse Gas Protocol, *Scope 3* emissions are categorised into 15 categories, shown in Table 6.

Table 6: Upstream and downstream Scope 3 emissions categories

Upstream			Downstream		
Greenhouse Gas Protocol Scope 3		OECM 2.0—emissions included in the following sectors	Greenhouse Gas Protocol Scope 3		OECM 2.0—emissions included in the following sectors
U1	Business travel	Part of the respective transport mode (aviation, road, rail, etc.)	D1	Use of solid products	All sector uses of solid products are included
U2	Purchased goods and services	All sector-specific goods and services are included	D2	Downstream transportation and distribution	Sector-specific transportation and distribution and end-of-life treatment are included. This includes the actual use of the product, e.g., emissions when driving a manufactured car.
U3	Waste generated in operations	All waste generated in sector-specific operations are included	D3	End-of-life treatment of solid products	
U4	Fuel- and energy-related activities	All sector fuel- and energy-related activities are included	D4	Investments	Not included
U5	Employee commuting	Part of the respective transport mode (aviation, road, rail, etc.)	D5	Downstream leased assets	Not included
U6	Upstream transportation and distribution	Part of the respective transport mode (aviation, road, rail, etc.)	D6	Processing of solid products	All sector processing of solid products is included
U7	Capital goods	Not included	D7	Franchises	Not included
U8	Upstream-leased assets	Not included			

To include all the upstream and downstream categories shown in **Error! Reference source not found.** 6 for an entire industry sector is not possible because first, complete data are not available—for example, how many kilometres employees of the agricultural or forestry sector commute; and second, it is impossible to avoid double counting—for example, when calculating *Scope 3* for the car industry.

Table 6 identifies how the 15 categories are handled in the proposed OECM 2.0 methodology.

The OECM 2.0 methodology is based on the *Technical Guidance for Calculating Scope 3 Emissions* of the World Resource Institute, but is simplified to reflect the higher levels of industry- and country-specific pathways. OECM defines the three emissions scopes as follows:

Scope 1—All direct emissions from the activities of an organisation or under its control, including fuel combustion on site (such as gas boilers), fleet vehicles, and air-conditioning leaks.

Limitations of the OECM *Scope 1* analysis: Only economic activities covered under the sector-specific GICS classification and that are counted for the sector are included. All energy demands reported by the IEA *Advanced World Energy Balances* for the specific sector are included.

Scope 2—Indirect emissions from electricity purchased and used by the organisation. Emissions are created during the production of energy and are eventually used by the organisation.

[38] Ducoulombier F. Understanding the Importance of Scope 3 Emissions and the Implications of Data Limitations. The Journal of Impact and ESG Investing 2021;1:63–71.

[39] Schulman DJ, Bateman AH, Greene S. Supply chains (Scope 3) toward sustainable food systems: An analysis of food & beverage processing corporate greenhouse gas emissions disclosure. Cleaner Production Letters 2021;1:100002.

Limitations of the OECM *Scope 2* analysis: Due to poor data availability, the calculation of emissions focuses on the electricity demand and 'own consumption', e.g., that reported for power generation by Schulman et. al.[40].

Scope 3—GHG emissions caused by the analysed industry that are limited to sector-specific activities and/or products classified in GICS.

Limitations of the OECM *Scope 3* analysis: Only sector-specific emissions are included. Traveling, commuting, and all other transport-related emissions are reported under *'transport'*. The lease of buildings is reported under '*buildings*'. All other financial activities, such as '*capital goods*', are excluded because no data are available for the GICS industry sectors and would lead to double counting. The OECM is limited to energy-related carbon dioxide (CO_2) and energy-related methane (CH_4) emissions. All other GHG gases are calculated outside the OECM model by Meinshausen et al. 2019[41].

The main difference between OECM and the World Resources Institute (WRI) concept is that the interactions between industries and/or other services are kept separate. The OECM reports only emissions directly related to the economic activities classified by GICS. Furthermore, the industries are broken down into three categories: Primary Class, Secondary Class, and End-use Activity Class.

Table 7: Schematic representation of OECM Scopes 1, 2, and 3 according to GICS classes to avoid double counting

	Primary Class					Secondary Class				End-use Activity Class			
	GICS 10 Energy	Scope 1	Scope 2	Scope 3		GICS 55 Utilities	Scope 1	Scope 2	Scope 3	All Other Industries & Services	Scope 1	Scope 2	Scope 3
CO_2					CO_2								
CH_2 AFOLU					CH_2 AFOLU								
CH_4					CH_4								
N_2O					N_2O								
					CFCs								
Total GHG		Sum of *Scopes 1*, *2*, & *3* equals total emissions			Total GHG		Sum of *Scopes 1*, *2*, & *3* equals total emissions				Sum of *Scopes 1*, *2*, & *3* equals total emissions		

AFOLU = Agriculture, Forestry and Other Land Use

Table 7 shows a schematic representation of the OECM *Scope 1*, *2*, and *3* calculation method according to GICS class, used to avoid double counting. The sum of Scopes 1, 2, and 3 for each of the three categories is equal to the actual emissions. Example: Total annual global energy-related CO_2 emissions are 35 Gt in a given year.

- The sum of Scope 1, 2, and 3 for the primary class (primary energy industry) is 35 Gt CO_2
- The sum of Scope 1, 2, and 3 for the secondary class (secondary energy industry/utilities) is 35 Gt CO_2
- The sum of Scopes 1, 2, and 3 for end-use activities (all end-use sectors) is 35 Gt CO_2

Double counting can be avoided by defining a primary class for the primary energy industry, a secondary class for the supply utilities, and an end-use class for all the economic activities that use the energy from the primary- and secondary-class companies. Furthermore, the separation of all emissions by defined industry categories—such as GICS—streamlines the accounting and reporting systems. The volume of data required is reduced and reporting is considerably simplified under the OECM methodology. Achieving the global target of 1.5 °C and net-zero emissions by 2050 according to the Paris Agreement for a specific industry sector requires that all its business activities are with other sectors also committed to 1.5 °C–net-zero emissions targets.

[40] IEA. World Energy Balances. IEA. 2021. https://www.iea.org/data-and-statistics/data-product/world-energy-balances

[41] Meinshausen M, Dooley K. Mitigation Scenarios for Non-energy GHG. In: Teske S, editor. Achieving the Paris Climate Agreement Goals Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2 °C. Springer Open; 2019

3 Australia: RENEWABLE ENERGY POTENTIAL

Australia's solar and wind potential was assessed as the input for development the of the energy scenario. In this section, we assess the technical potential under space-constrained conditions.

3.1 THE [R]E SPACE METHODOLOGY

GIS mapping was used to ascertain Australia's solar and wind energy resources. It was also used in the analysis of regional geographic and demographic parameters and the available infrastructure that could be leveraged in developing the scenarios. Mapping was performed with the software ESRI ArcGIS 10.6.1, which allows spatial analyses and maps the results. It was used to allocate solar and onshore wind resources and for the demand projections for the 11 modelling regions. Population density, access to electricity infrastructure, and economic development projections are the key input parameters in a region-specific analysis of Australia's future energy situation, to clarify the requirements for additional power grid capacities and/or micro-grids (Table 8).

The [R]E Space methodology is part of the OECM methodology to map solar energy potential and onshore energy potential. Open-source data and maps from various sources were collected and processed to visualize the country, its regions, and districts. Further demographic data related to the population and poverty were plotted on the maps, together with transmission networks and power plants. The main data sources and assumptions made for this mapping are summarized in Table 8.

Table 8: Australia—[R]E 24/7—GIS-mapping—data sources

Data	Assumptions	Source
Land use	Catchment-scale land use in Australia – December 2020	ABARES, Australian Government [42]
Digital Elevation Model (DEM)	For both solar and offshore wind analyses, any land with a slope of > 30% was excluded from all scenarios.	Multi-Error-Removed Improved-Terrain DEM[43]
Protected Areas	All protected areas designated national parks, wildlife reserves, hunting reserves, conservation areas, or buffer zones were excluded from all scenarios.	World Database on Protected Areas[44]
Electricity Transmission Lines	Solar and wind potentials of areas ≤ 10 km from transmission lines were considered (Scenario 2).	Geoscience Australia[45]
Solar Irradiance (direct normal irradiation: DNI)	The average yearly direct normal insolation/irradiation (DNI) values range from 1 to 5 MWh/m^2 per year (2.7–13.6 kWh/m^2 per day).	Global Solar Atlas[46]
Wind Speeds	Wind speeds ≥ 5 m/s were considered at a height of 100 m.	Global Wind Atlas [47]

The [R]E Space mapping procedure is summarised in Figure 7. The land areas available for potential solar and onshore wind power generation were calculated and visualized at the national and provincial levels with ArcGIS. The land-cover map, elevation (DEM), World Database on Protected Areas, solar irradiation (direct normal irradiation, DNI) and wind speed data were obtained as raster data from the websites cited above, and were all converted into binary maps (0 = area not suitable as a potential area, 1 = area suitable as a potential area) against all the assumptions in

, and then combined into one binary map by overlaying all the raster data. This map integrates all the criteria cited above in one map with a value of 1 (land included in the potential area) or a value of 0 (land not included in the potential area).

Data on transmission lines and protected areas exist as vector data. All protected areas were excluded from the value 1 areas in the integrated raster data using a mask layer generated from the 'erase' function. For a second scenario (see Figure 7), buffer layers were generated from transmission line (10 km) data, and then the raster data without protected areas were clipped by these buffer layers to generate potential area maps under Scenario 2. This input was fed into the calculations for the [R]E 24/7 model, as described below.

[42] Catchment scale land use of Australia—December 2020: https://www.agriculture.gov.au/abares/aclump/catchment-scale-land-use-of-australia-update-december-2020
[43] Multi-Error-Removed Improved-Terrain DEM: https://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/
[44] World Database on Protected Areas: https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA
[45] Electricity Transmission Lines: https://digital.atlas.gov.au/datasets/digitalatlas::electricity-transmission-lines/about
[46] Global Solar Atlas: https://globalsolaratlas.info/map
[47] Global Wind Atlas: https://globalwindatlas.info/en

Disclaimer: The environmental criteria used to identify suitable areas for utility-scale solar and wind projects do not reflect the current legislation in Australia, and the potential provided is a conservative estimate and may ultimately be larger.

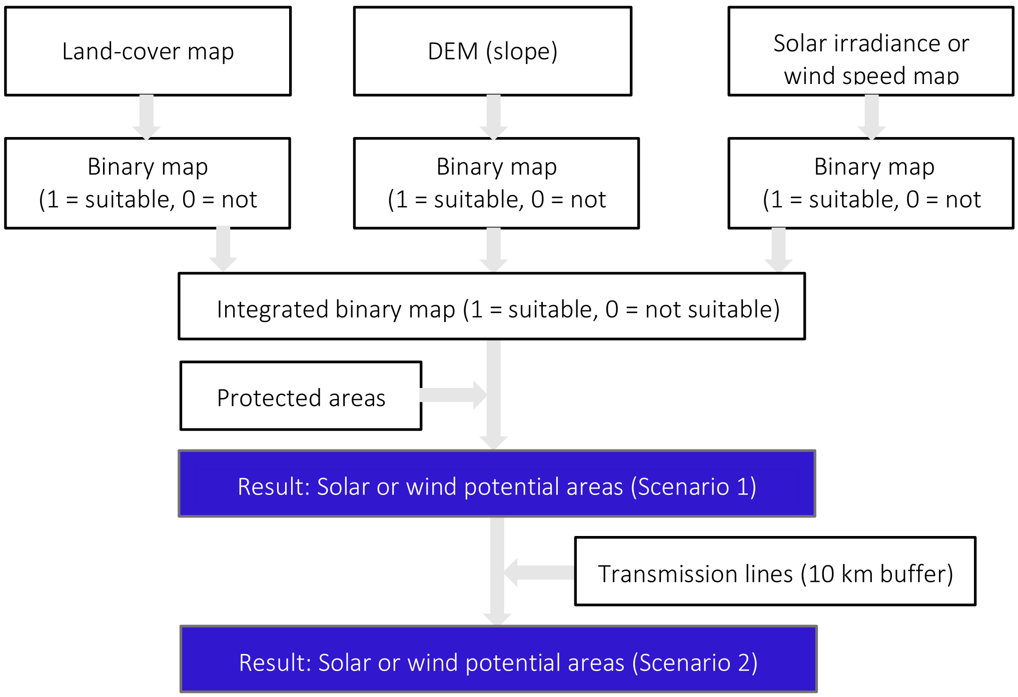


Figure 7. [R]E Space methodology—solar potential and onshore wind potential analyses

3.2 MAPPING METHODOLOGY FOR OFFSHORE WIND

The offshore wind energy potential for Australia is also mapped for two scenarios. Open-source data and maps from various sources were collected and processed to visualize the offshore potentials.

Table 9: Australia—Offshore wind—GIS-mapping—data sources

Data	Assumptions	Source
Gridded Bathymetry Data—Water depth	For offshore wind maps, two scenarios are generated: areas with water depths , < 50 m and areas with water depths > 500 m were excluded from all scenarios.	GEBCO_2023 Grid[48]
Protected Areas	All protected areas designated national parks, wildlife reserves, hunting reserves, conservation areas, or buffer zones were excluded from all scenarios.	World Database on Protected Areas
Major Maritime Ports	Areas within a 50 km radius from ports were excluded from areas of offshore wind potential	Digital Atlas Australia [49]
Maritime Boundaries	Australia Exclusive Economic Zone (200 nautical miles)	Pacific Data Hub [50]
Wind Speeds	Wind speeds ≥ 6 m/s were considered at a height of 100 m.	Global Wind Atlas

[48] GEBCO_2023 Grid: https://www.gebco.net/data_and_products/gridded_bathymetry_data/
[49] Major Maritime Ports: https://digital.atlas.gov.au/datasets/digitalatlas::major-maritime-ports/explore
[50] Australia EEZ (200NM): https://pacificdata.org/data/dataset/australia-exclusive-economic-zone-200-nautical-mile/resource/6019f8eb-7da2-453e-9c58-d2c6def1f8ab

The mapping procedure for offshore wind potential involved gridded bathymetry data (GEBCO_2023) for ocean depth, the World Database on Protected Areas for marine and costal protected areas, and wind speed data (≥ 6 m). Similar to the [R]E Space methodology, all data were converted into binary maps (0 = not suitable as a potential area, 1 = suitable as a potential area) against all the assumptions in **Error! Reference source not found.**, and then combined into one binary map by overlaying all the raster data. The latest data from the Digital Atlas of Australia was used to map the locations of ports and the 50km radii around them.

3.3 MAPPING Australia

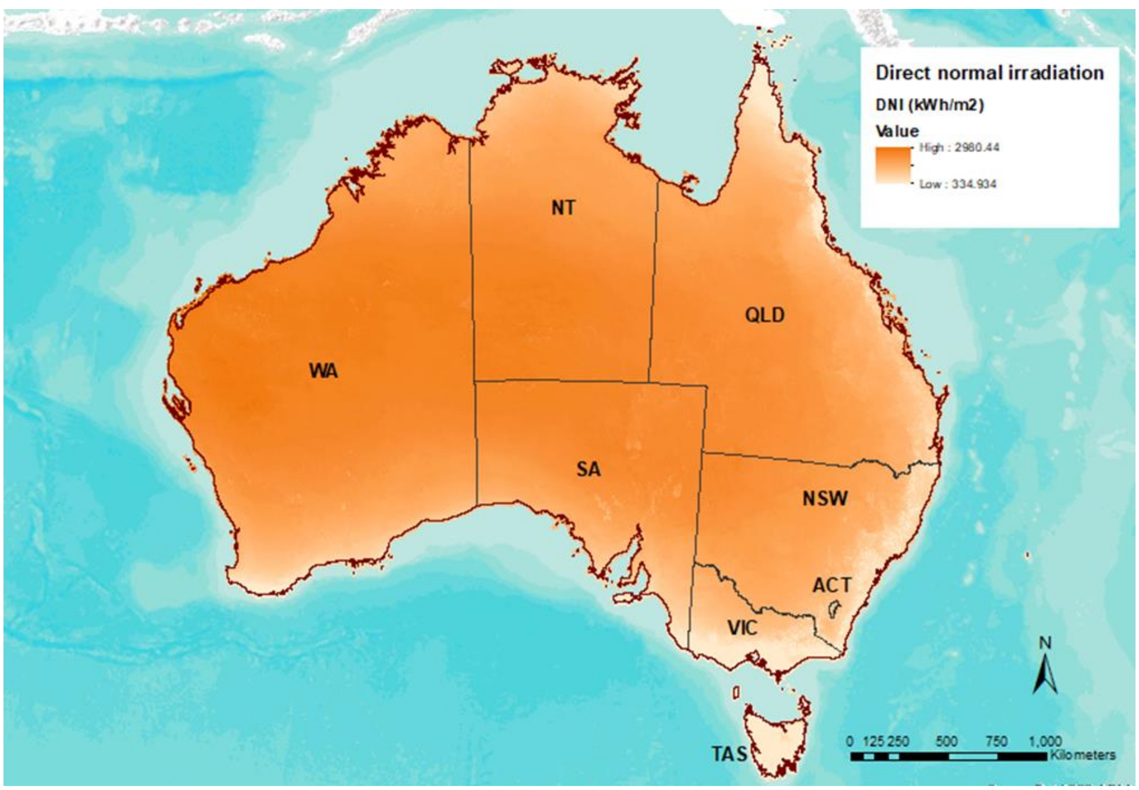
Australia's power sector is currently mainly based on coal and gas power plants, but with rapidly increasing solar and wind electricity shares. In 2022, solar photovoltaic produced 22 TWh and wind around 19 TWh, both playing major roles in 2022 in combination with hydropower (16 TWh) and bio-energy (4 TWh)[51]. Given Australia renewable electricity target of 82% by 2030, significant additional renewable electricity—especially solar photovoltaics and wind power—is required. The aim of mapping the solar and wind resources of Australia is to quantify their short- and long-term potential and to identify possible locations for additional renewable energy zones.

3.3.1 SOLAR POTENTIAL

The yearly total solar irradiation (DNI) level in Australia is 334–2,980 kWh/m^2, and the higher end of that range is in the central outback regions of the Western Australia, South Australian, the Northern Territory, Queensland, and New South Wales. Solar radiation is lower in the southern and eastern coastal regions and in Tasmania. Australia's solar potential has been mapped under two different scenarios.

Scenario 1. Available land—excluding protected areas (PA), extreme topography (slope > 30%, mountainous areas; S30), and certain land-cover classes (including closed forests, wetlands, moss and lichen, snow and ice, and water [permanent water bodies]; LU).

Scenario 2. See Scenario 1, with the additional restriction that excludes areas ≤ 10 km from an existing transmission line (PT10).



[51] International Energy Agency: https://www.iea.org/data-and-statistics/charts/tanzania-electricity-generation-by-technology-in-the-stated-policies-scenario-2010-2040

Figure 8. Australia direct normal irradiation (DNI) (generated from data from the Global Solar Atlas)

Table 10 shows the solar potential areas under Scenario 1 (LU + PA + S30) (Figure 8) and Scenario 2 (LU + PA + S30 + PT10) (Figure 9). All results indicate extremely large solar energy potentials in Australia.

Table 10: Australia's potential for utility-scale solar photovoltaic

Scenarios	1. LU + PA + S30		2. LU + PA + S30 + PT10	
Scenario Regions	Solar Potential Area (km^2)	Solar Potential (GW)	Solar Potential Area (km^2)	Solar Potential (GW)
Australian Capital Territory	721	18.0	700	17.5
New South Wales	657,654	16,441.4	137,056	3,426.4
Northern Territory	621,277	15,531.9	11,545	288.6
Other Territories	9	0.2	0	0.0
Queensland	1,419,857	35,496.4	132,412	3,310.3
South Australia	512,137	12,803.4	57,203	1,430.1
Tasmania	19,134	478.3	10,128	253.2
Victoria	134,222	3,355.5	45,922	1,148.0
Western Australia	1,775,960	44,399.0	81,251	2,031.3
TOTAL	**5,140,970**	**128,524.3**	**476,217**	**11,905.4**

Scenario 1 provides 5,140,970 km^2 of area with solar potential and a total potential solar photovoltaic capacity of 128,524 GW and excludes all protected areas and areas with slopes > 30%, because installing and maintaining solar panels in steep areas is unrealistic. Most agricultural and rural land-use classes (e.g., grazing, cropping, horticulture) and some urban land-use classes (e.g., manufacturing and industrial, services, utilities) in the catchment-scale land use of the Australia dataset (Australian Bureau of Agricultural and Resource Economics) are included. However, certain land-use classes (e.g., nature conservation, managed resource protection, all forest land-use classes, some urban and infrastructure land uses, and water bodies) are excluded from the scenarios selected for the consideration of solar energy potential.

Figure 10 shows the areas of solar potential under Scenario 2 (LU + PA + S30 + PT10). When the land area is restricted by its proximity to electricity transmission lines (10 km), the potential solar areas decrease to 476,217 km^2. However, solar energy in Australia can still harvest 11,905 GW of solar photovoltaic under Scenario 2.

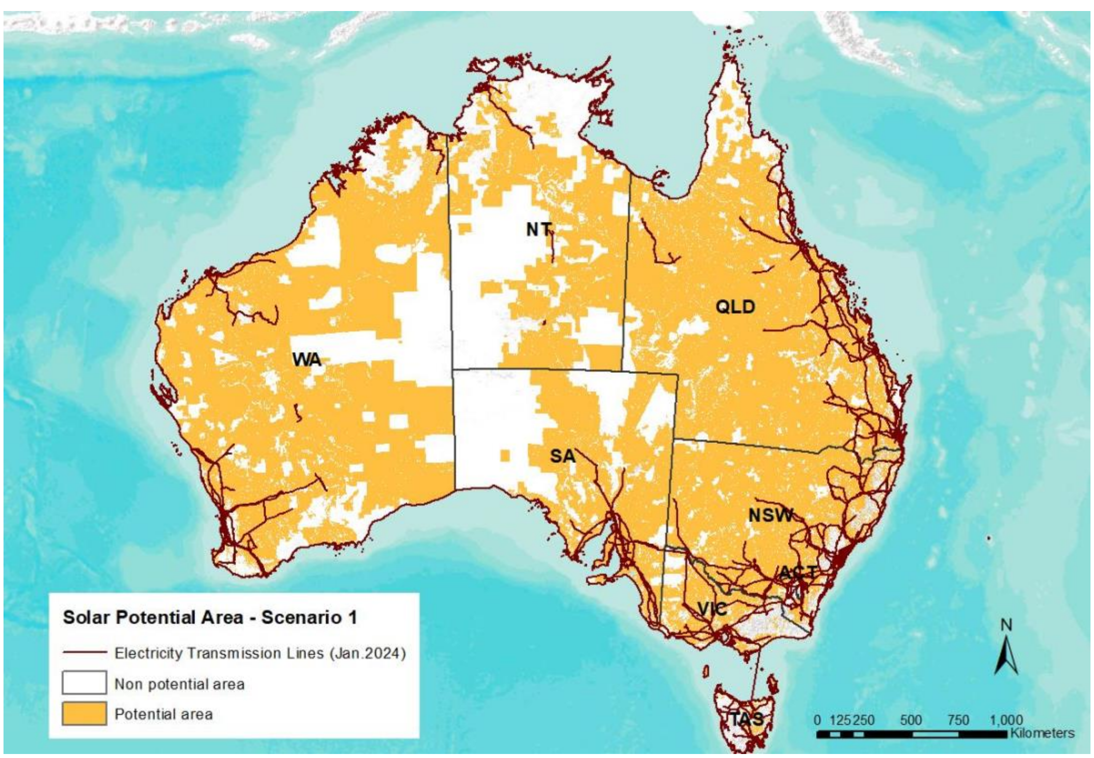


Figure 9. Australia areas of solar potential (Scenario 1: LU + PA + S30)

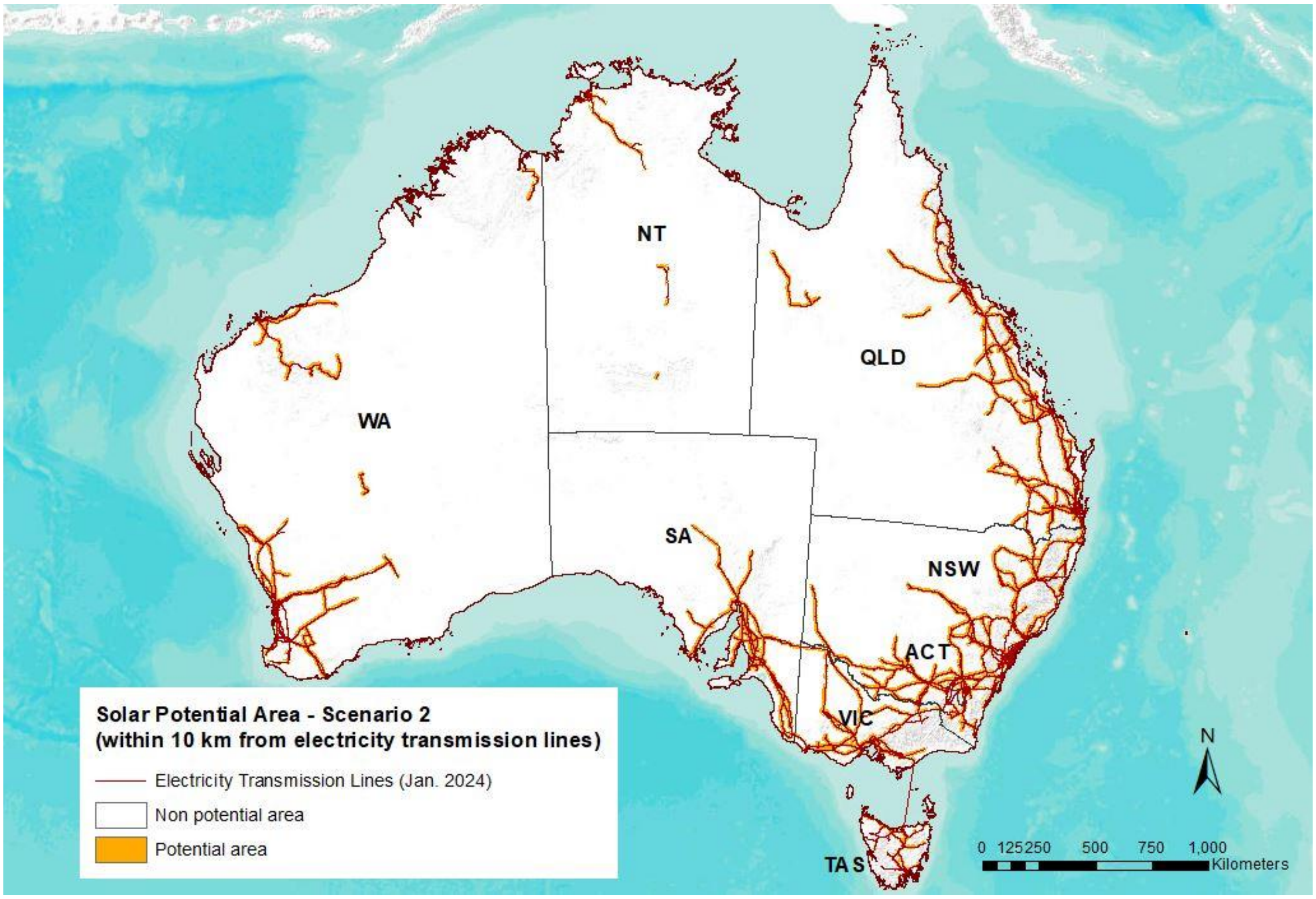


Figure 10. Australia areas of solar potential (Scenario 2: LU + PA + S30 + PT10)

3.3.2 Onshore Wind Potential

The overall onshore wind resources are low in Australia compared with its solar potential. The wind speeds in Australia range from 1.7 to 17.3 m/s at 100 m height, and high-wind-speed areas are located around Victoria and Tasmania (Global Wind Atlas).

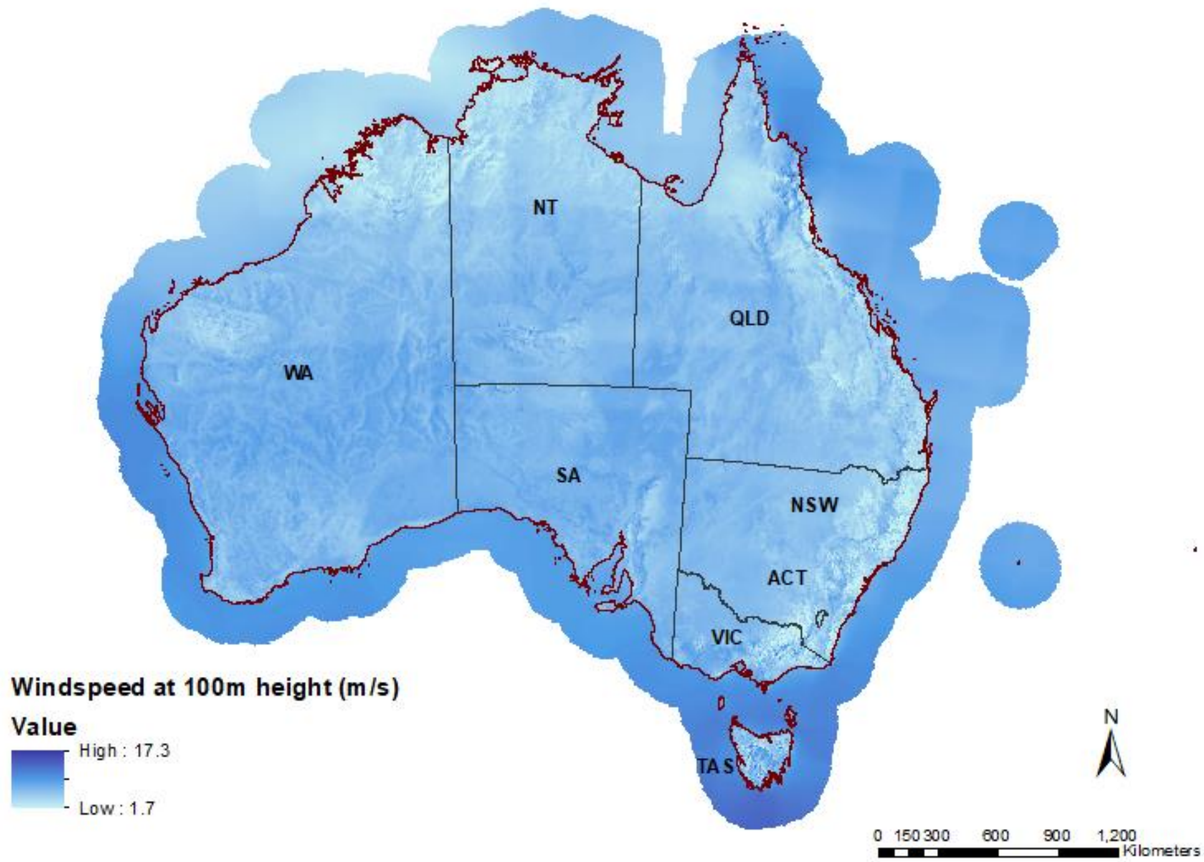


Figure 11. Australia wind speeds at 100 m height (m/s) (data generated from the Global Wind Atlas)

In this analysis, we include only areas with an average annual wind speed of ≥ 5 m/s for onshore projects. Australia's wind potential has been mapped under two different scenarios. The current use of wind energy in Australia involves utility-scale wind turbines in the range up to 10 kilowatts, operated both on- and off-grid as battery chargers.

Scenario 1: Available land—excluding protected areas (PA), extreme topography (slope > 30%, mountain areas; S30), and some existing land use, including forests and urban areas (LU).

Scenario 2: See Scenario 1, with the additional restriction that areas ≤ 10 km from existing transmission lines are excluded (PT10).

Most agricultural and rural land-use classes (grazing, cropping, rural residential and agriculture, farm buildings) are included in the available land (LU) for the two wind scenarios, whereas the land-use classes of nature conservation, managed resource protection, all forest land-use classes, intensive agriculture, urban/built-up areas, and permanent water bodies are excluded in this analysis of wind potential.

Table 11 shows that the overall total onshore wind potential under all restrictions is 24,254 GW for Scenario 1. Overall, the spatial analysis identified limited wind potential in Australia, especially under Scenario 2 (2,006 GW) because there are limited areas with an annual wind speed of ≥ 5 m/s and most of these areas are not located within close proximity to transmission lines (≤ 10 km). However, the results show that Australia has a large wind energy potential, even with all the restrictions.

Table 11: Australia's potential for utility-scale onshore wind power

Scenarios	1. LU + PA + S30		2. LU + PA + S30 + PT10	
Regions	Onshore Wind Potential Area (km^2)	Onshore Wind Potential (GW)	Onshore Wind Potential Area (km^2)	Onshore Wind Potential (GW)
Australian Capital Territory	146	0.7	145	0.7
New South Wales	598,145	2,990.7	106,622	533.1
Northern Territory	566,679	2,833.4	6,698	33.5
Other Territories	7	0.0	0	0.0
Queensland	1,326,639	6,633.2	109,726	548.6
South Australia	505,265	2,526.3	54,480	272.4
Tasmania	16,362	81.8	8,226	41.1
Victoria	121,555	607.8	38,874	194.4
Western Australia	1,715,955	8,579.8	76,601	383.0
Total	**4,850,753**	**24,253.8**	**401,370**	**2,006.3**

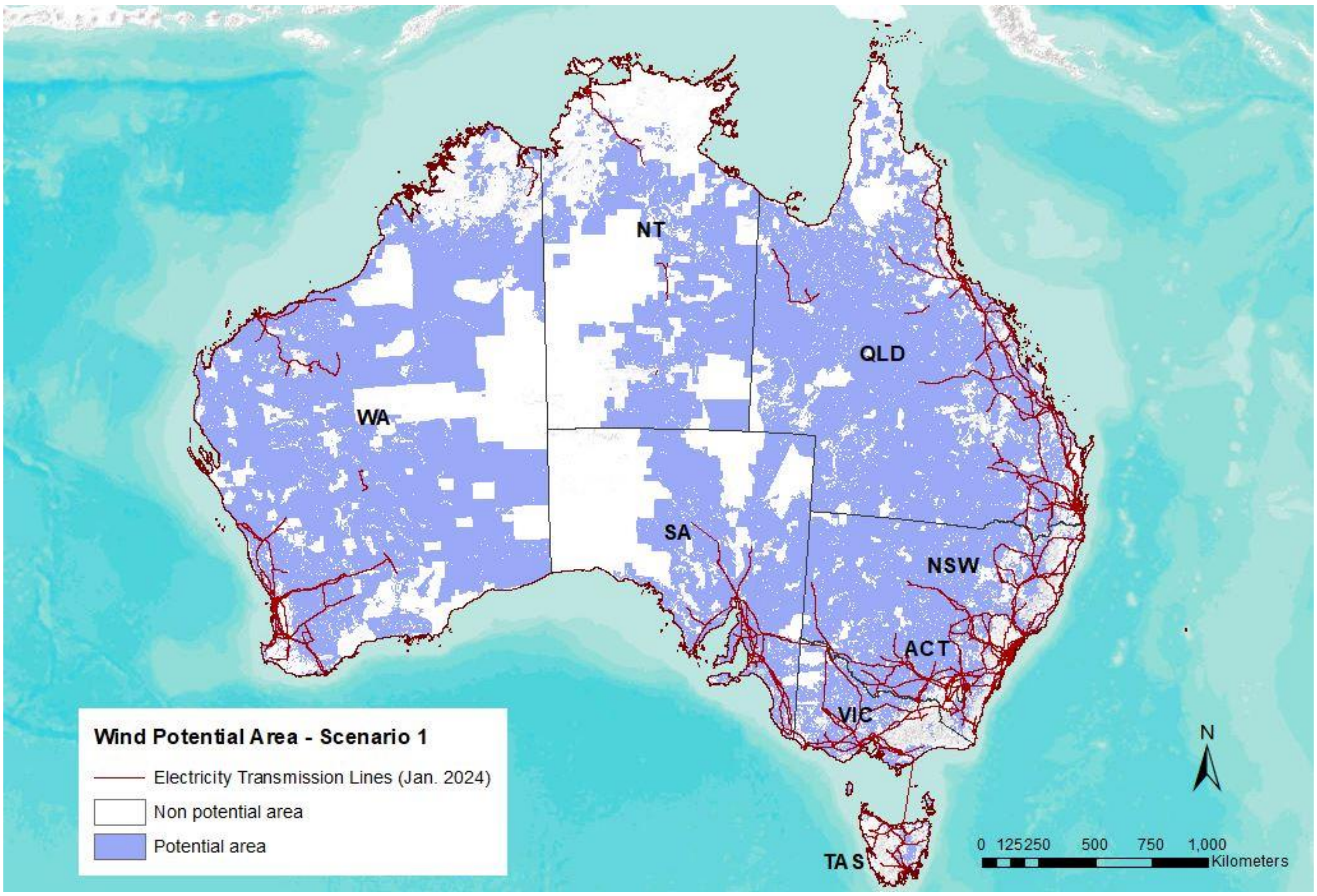


Figure 12. Australia areas of onshore wind potential (Scenario 1: LU + PA + S30)

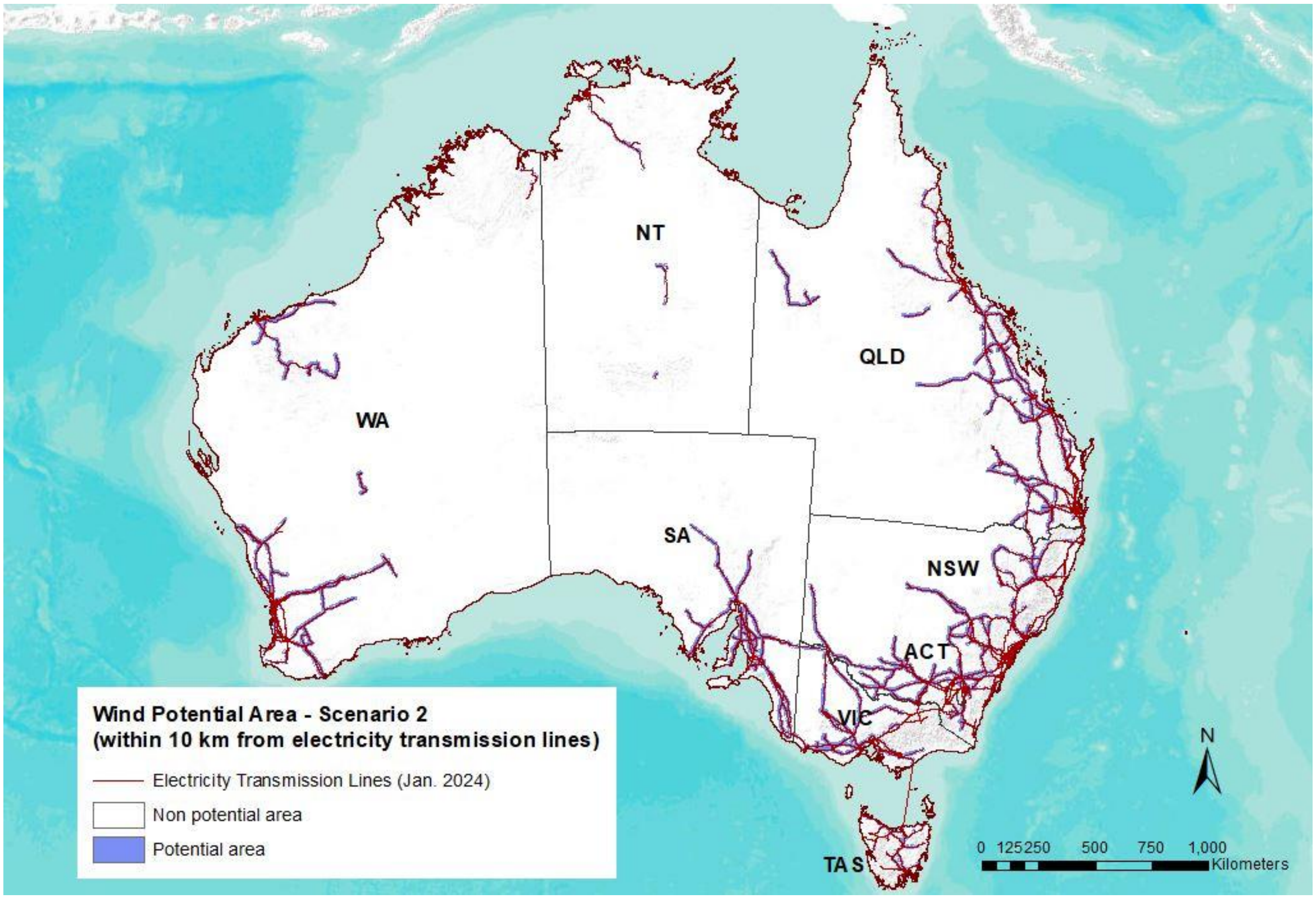


Figure 13. Australia areas of onshore wind potential (Scenario 2: LU + PA + S30 + PT10)

3.3.3 OFFSHORE WIND POTENTIAL

The wind speeds in the offshore areas of Australia range from 2.7 to 12.2 m/s at 100 m height (Global Wind Atlas). For the analysis of offshore wind, we have included areas with an average annual wind speed of ≥ 6 m/s, because offshore wind projects usually require higher wind speeds than onshore wind projects to ensure its economic viability. Australia's offshore wind potential has been mapped under two different scenarios.

Scenario 1: Available offshore areas—excluding protected areas (PA), ocean depths ≤ 50 m (WD50), and proximity to major maritime ports (≤ 50 m, PRT50) (PA + WD50 + PRT50).

Scenario 2: Available offshore areas—excluding protected areas (PA), ocean depth of ≤ 500 m, WD50), and proximity to major maritime ports (≤ 50m, PRT50) (PA + WD500 + PRT50).

The overall total area of offshore wind potential is 347,578 km^2 (1,738 GW) for Scenario 1 and 1,063,527 km^2 (5,318 GW) for Scenario 2.

Figure 15 show the offshore wind potential areas for Scenario 1 and Scenario 2.

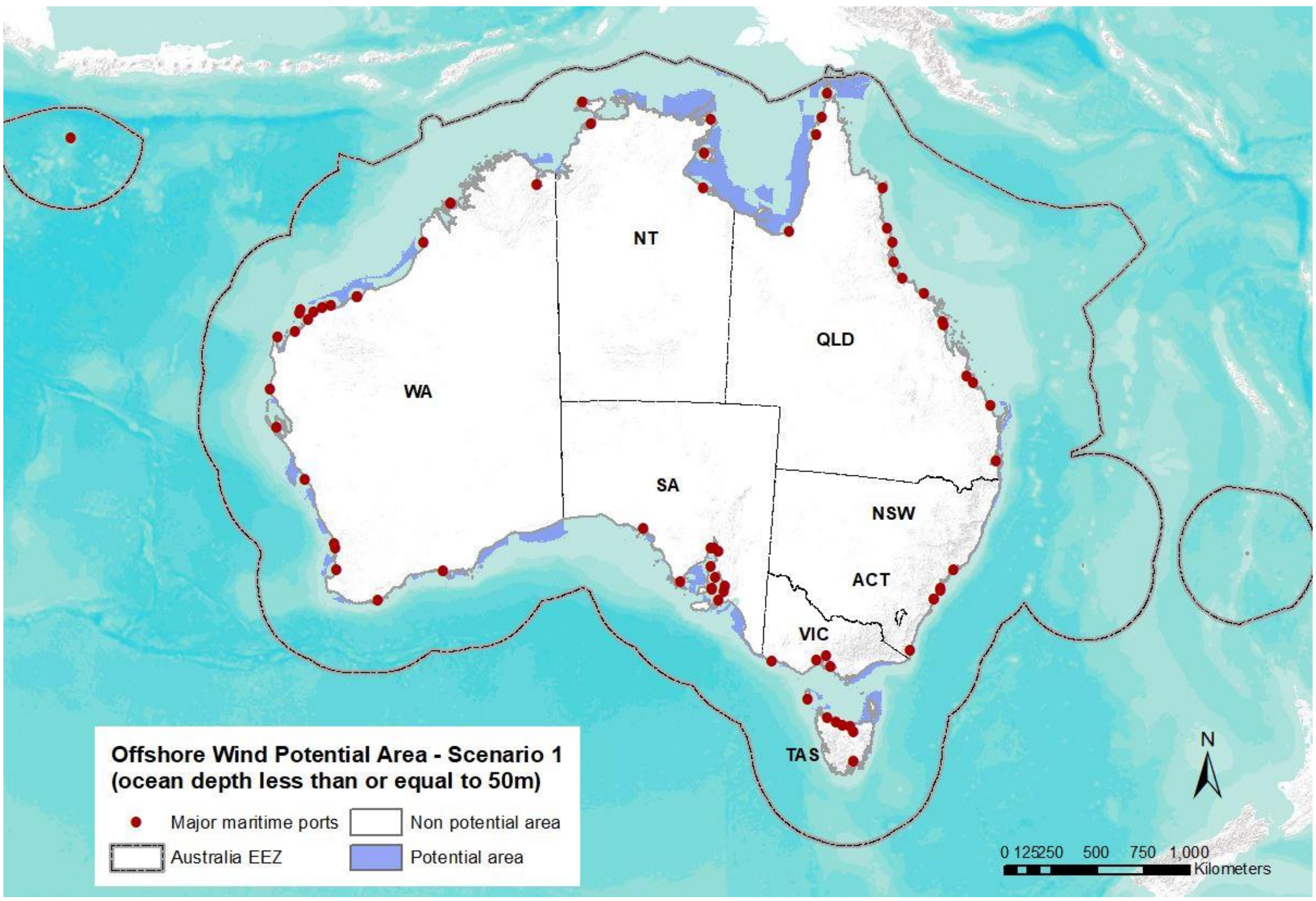


Figure 14. Australia areas of offshore wind potential (Scenario 1: PA + WD50 +PRT50)

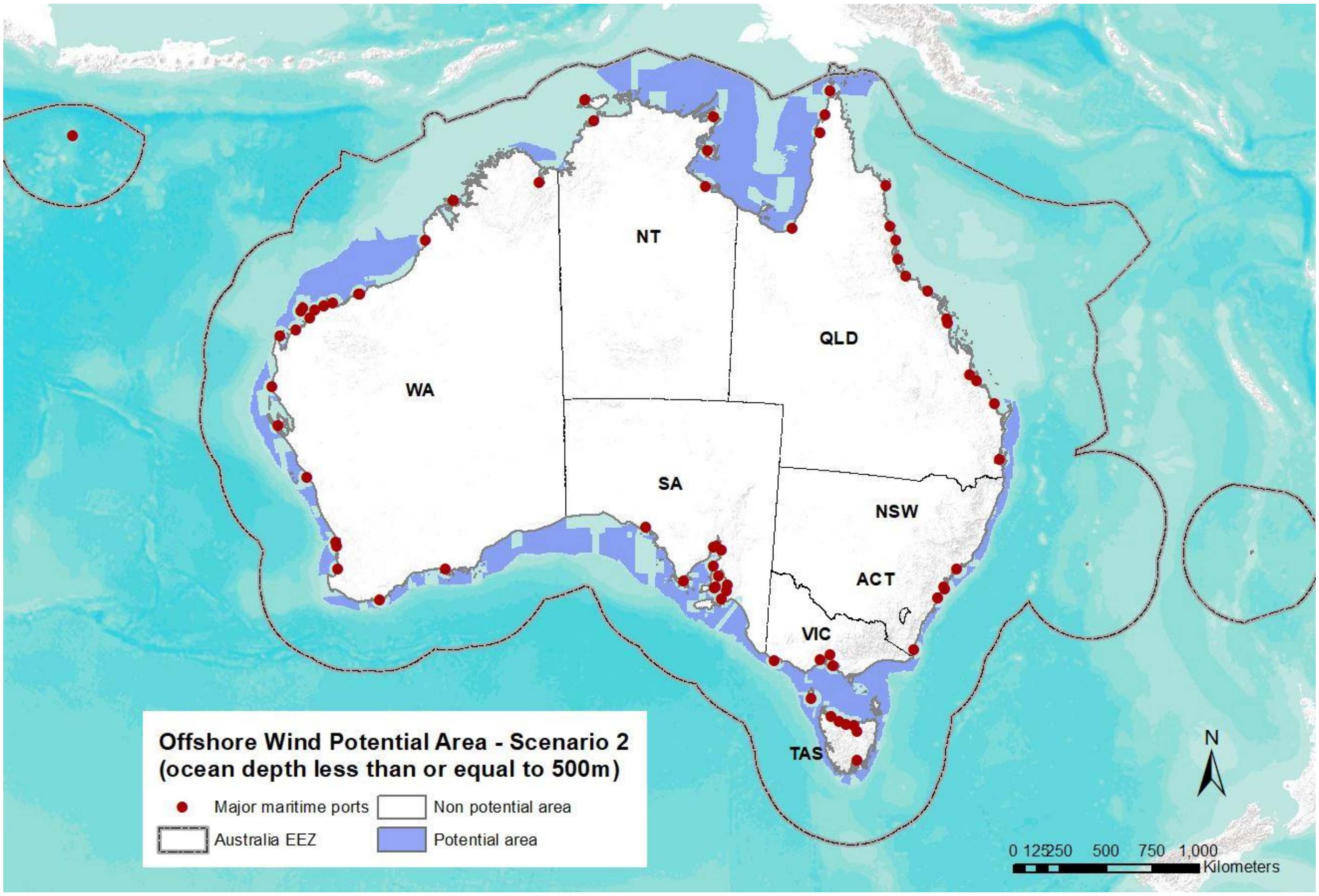


Figure 15. Australia areas of offshore wind potential (Scenario 2: PA + WD500 + PRT50)

4 ASSUMPTIONS & SCENARIO NARRATIVES: TOWARDS A ZERO-EMISSIONS

Modelling the energy system to assess the impact of the energy system on climate change involves a variety of methodological requirements, which pose specific challenges when addressed on the national level: the quantitative projection of developments in (future) technologies and potential markets; a consistent database of renewable energy potentials and their temporal and spatial distributions; reliable data on the current situation in all regions; an assessment of energy flows and emissions across all energy sub-sectors, such as industry, transport, residential, etc.; and a comprehensive assessment of all CO_2 emissions, Finally, analysing and assessing the energy transition require a long-term perspective on future developments.

Changes to energy markets require long-term decisions to be made because infrastructure changes are potentially required and are therefore independent of short-term market developments. The energy market cannot function optimally without long-term infrastructure planning. For example, grid modifications and the roll-out of a smart metering infrastructure require several years to implement. These technologies form the basis of the energy market and allow energy trading. Therefore, the time required for infrastructure planning and other substantial transformation processes must be considered in the scenario-building approach.

4.1 SCENARIO DEFINITIONS

In this analysis, three different scenarios have been calculated.

4.1.1 THE *BASE AMBITION* PATHWAY (*BA*)

The ***Base Ambition*** pathway (*BA*) is based on the OECM 1.5 °C pathways for G20 countries[52] and takes international and national market and policy developments into account. Whereas the ambition for the decarbonization pathway is high, the main focus of this scenario is on the power sector. The development of demand in the transport sector is assumed to remain relatively stable, with moderate reductions in the overall passenger–kilometres and accelerated electrification rates in road transport. Decarbonization of the industry and building sectors follows the international best practice pathways developed under the OECM research project between 2017 and 2022, documented in the scientific literature[53] [54].

4.1.2 THE *NECESSARY AMBITION* PATHWAY (*NP*)

The ***Necessary Ambition*** pathway (*NP*) is based on the *BA* pathway but goes further, aiming to achieve an energy-related CO_2 reduction of 75% relative to 2005 by 2030. The main differences from the *BA* pathway are:

- accelerated implementation of solar photovoltaic, onshore and offshore wind installations;
- accelerated phase-out of oil and gas for residential and industrial process heating;
- accelerated mode shift towards public transport and increases in active transport modes—such as walking and cycling—in urban areas, to reduce passenger transport, especially vehicles with internal combustion engines (ICEs).

4.1.3 *NECESSARY AMBITION PATHWAY PLUS RENEWABLE ENERGY EXPORT* (*NPX*)

The ***Necessary Ambition pathway plus Renewable Energy Export*** (*NPX*) is based on the *NP* scenario with the development of additional renewable energy exports for the steel and aluminium value chains. Whereas the domestic energy demand developments between 2020 and 2050 are identical to those of the *NP* scenario, the iron ore and bauxite-mining industries are assumed to transition to the export of HBI and alumina, respectively. The additional industrial processes will require a significant amount of additional electricity from 2035 onwards.

4.2 SOCIO-ECONOMIC ASSUMPTIONS

The population growth until 2050 is based on the Australian Government projection of an average of 1.05% per year. The long-term GDP development is based on Government projections.

[52] Teske, S. The 'Global Stocktake' and the remaining carbon budgets for G20 countries to limit global temperature rise to +1.5 °C. SN Applied Sciences 2023;5:256. https://doi.org/10.1007/s42452-023-05482-w

[53] Teske S, Niklas S, Talwar S (2022). Decarbonisation Pathways for Industries. In: Teske S. (ed.) Achieving the Paris Climate Agreement Goals. Springer, Cham. https://doi.org/10.1007/978-3-030-99177-7_5

[54] Chatterjee S, Kiss B, Ürge-Vorsatz D, Teske S (2022). Decarbonisation Pathways for Buildings. In: Teske S (ed.) Achieving the Paris Climate Agreement Goals. Springer, Cham. https://doi.org/10.1007/978-3-030-99177-7_7

Table 12: Australia—population and economic development 2019–2050

Socio-economics		2019	2020	2025	2030	2035	2040	2045	2050
Population	[million]	25.4	25.7	27.4	29.1	30.5	31.7	32.7	33.6
GDP	[billion]	1,491	1,327	1,717	1,991	2,308	2,637	2,940	3,151
GDP growth	[%/a]	2.1%	-0.1%	3.0%	3.0%	3.0%	2.5%	2.0%	1.0%

4.3 SCENARIO NARRATIVES

Scenario studies cannot predict the future, but they can describe what is needed for a successful pathway in terms of technology implementation and investment. Scenarios also help us to explore the possible effects of transition processes, such as supply costs and emissions. The energy demand and supply scenarios in this study are based on information about current energy structures and today's knowledge of energy resources and the costs involved in deploying them.

However, to develop a long-term energy scenario for Australia requires a shared vision. This section provides an overview of the narratives that explain the primary technology solutions and high-level sectorial pathways by which Australia can achieve the transformation of our energy, transport, and industrial systems presented in the modelling.

Scenario logic: Aim High, Go Fast!

The basic idea behind the Climate Council pathway: A.U.S.TRA.LI.A

1. Accelerated uptake of renewable energy
2. Utilisation of energy efficiency potential
3. Switching to electrification and sustainable fuels
4. TRAnsport mode shift (and electrification)
5. Liveable Architecture through sustainable buildings

This section provides an overview of the assumed future developments of energy demand and supply, required to achieve the overall goal of decarbonizing Australia's economy.

4.3.1 Primary Energy—Oil, Gas, and Coal

Decarbonization requires a complete phase-out of all fossil fuels in the energy sector. The four different fuels currently in use will be phased-out according to their carbon intensity and depending on the fastest possible introduction of alternative technologies.

Brown coal has a higher carbon intensity than black (hard) coal and will therefore be phased-out first. The carbon intensity of gas is lower than that of hard coal—although methane emissions during its extraction and transportation can nullify this advantage.

Oil is used to a very large extent in the transport sector. Its phase-out requires a technology change towards electric vehicles, but also a major shift towards other transport modes, such as rail, public transport, and active transport—like walking and cycling.

In the *BA* scenario, brown and hard coal are phased-out from electricity generation by 2035. Whereas brown coal will not be used at all after 2035, it is assumed that hard coal will be used to generate industrial process heat beyond 2035, but will be phased-out entirely by 2040. The gas demand will be reduced to almost half within the next decade, but has a 'longer tail', in both the power and heating sectors, until 2045. This will provide the required time to ramp-up renewables and help supply the increasing electricity demand arising from the electrification of the heating and transport sectors. Oil phase-out is achieved through the electrification of space and process heating, electric mobility, and mode shifts to active and public transport.

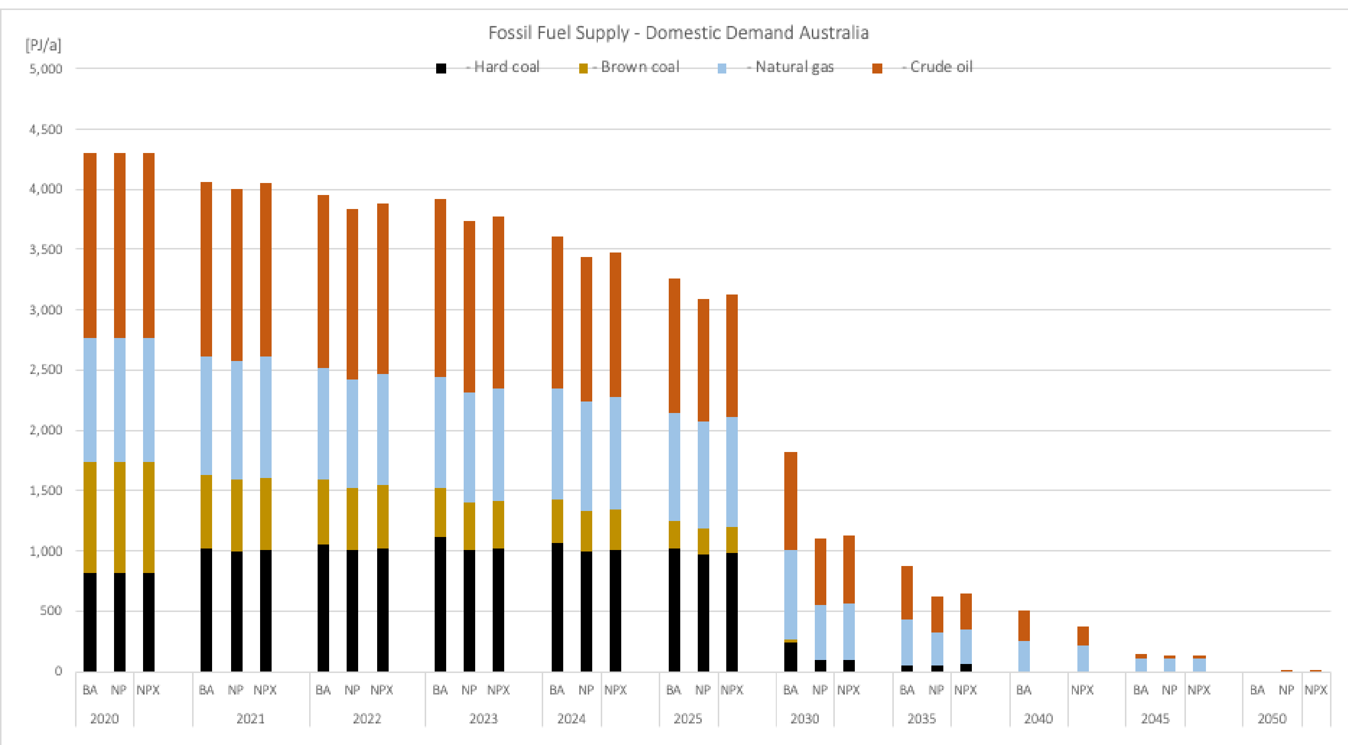


Figure 16. Australia's phase-out of fossil fuels for domestic energy supply over time under three different scenarios

4.3.2 SERVICE SECTOR

Table 13: Service sector—market development and energy intensities

Services		2019	2020	2025	2030	2035	2040	2045	2050
Water Utilities									
Water withdrawal—total	[billion m³]	16	16	16	16	18	19	21	22
- saltwater component	[billion m³]	0	0	0	0	0	1	1	1
Saltwater share (of total water withdrawal)	[%]	0%	0%	1%	2%	3%	3%	3%	4%
Agricultural water	[billion m³]	10	10	10	10	12	12	13	14
Municipal water	[billion m³]	3	3	3	3	4	4	4	4
Industrial water	[billion m³]	3	3	3	3	3	3	3	3
Water Utilities Energy Intensities									
Water Pumping & Distribution	[kWh/m³]	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.17
Desalination	[kWh/m³]	4.50	4.50	4.44	4.39	4.33	4.28	4.23	4.17
Wastewater Treatment	[kWh/m³]	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Average Electricity Intensity (across all processes)	[kWh/m³]	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Average Heat Intensity (across all processes)	[MJ/m³]	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Agriculture									
Agriculture—Economic Value	[bn $]	33	33	38	44	51	59	65	70
Food & Processing Industry—Economic Value	[bn $]	35	35	41	48	55	63	70	75
Tobacco Industry—Economic Value	[bn $]	2	2	2	3	3	3	4	4
Average Energy Intensity: Agriculture & Food Processing	[MJ/$GDP]	3.49	3.49	3.44	3.40	3.36	3.31	3.27	3.23
Tobacco Products Industries	[MJ/$GDP]	0.40	0.40	0.40	0.39	0.39	0.38	0.38	0.37
Forestry & Wood									
Forestry Industry—Economic Value	[bn $]	6.1	6.1	7.1	8.2	9.6	10.9	12.2	13.1
Wood - Industry—Economic Value	[bn $]	7.1	7.1	8.4	9.7	11.3	12.9	14.4	15.4
Pulp & Paper Industry—Economic Value	[bn $]	5.8	5.8	6.9	8.0	9.2	10.5	11.8	12.6
Forestry—total	[MJ/$GDP]	3.38	3.38	3.34	3.30	3.25	3.21	3.17	3.13
Wood Products Industries	[MJ/$GDP]	16.46	16.46	16.25	16.05	15.85	15.65	15.46	15.26
Pulp Mills	[MJ/$GDP]	269	269	266	262	259	256	253	249
Paperboard Mills	[MJ/$GDP]	67	67	66	65	64	64	63	62
Average Energy Intensity: Forestry, Wood and Paper Industry	[MJ/$GDP]	4	4	3	3	3	3	3	3

4.3.3 Industry Sector

Table 14: Industry sector—market development and energy intensities

Industry Sector		2019	2020	2025	2030	2035	2040	2045	2050
Chemical Industry									
Market Chemical Industry	[bn $GDP]	11.6	11.9	13.7	15.9	18.5	21.1	23.5	25.2
Average growth rate	[%/a]		0%	3%	3%	4%	4%	4%	4%
Chemical Industries—average energy intensity	[MJ/$GDP]	4.31	4.24	4.05	4.01	3.97	3.93	3.89	3.85
Steel Industry									
Regional: Mining iron ore—production volume	[Mt/a]	919	912	940	992	1,059	1,129	1,217	1,311
Annual production volume—Iron & Steel Industry	[Mt/a]	5.4	5.5	5.7	6.0	6.4	6.8	7.3	7.9
Primary steel production—share of total production	[%]	79%	79%	69%	64%	59%	56%	54%	52%
Secondary/scrap steel—share of total production	[%]	21%	21%	31%	36%	41%	44%	46%	48%
Average Energy Intensity: Steel Production	[GJ/tonne]	12.1	12.1	11.7	11.3	11.9	11.1	11.1	10.8
Energy Intensity—PRIMARY steel (FINAL ENERGY)	[GJ/tonne]	14.1	14.1	14.1	14.1	13.3	12.2	11.6	10.9
Energy Intensity—SECONDARY steel (FINAL ENERGY)	[GJ/tonne]	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Aluminium Industry									
Mining bauxite—production volume	[Mt/yr]	105	104	111	122	132	143	154	165
Annual production volume—aluminium Industry	[Mt/yr]	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7
Primary aluminium production—share of total production	[%]	99%	99%	63%	59%	57%	54%	50%	48%
Secondary/scrap aluminium—share of total production	[%]	1%	1%	37%	41%	43%	46%	50%	52%
Bauxite Mining—Energy Intensity	[PJ/Mt]	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6
Primary Aluminium—Energy intensity - Electricity (Anode, Electrolysis + Ingot)	[PJ/Mt]	55.8	55.8	54.4	53.1	51.7	50.4	49.2	47.9
Secondary Aluminium—Energy intensity - Electricity (Anode, Electrolysis + Ingot)	[PJ/Mt]	2.8	2.8	2.7	2.7	2.6	2.5	2.5	2.4
Cement Industry									
Cement—production volume	[Mt/yr]	10	11	12	12	12	12	13	13
Clinker—production volume (based on clinker to cement ratio)	[Mt/yr]	8.3	9.2	8.9	8.3	8.1	8.0	7.8	7.7
Thermal energy intensity—per tonne of clinker	[GJ/tonne]	3.5	3.5	3.4	3.3	3.3	3.2	3.2	3.1
Cement production—electricity intensity	[kWh/tonne]	116	116	103	87	85	83	81	79
Thermal energy intensity—per tonne of cement (final energy)	[GJ/tonne]	5.2	4.7	4.0	3.5	3.0	2.1	2.0	2.0
Product Energy Intensity (thermal + electricity)	[GJ/tonne cement]	5.6	5.1	4.4	3.8	3.3	2.4	2.3	2.3
Textile & Leather Industries									
Textile Industries—Economic value	[bn $GDP]	0.5	0.5	1.2	1.4	1.6	1.9	2.1	2.2
Leather Industry—Economic value	[bn $GDP]	0.6	0.6	0.8	0.9	1.1	1.3	1.4	1.5
Total Textile & Leather	[bn $GDP]	1.1	1.1	2.0	2.4	2.7	3.1	3.5	3.7
Textile Mills—Energy Intensities	[MJ/$GDP]	4.53	4.53	4.42	4.31	4.20	4.09	3.99	3.89
Textile Products Mills—Energy Intensities	[MJ/$GDP]	4.58	4.58	4.47	4.35	4.25	4.14	4.04	3.94
Clothing Industries—Energy Intensities	[MJ/$GDP]	0.86	0.86	0.84	0.82	0.80	0.78	0.76	0.74
Textile Industry—Average Energy Intensity	[MJ/$GDP]	4.37	4.37	4.26	4.15	4.05	3.95	3.85	3.75
Leather and Allied Products Industries—Energy Intensity	[MJ/$GDP]	1.49	1.49	1.45	1.42	1.38	1.35	1.31	1.28

4.3.4 BUILDINGS

Table 15: Building stock—development and energy intensities

Buildings		2019	2020	2025	2030	2035	2040	2045	2050
Building Stock: Residential	[billion m^2]	1.9	2.5	4.0	6.2	7.1	7.2	7.2	1.9
Building Stock: Commercial	[billion m^2]	0.7	0.8	1.2	1.8	2.1	2.1	2.3	0.7
Residential Buildings: Energy Intensity	[kWh/m^2]	138	138	134	126	118	110	101	93
Commercial Buildings: Energy Intensity	[kWh/m^2]	88	88	84	77	71	65	61	57
Construction: Residential and Commercial Buildings—Energy Intensity	[MJ/$GDP]	0.70	0.70	0.67	0.66	0.66	0.65	0.64	0.64
Residential Buildings: Total Emissions Intensity (Heating & Electricity)	[kgCO_2/kWh]	0.89	0.87	0.51	0.13	0.03	0.01	0.00	0.00
Residential Buildings: Emissions Intensity—Heat per square metre	[kgCO_2/m^2]	19.5	18.4	13.8	4.4	2.5	1.4	0.3	0.0
Residential Buildings: Emissions Intensity—Heat	[kgCO_2/kWh]	0.141	0.133	0.103	0.035	0.021	0.013	0.003	0.000
Residential Buildings: Emissions Intensity—Electricity	[kgCO_2/kWh]	0.748	0.734	0.405	0.097	0.007	0.000	0.000	0.000
Commercial Buildings: Total Emissions Intensity (Heating & Electricity)	[kgCO_2/kWh]	29.17	27.50	21.06	7.00	4.07	2.33	0.63	0.00
Commercial Buildings: Emissions Intensity—Heat per square metre	[kgCO_2/m^2]	28.8	27.2	20.8	6.9	4.0	2.3	0.6	0.0
Commercial Buildings: Emissions Intensity—Heat	[kgCO_2/kWh]	0.328	0.310	0.248	0.089	0.056	0.035	0.010	0.000
Commercial Buildings: Emissions Intensity—Electricity	[kgCO_2/kWh]	0.748	0.734	0.405	0.097	0.007	0.000	0.000	0.000

4.3.5 TRANSPORT

The demand developments (in annual kilometres) in the transport sector differ in the *BA* and the *NP(X)* pathways, whereas the energy intensity assumptions are identical (Table 16). The *NP* and *NPX* pathways reduce passenger–kilometres, especially for private vehicles, and shift them to public transport and increased walking and cycling in urban areas (Table 17).

Table 16: Transport sector—energy intensities

Total Transport Sector		2019	2020	2025	2030	2035	2040	2045	2050
Aviation Passenger: Energy Intensity	[MJ/pkm]	5.81	5.81	4.83	4.51	4.39	4.28	4.23	4.18
Aviation Freight: Energy Intensity	[MJ/tkm]	32.20	32.20	29.12	27.16	26.46	25.76	25.48	25.20
Shipping Passenger: Energy Intensity	[MJ/pkm]	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Shipping Freight: Energy Intensity	[MJ/tkm]	0.20	0.20	0.19	0.18	0.18	0.18	0.17	0.17
Road Passenger: Energy Intensity	[MJ/pkm]	2.49	2.64	1.82	1.53	0.98	0.87	0.63	0.43
Road Freight: Energy Intensity	[MJ/tkm]	1.34	1.34	1.17	1.08	0.86	0.79	0.59	0.58

Table 17: Transport sector—assumed development of passenger–kilometres

[million pkm/a]	2020		2025		2030		2040		2050	
	BA	NP	BA	NP	BA	NP	BA	NP	BA	NP
Aviation	55,708	55,708	72,255	72,255	65,313	65,313	50,697	50,697	37,385	37,385
Rail	15,139	15,139	25,279	27,812	40,035	63,563	64,493	99,592	89,056	100,527
Road	295,158	295,158	263,911	258,525	257,313	245,599	244,608	216,986	232,531	191,707
Passenger cars	277,449	277,449	248,076	243,013	238,014	221,039	214,032	189,863	197,651	153,366
Buses	17,710	17,710	15,835	15,511	19,298	24,560	30,576	27,123	34,880	38,341
Bus passenger–km in % (BITRE data 2020)	6%	6%	6%	6%	8%	10%	13%	13%	15%	20%
Active transport (increase from 2022)	0	0	2,533	5,065	14,756	19,251	11,456	22,206	5,336	23,371
Active transport per person and day in km	0	0	0	1	1	2	1	2	1	2

5 KEY RESULTS

This section provides an overview of the key results for the three calculated energy pathways for Australia. We focus on a comparison of the demand and supply trajectories of the *Basic Ambition* (*BA*) and the *Necessary Ambition* (*NP*) pathways both with and without renewable energy export development (*N[PX]*). Where the results for the *NP* and the *NPX* are similar, the acronym *NP(X)* is used.

5.1 FINAL ENERGY DEMAND

The final energy demand[55] for Australia decreases under the *BA* and the *NP* scenarios until the end of the modelling period in 2050. This is mostly due to increased efficiencies associated with electrification. The *BA* energy demand will decrease by around 1.5% per year until 2030 and by approximately 3% between 2031 and 2050. The *NA* scenario accelerates the efficiency measures across all sectors—mainly by faster electrification of the transport sector combined with behavioural changes—leading to annual reduction rates of 3.5%–4% between 2030 and 2050 (Figure 17).

The *NPX* pathway leads to an increase in the final energy demand—mainly electricity—after 2030 due to the increased renewable electricity required for the onshore manufacturing of HDI and alumina. The *NPX* energy demand will increase by 4% annually between 2030 and 2040 and by 10% between 2041 and 2050. Australia will export energy equivalent to 85% of the domestic energy demand by 2050 in the form of these goods manufactured with zero emissions.

Figure 17. Projection of total final energy demands by sector under different scenarios

As a result of the electrification of all sectors to phase-out fossil fuels, the electricity demand will increase constantly from the first year of projection (2024), with a significant jump under the *NPX* scenario (Figure 18). By 2050, Australia will export 75% of the domestically generated electricity in the form of manufactured goods. The overall electricity demand under the *BA* and *NP* scenarios will grow by a factor of around 2.5 between 2025 and 2050.

[55] Final energy consumption is the total energy consumed by end users, such as households, industry, and agriculture. It is the energy that reaches the final consumer's door and excludes that which is used by the energy sector itself. Final energy consumption excludes the energy used by the energy sector, including for deliveries, and transformation. It also excludes fuel transformed in the electrical power stations of industrial automobile producers and coke transformed into blast-furnace gas, when this is not part of the overall industrial consumption but of the transformation (= end-use) sector.

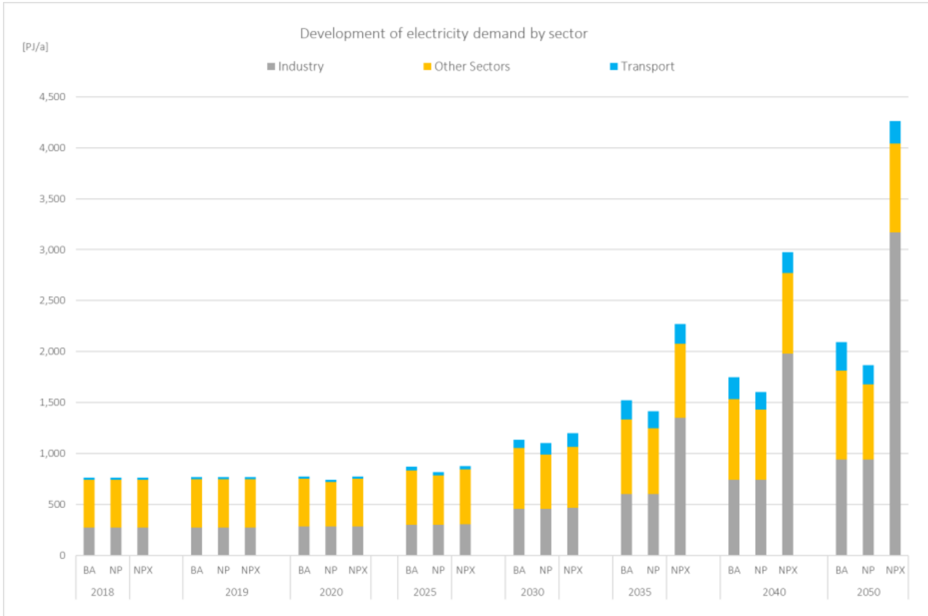


Figure 18. Development of electricity demand by sector

5.2 TRANSPORT DEMAND

The final energy transport demand will decrease under the *BA* and *NP(X)* scenarios between 2025 and 2050 by 2% and 3%, respectively, as an annual average (Figure 19). Passenger transport modes will shift from private vehicles towards public transport (bus and rail) and—for urban areas—to active transport (walking and cycling). The overall final energy demand will decrease significantly by 65% (*BA*) and 70% (*NP(X)*), respectively, due to a combination of this mode shift and the replacement of inefficient ICEs with highly efficient electric drivetrains.

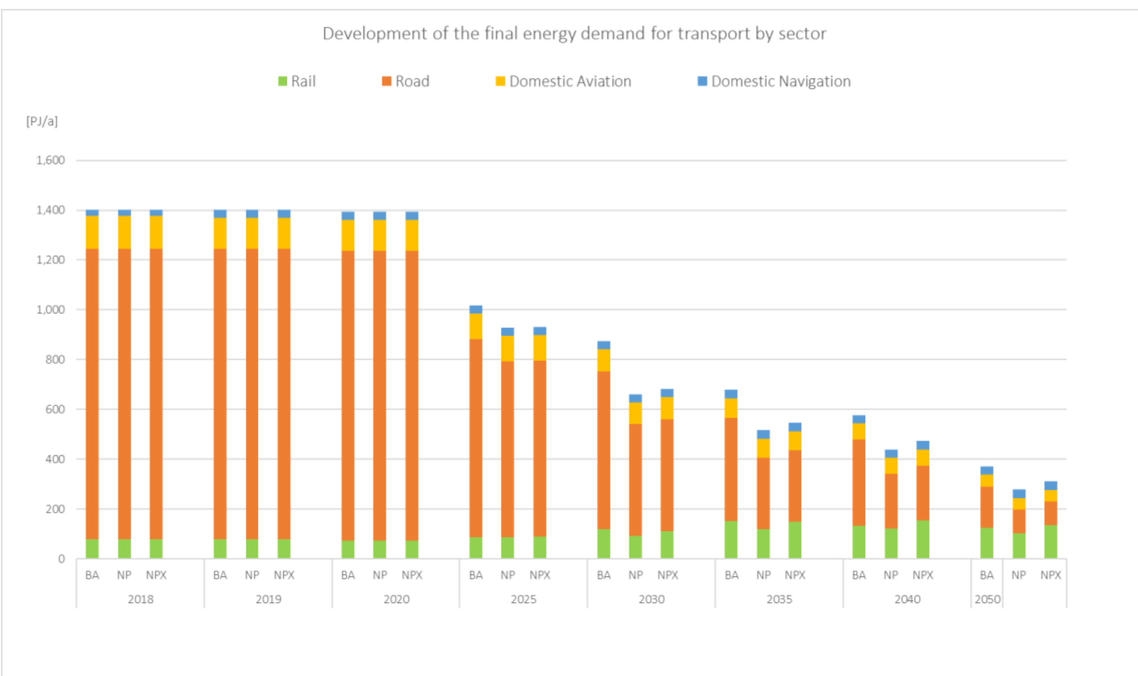


Figure 19. Development of the final energy demand for transport by sector

Fossil fuels—almost exclusively oil for ICEs—will be replaced by renewable electricity as the main energy source. Biofuels will be used mainly for shipping and aviation (Figure 19). Synthetic aviation fuels (SAF), produced with green hydrogen, will be introduced after 2040.

Figure 20. Final energy consumption by transport under the scenarios

The overall passenger–kilometres in domestic aviation will decrease across all scenarios by 1.7% per year between 2020 and 2050 (Figure 21). Although land-based travel—rail and road combined—will remain stable under all three scenarios, the transport modes will develop differently. The *BA* scenario projects a shift from road to rail of around 1% per year on average between 2025 and 2050; the *NP(X)* scenario, in contrast, is more ambitious, with an annual rate of 2%. Furthermore, the use of public transport buses will grow from 5% (2020) to 20% (2050) at the expense of individual passenger cars. Reduced demand in the transport sector will not only be based on technical measures but also on behavioural changes, e.g., commuters in urban areas will not only shift from private vehicles to public transport but also to active forms of transport, such as walking and cycling.

Figure 21. Development of passenger transport in million kilometres

The freight transport demand will increase in line with economic growth. The *NP(X)* pathway assumes a slight reduction in demand in freight transport, with a shift from trucks to cargo bicycles. However, the reduction is difficult to quantify because developments towards transport bikes—that mainly started in European cities—are yet to be determined. Additional freight transport demand will shift mainly towards railways under all scenarios (Figure 22).

Figure 22. Development of freight transport in **million** kilometres

5.3 POWER SECTOR

The decarbonization of the power sector is vital under all three scenario narratives. New renewable power generation—mainly solar photovoltaic, onshore and offshore wind—will not only replace existing coal and gas power plant capacities, but must meet the increasing electricity demand as the transport, buildings, and industry sectors are increasingly electrified. Sector coupling—the connection of the transport and heating sector to the power sector via increased electrification—and new power system management are essential[56]. Figure 23 shows the development of the electricity sector across all three scenarios until 2050. By 2025, over 40% of Australia's power generation will be from renewable electricity, increasing to over 80% by around 2030. By 2035, Australia's entire electricity demand will be generated with renewables under all three scenarios.

The renewable energy generation capacity will increase significantly until 2050 under all scenarios (Table 18). The capacity increase will be due to the higher electricity demand for and the lower capacity factors of solar and wind power plants relative to those of coal and gas power plants. The higher capacity requirements come with additional requirements for storage capacity, but an almost complete phase-out of fuel costs.

[56] AEMO—Australian Energy Market Operator, 2022 Integrated System Plan, https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf?la=en

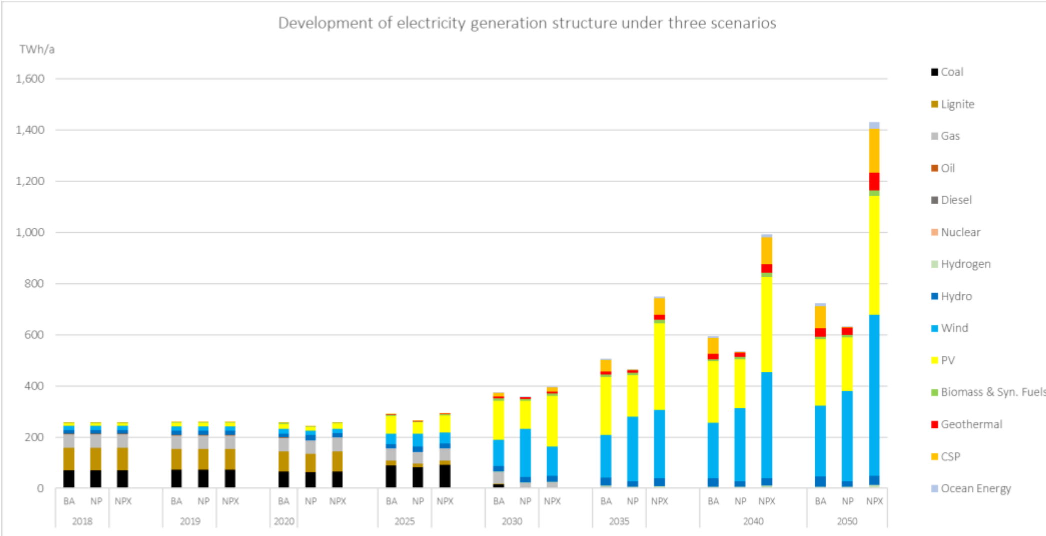


Figure 23. Development of electricity generation structure under three scenarios

Table 18: Projection of required renewable electricity generation capacity under the three scenarios

[GW}		2020	2025	2030	2035	2040	2050
Hydro	BA	6	6	8	10	11	13
	NP	6	6	7	7	7	7
	NPX	6	6	8	10	10	11
Biomass	BA	1	2	2	2	2	2
	NP	2	2	2	2	2	2
	NPX	1	2	2	3	4	5
Wind	BA	9	16	37	58	72	88
	NP	8	17	69	88	95	109
	NPX	9	17	42	94	141	205
Geothermal	BA	1	0	1	2	3	5
	NP	1	0	1	2	2	4
	NPX	1	0	1	2	5	9
Photovoltaic	BA	22	45	107	163	165	167
	NP	21	45	79	118	135	142
	NPX	22	47	139	234	266	300
Concentrated Solar Power	BA	0	0.2	7	20	28	37
	NP	0	0.2	0	1	1	1
	NPX	0	0.2	7	26	41	76
Ocean	BA	0	0	1	3	4	7
	NP	0	0	0	1	1	1
	NPX	0	0	1	4	6	15
Total	BA	38	69	163	257	285	321
	NP	38	70	158	218	243	266
	NPX	38	73	200	373	472	621

Table 19 shows the new installed capacity required annually for solar photovoltaic and onshore and offshore wind under the three scenarios. The capacities for 2040, 2045, and 2050 include repowering capacities—to replace generators after 20–25-year lifetimes. This is assumed based on the annual market sizes in 2020, 2025, and 2030. To avoid boom and bust cycles, the repowering capacities for generators built before 2020 are distributed across 2030 and 2035 because the technical lifetimes for solar and wind turbines have shown to be 5–10 years longer than the assumed 20 years. Solar photovoltaic is projected to remain the technology with the highest capacity in Australia across the modelling period, followed by onshore wind and then offshore wind.

The Australian solar photovoltaic industry must increase its annual capacity—including the required supply chains—from an installation rate of around 5 GW per year to around 10 GW per year under the *BA* scenario. Both the *NP* and *NPX* scenarios increase solar and wind capacities faster than *BA* between 2025 and 2030, leading to 30%–50% higher annual installation rates. Whereas the *NP* increases 2030 solar installation levels for the coming decade only moderate, the annual capacities will continue to increase under the *NPX*, such that they are four times higher in 2050 than in 2023 for solar photovoltaic and 2–3 times higher for the wind industry (Table 15). The *NPX* scenario will require significant additional capacity—especially solar—for the ramp-up phase of export activities.

The onshore wind market will increase from around 1.5 GW per year to about 4 GW, whereas the offshore wind industry is assumed to ramp-up between 2023 and 2030, with the first installation just before 2030 and a long-term annual capacity of 1.5–2 GW per year.

Table 19: Annual market developments in solar **photovoltaic**, onshore and offshore wind in 2023–2050

[GW/a]	2023			2025			2030			2040			2050		
	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX
- Solar photovoltaic	5.8	8.3	8.3	9.0	4.8	5.0	9.6	3.9	4.1	10.4	6.8	7.0	11.5	20.9	18.2
- Onshore Wind	1.0	0.8	0.8	1.2	2.0	2.0	2.3	7.0	7.2	3.2	8.6	9.5	4.3	6.4	8.9
- Offshore Wind	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	1.0	1.0	1.1	1.0	0.9	2.0
Renewables Share in % (Generation)	34%	36%	36%	39%	40%	40%	47%	47%	47%	83%	94%	94%	100%	100%	100%

Figure 24 shows the overall development of the solar and wind industry ramp-ups from the current ~8 GW per year to 15 GW per year under *BA* and over 20 GW under *NP(X)* around 2030. Whereas new solar and wind capacities will remain at 20 GW per year under the *NP* pathway, approximately 10 GW of additional new solar and wind power plants must be built to supply the increased demand for clean exports under the *NP(X)* scenario.

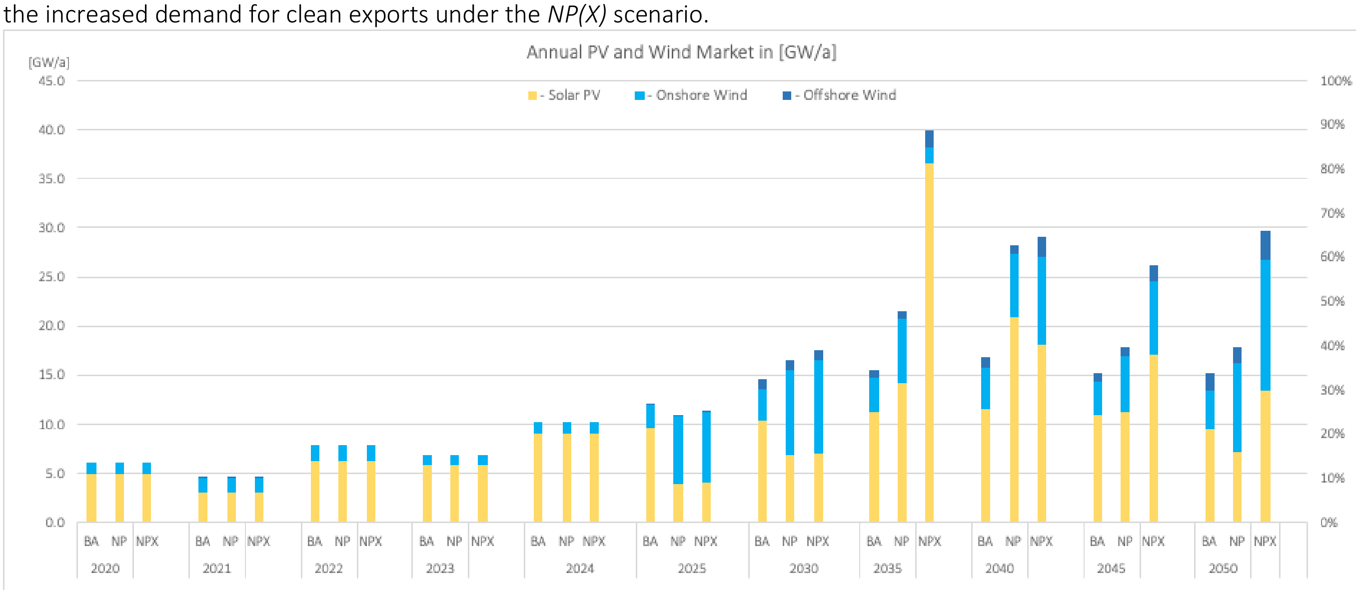


Figure 24. Annual market development for solar photovoltaic, onshore and offshore wind in 2023–2050

5.4 HEATING SECTOR

Heat demand in Australia is assumed to increase only slightly over time in response to increases in building stock, but increased efficiency measures, electrification, and increased economic activity are expected to keep demand almost stable The domestic heat demand for residential buildings, and especially industrial process heat, will increase by only 15% in total between 2020 and 2050, whereas over the same period, GDP will increase by around 2% per year and the population by 1% annually (Figure 25). Electric heating systems—especially heat pumps, but also electric arc furnaces (EAFs) for the steel and chemical industries—will increase the overall electricity share in Australia's heating supply from 2% currently to over 35% by 2035 and 50% in 2050.

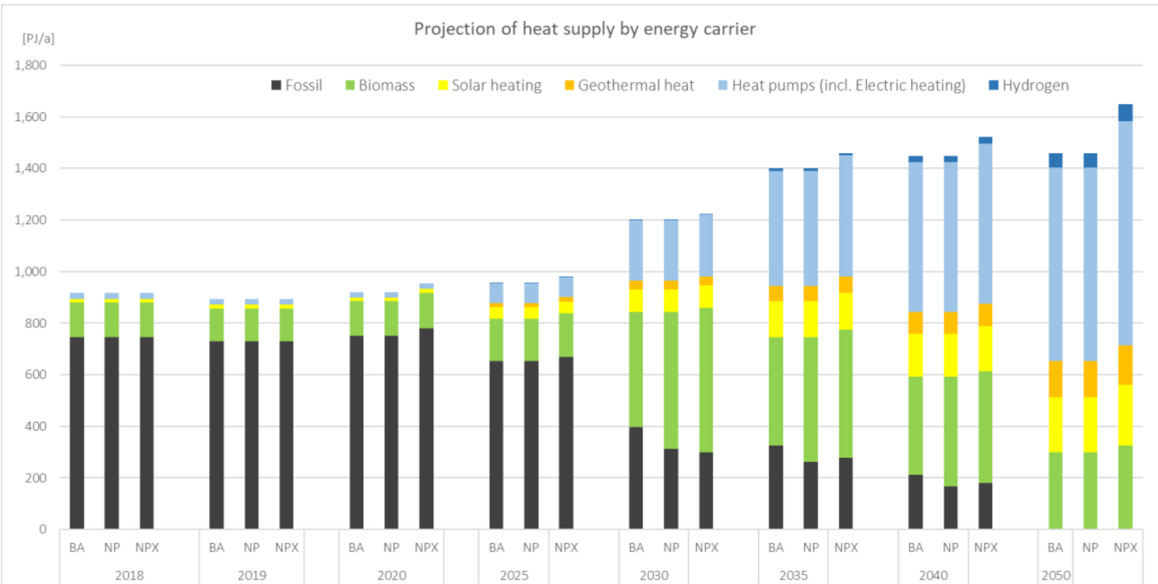


Figure 25. Projection of heat supply by energy carrier

5.5 PRIMARY ENERGY DEMAND

Finally, the primary energy demand for Australia will decrease by 0.6% per year due to high electrification under the *BA* scenario and by 1.9% per year under the *NP* scenario between 2020 and 2050 (Figure 26). Under the *NPX* scenario, an increase in Australia's primary energy demand of 35% will occur in the same time frame, which is an increase of around 1.2% per year.

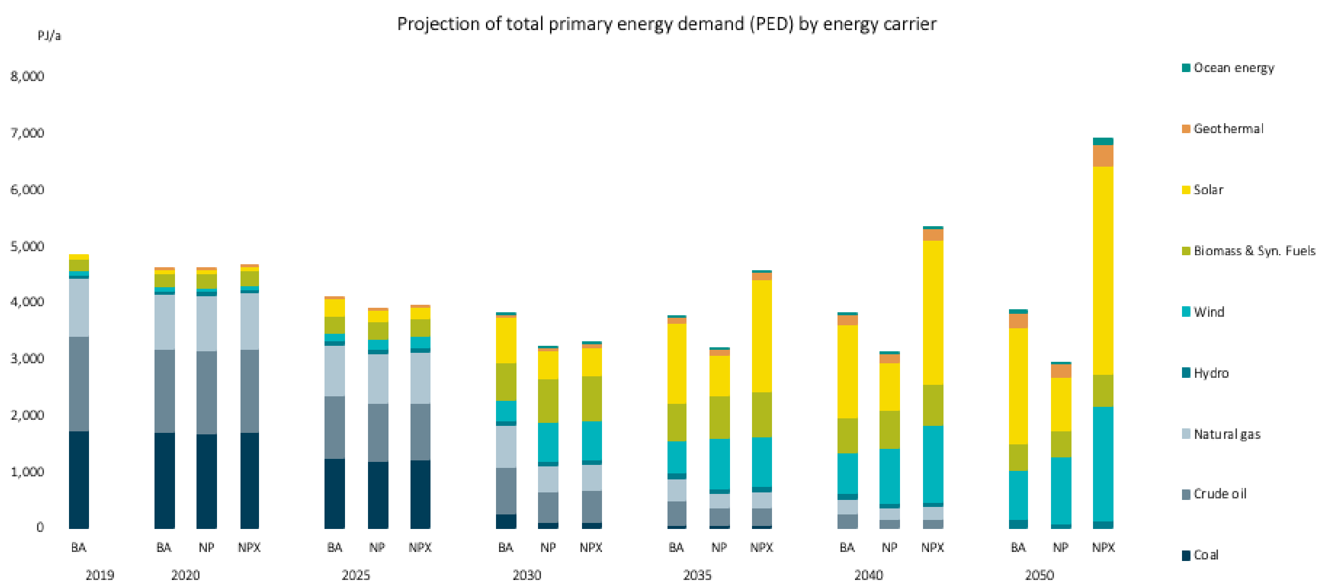


Figure 26. Projection of total primary energy demand by energy carrier

5.6 ENERGY-RELATED CO_2 EMISSIONS

As a result of the fossil-fuel phase-out across all three scenarios and the significant increases in the renewable energy supply, the 2030 emissions will decrease by 61% relative to Australia's energy-related CO_2 emissions in 2005 under *BA* and by 75% under *NP(X)* (Figure 27). The *BA* scenario will lead to an 84% reduction relative to the 2005 level by 2035; the *NP* scenario will lead to an 88% reduction; and the *NPX* scenario to an 87% reduction, and all three scenarios will achieve complete decarbonization by 2050 (Table 20). Importantly, this demonstrates a 'real zero' approach for the energy sector, in which CO_2 emissions are fully eliminated—rather than relying on carbon offsets, carbon capture and storage, or other proposed alternatives to achieve notional reductions in emissions.

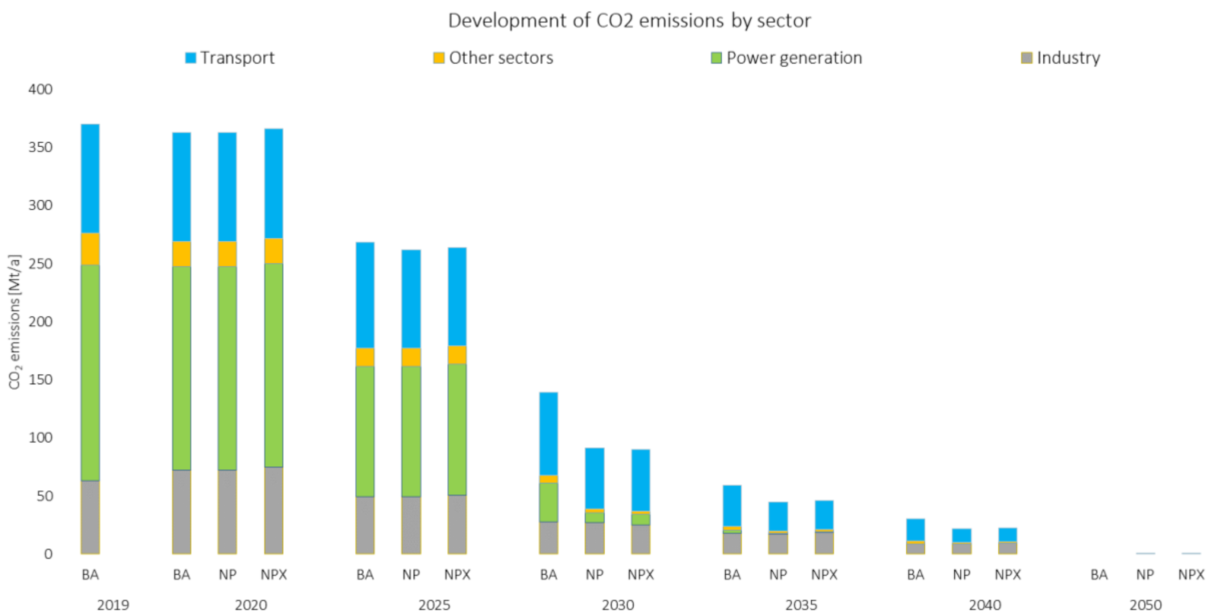


Figure 27. Development of CO_2 emissions by sector

Table 20: Australian CO_2 emissions—historical data (2005–2022 AGEIS) and projections (2023–2050) based OECM 1.5 ˚C

[Mt CO_2/year]	2005			2021			2025			2030			2035			2040			2050		
	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX	BA	NP	NPX
Electricity	197	197	197	164	164	164	113	107	108	34	13	13	3	0	1	0	0	0	0	0	0
Stationary energy	82	82	82	99	99	99	67	66	68	38	31	32	28	23	24	16	12	13	0	0	0
Transport	82	82	82	92	92	92	73	66	66	57	38	39	30	20	20	18	11	11	0	0	0
Total energy-related CO_2	361	361	361	355	355	355	253	239	242	129	82	84	61	43	45	34	23	24	0	0	0
Reduction Relative to 2005	0%	0%	0%	2%	2%	2%	30%	34%	33%	64%	75%	73%	84%	88%	88%	91%	94%	93%	100%	100%	100%

6 AUSTRALIA AND THE NEM: POWER SECTOR ANALYSIS

In previous sections, energy demand development was calculated with a detailed bottom-up analysis for 20 industry and service sectors (**Error! Reference source not found.** and **Error! Reference source not found.**), the residential (4.3.4), and transport sector (4.3.5). Based on the projected energy demand, Australia's solar and wind generation potential was assessed under two different land-use scenarios (3.3), and an energy supply concept was developed (5.1–5.5). In this section, we analyse the power sector of Australia with a focus on the security of supply and the requirements for infrastructural changes and storage.

The [R]E 24/7 model calculates the demand and supply by cluster (see Methodology section 2.4). The electricity market in Australia is under dynamic development, with rapidly increasing shares of solar photovoltaic and wind power generation. This analysis is based on various consultations with stakeholders in the Australian power sector, including an in-depth analysis of the 2022 Integrated System Plan (ISP).

The power sector analysis documented in this section assesses the implications of the rapid increases in variable renewable power generation on the power grid and the infrastructure requirements for a secure power supply in Australia. This analysis focuses on the *Necessary Ambition Pathway* (*NP*), as defined in section 4.1.2.

The technical input parameters are based on the Australian Market Operators *Integrated System Plan*, published in 2022 (AEMO ISP).

The Integrated System Plan (ISP)

The Australian Energy Market Operator (AEMO) is a joint industry (40%) and government (60%) organisation. AEMO government members are all the Australian state governments (Australian Capital Territory, New South Wales, Queensland, South Australia, Tasmania, Victoria, and Western Australia) and the Commonwealth Government. The industry members include all electricity and gas utilities and independent power producers, as well as energy traders and financial institutions with investments in the energy sector.

In the AEMO constitution, as well as Australian energy laws, such as the National Electricity Law and the National Gas Law, the roles and responsibilities of the AEMO are defined as follows (AEMO, 2020[57]):

- to maintain secure electricity and gas systems;
- to manage electricity and gas markets;
- to lead the design of Australia's future energy system.

AEMO's ISP for Australia's future energy systems was first published in 2018, the second edition was released in July 2020, and the third and most up-to-date version in June 2023 (AEMO 2022[58]), with an update published in December 2023 (AEMO 2023[59]).

[57] AEMO (2020), 2020 Integrated System Plan – For the National Electricity Market, Australian Energy Market Operator, July, https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp

[58] AEMO 2022, 2022 Integrated System Plan, June 2022, For the National Electricity Market, https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf?la=en

[59] AEMO 2023, Update to the 2022 Integrated System Plan, 15 December 2023, https://aemo.com.au/-/media/files/major-publications/isp/2022/update-to-the-2022-integrated-system-plan.pdf?la=en

6.1 KEY ASSUMPTIONS FOR THE POWER SECTOR ANALYSIS

The key technical assumptions for the OECM [R]E 24/7 modelling of the *NP* scenario are based on the AEMO ISP as the most detailed information source about the Australian NEM power grid.

6.1.1 REGIONAL BREAKDOWN: THE NATIONAL ELECTRICITY MARKET (NEM) AND AUSTRALIA

Figure 28 shows the regional break-down of the NEM calculated with the OECM-[R]E 24/7 model. The regions are largely based on the AEMO ISP regions, except that the *Gladstone Region* is merged with the *Central Queensland Region* and the *Sydney, Newcastle & Wollongong Region* is part of the *Central New South Wales Region*. Western Australia and the Northern Territory are calculated as independent regions (Figure 28). This slight simplification of the NEM regions retains the important distinctions between transmission regions and captures the transmission bottlenecks caused by interconnectors and power lines carrying over 132 kV. Transmission constraints below 132 kV are not considered. This choice of regions allows the alignment of AEMO and Government predictions of the proportional breakdown of the generation and storage technologies across regions, e.g., alignment with AEMO's *2023 Inputs Assumptions and Scenario Workbook* on regional capacity forecasts[60]. Data from WA and NT government documents were used to inform the proportions of the Australia-wide generation capacity allocated to these areas[61,62,63]. Thus, the entirety of Australia's electricity system is modelled in 11 regions:

North and Far North Queensland (NQ), Central Queensland (CQ), Southern Queensland (SQ), North NSW (NNSW), Central NSW & Sydney (CNSW), Southern NSW (SNSW), Victoria (VIC), South Australia (SA), Tasmania (TAS), Northern Territory (NT), and Western Australia (WA).

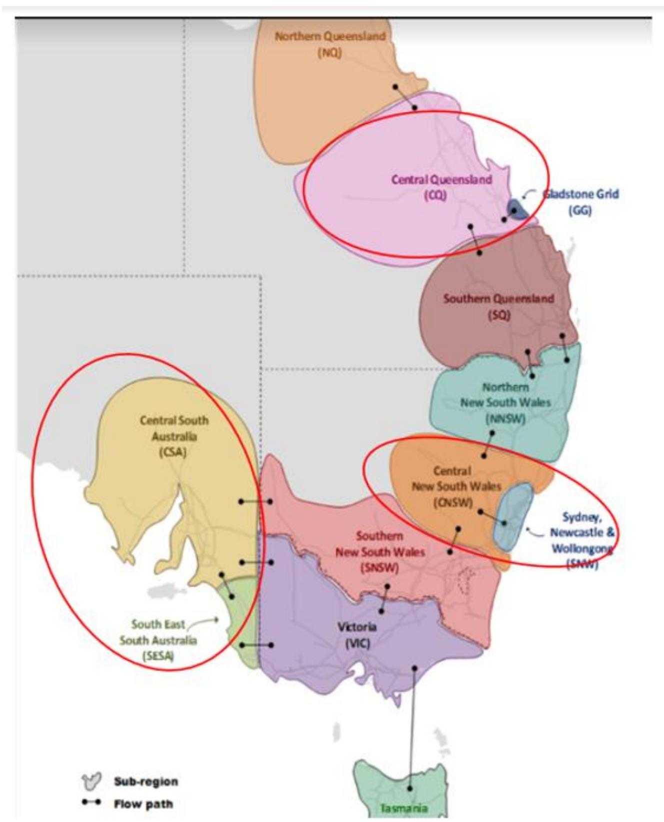


Figure 28. Power sector analysis of the National Electricity Market (NEM)—regional breakdown[64]

[60] https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp/current-inputs-assumptions-and-scenarios
[61] https://www.wa.gov.au/government/document-collections/whole-of-system-plan
[62] https://territoryrenewableenergy.nt.gov.au/strategies-and-plans/electricity-system-plans#Darwin-Katherine-electricity-system-plan
[63] Alice Springs Future Grid—Roadmap to 2030 (CSIRO Public Release Session) - https://www.youtube.com/watch?v=fuSztZnFj0w
[64] Ibid. (https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp/current-inputs-assumptions-and-scenarios)

6.1.2 Scenario design for power system analysis

As discussed in earlier chapters, the *Necessary Ambition Pathway* (*NP*) is an ambitious net-zero pathway for Australia based on accelerating Australia's current decarbonization efforts. The power sector analysis of the *NP* analyses the predicted energy system required under this pathway to provide insights into the supply and demand balance under the *NP* scenario in 2030. Under the Australian Electricity Market Commission's (AEMC) *Reliability Standard*[65], there are strict regulations on how much forecast unserved energy (supply gap) can occur, with "the maximum expected unserved energy in a region of 0.002 per cent of the total energy demanded in that region for a given financial year". Therefore, AEMO, government, and policy makers must ensure that there is adequate forecasted supply to meet demand. Because the forecasted power supply in 2030 is based on the accelerated decarbonization efforts required to meet the Paris Agreement climate targets, the supply forecast must be sufficient to meet demand—and will particularly affect Australia's electricity regulations and possible changes that might be required.

Because there is limited time before 2030, the large build-up of additional storage beyond the existing 2030 forecasts, which is required to meet supply gaps, is challenging and may require further changes in policy and the market framework. Therefore, the power system analysis undertaken in this chapter should be viewed as a modelling exercise that assesses the energy balance with a high share of variable solar and wind power generation across Australia under possible 2030 storage levels, and as a critical review of the forecasts of storage capacities.

Table 21 provides an overview of the narratives of the four different generation and storage scenarios (DP_DS, DP_CS, CP_CS, and CP_DS). The effects of decentralised versus centralised installations is tested, rather than the overall capacity changes. The aim of this analysis is to evaluate whether centralised or decentralised generation and storage better favours the power system, or if a combination of centralised and decentralised capacities offer benefits. It provides an overview of the narratives of the four different generation and storage scenarios. The underlying assumptions about generation capacity do not change across the generation scenarios—only the proportions of roof-top solar vary. In the centralised generation scenario, utility-scale solar will reach its 2030 potential according to AEMO's *Green Energy Export* scenario[66], so roof-top photovoltaic will be ~50% of total solar, whereas under the decentralised generation scenarios, roof-top photovoltaic will retain its current proportion of total solar (~62%), and therefore, total decentralised photovoltaic will align with the value expected in 2035 under the *Step Change* scenario[67].

Table 21: Scenario design for power system analysis

		Distribution of power generation	
		Greater decentralised generation	Greater centralised generation
Distribution of storage	Greater decentralised storage	Distributed power generation, distributed storage (DP_DP) ● Most of the shortfall in supply between what is planned and what is needed to meet the generation target will be met with residential and commercial roof-top solar. ● Co-ordinated and decentralised storage will make a strong contribution to our storage needs ● No more additional pumped ordinated meeting hydro in Australia by 2030 beyond what is already planned. • Participation in demand-side management and electric vehicle battery charging schemes.	Centralised power generation, decentralised storage (CP_DS) ● The bulk of renewable energy generation will be supplied by utility-scale solar, onshore wind and offshore wind in locations that guarantee the highest capacity factors. ● Co-ordinated and uncoordinated decentralised storage makes a strong contribution to storage needs. ● No more additional pumped hydro in Australia by 2030 beyond what is already planned.
	Greater centralized storage	Decentralised power generation, centralised storage (DP_CS) ● Most of the shortfall in supply between what is planned and what is needed to meet our generation target will be met by residential and commercial roof-top solar. ● Storage needs will primarily be met with a combination of pumped hydro, utility-scale batteries, and smaller contributions from co-ordinated and uncoordinated decentralised storage. ● Pumped hydro is implemented as scheduled, with potentially more built if required.	Centralised power generation, centralised storage (CP_CS) ● The bulk of renewable energy generation is supplied by utility-scale solar, onshore wind and offshore wind in locations that guarantee the highest capacity factors. ● New medium-scale pumped hydro contributes strongly to meeting storage needs, alongside utility-scale batteries. ● Decentralised storage systems will not grow fast enough to take over significant power-system-relevant storage services.

[65] AEMC Reliability Panel, The Reliability Standard,
[66] https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/a3-renewable-energy-zones.pdf
[67] 2023 IASR workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

The values for storage will vary according to the scenario being tested, as described in Table 22. The aim of this analysis is to evaluate whether centralised or decentralised generation and storage is more favourable for the power system, or if a combination of centralised and decentralised capacities offers benefits.

Table 22: Storage assumptions for centralised and decentralised scenarios

Storage Type	Centralised Scenario [GW]	Decentralised Scenario [GW]
Distributed Batteries	11.60[68]	25.49[69]
Utility-scale Batteries	26.83[70]	16.84[71]
Pumped Hydro	8.44[72]	4.28[73]
Total	46.87	46.61

Note: Although values based on AEMO's *2023 IASR Assumption Workbook*, they do not match the Excel file because these values were scaled to Australia-wide potential.

6.1.3 Interconnector Limits

The power-carrying capacity of a power line varies over time and is dependent upon several parameters, including the outside temperature, the utilisation of the line, the frequency, the physical characteristics of the line, the length of the line, and the power generation capacity connected to the line.

Because the modelling year was set to 2030 across the power sector analysis scenarios, a methodology was developed for linking the *NP* generation capacities to the regional interconnection limits, such that the interconnection limits would be appropriate under all scenarios when the input parameters were changed—while leaving sufficient flexibility in the model to easily allow for different transmission scenarios if required. The following steps were used to model the regional interconnection limits:

- Development of a table of forecasted 2030 interconnection limits according to the AEMO documentation.[74]
- Development of tables of the forecasted regional breakdown of generation capacity under the *NP* scenario.
- Use of steps 1 & 2 to calculate the percentages of interconnection relative to the regional generation capacities.

Using these three steps, the percentages for different scenarios can easily be modified if required, and used for the analysis of different years if required. The calculations undertaken for the different scenarios indicated a relatively constant percentage value based on the underlying assumptions, so the percentages were held relatively constant across the 2020–2030 period. The details of the interconnection limits are outlined below.

The inter-regional exchange of capacity is a function of load development and generation capacity in all nine NEM regions. The [R]E 24/7 model distributes generation capacity according to the regional load and the conditions for power generation. The locations of gas power plants are fixed and the installation of new capacities will depend on the possibility of fuel supply. Renewable power generation is more modular and can be distributed according to the load in the first place. However, as the share of renewable electricity increases, and the space available for utility-scale solar and onshore wind generation facilities and the availability and quality of local resources (such as solar radiation and/or wind speed) decrease, power might be generated further from its point of consumption. This will require more transmission capacity to exchange generation capacities between the nine NEM region and the two independent grids of Australia analysed here.

The current assumed interconnection limits between the nine analysed regions are shown in Table 23, and the projections for 2025 (Table 24) and 2030 (Table 25Table 26) are based on those values.

68 In line with forecasted value 2030 under *Step Change*, 2023 IASR workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

69 In line with 2035 *Step Change*, *2023 IASR Workbook*, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

70 2030 Forecast + Announced *and* Proposed projects from Renew Economy Map, https://reneweconomy.com.au/big-battery-storage-map-of-australia/

71 2030 Forecast + Announced projects from Renew Economy Map, https://reneweconomy.com.au/big-battery-storage-map-of-australia/

72 2030 Forecast + Battery of the Nation + NSW projects which could be supported through policy/storage target, https://www.energy.nsw.gov.au/nsw-plans-and-progress/major-state-projects/shift-renewables/emerging-energy-program

73 2030 Forecast value, *2023 IASR Workbook*, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

74 https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-transmission-expansion-options-report.pdf

Table 23: Interconnector capacities of the NEM—assumptions for [R]E24/7 analysis and sources

Cut-Set	Current max. capacity (MW)	Max. capacity to be built by 2030	Max. capacity considered in ISP—option short lead time	Max. capacity considered in ISP—option medium/long lead time (max. capacity option)	Notes/source
NQ–CQ	1200			5384	Peak demand value, can be up to 1400 MW in winter. [75]
CQ–GG	700		3300		Summer maximum, can be up to 1200 MW in winter.[15]
CQ–SQ	2100			5200	Five augmentation options outlined in document, including one that removes all transmission constraints[15].
SQ–NNSW	685			3685	Peak demand from NSW to QLD up to 745 MW and up to 1200 MW in the opposite direction[15].
CNSW–NNSW	910			4510	Five augmentation options outlined in document[15].
CNSW–SNW	2540			11140	As outlined on page 57 of the reference document, northern flow assumed with 4,500 MW capacity[15].
CNSW–SNSW	2320		4520	8320	Source[15]
SNSW–CSA	0	800			Source[15]
SNSW–VIC	400	2069			Max. loads assumed with 800 MW and an average of 400 MW during daytime[15].
VIC–TAS	462	1212	2174		Source[15]
VIC–SESA	650			3650	Source[15]
VIC–CSA	220				Source[76]
SESA–CSA	650			3650	

In our analysis, an increase in the necessary inter-regional exchange of capacity, in addition to the increase in grid capacity within the regions as demand increases, will start between 2025 and 2030. This will be particularly true of those regions with a high population density, high demand, and high solar and wind generation potential. Our modelling assumes that between 2025 and 2030, the following interconnection changes will occur in line with AEMO's expected transmission expansion[77]:

1. Victoria–South New South Wales: increase from 400 MW to 2069 MW
2. Victoria–Tasmania: increase from 462 MW to 1212 MW
3. Southern New South Wales–Central South Australia: new connection with 800 MW capacity

Table 24: Interconnector capacities of the NEM (in MW) in 2023

CURRENT (MW)	NQ	CQ	GG	SQ	NNSW	CNSW	SNW	SNSW	VIC	TAS	SESA	CSA
NQ		1200	0	0	0	0	0	0	0	0	0	0
CQ			700	2100	0	0	0	0	0	0	0	0
GG				0	0	0	0	0	0	0	0	0
SQ					685	0	0	0	0	0	0	0
NNSW						910	0	0	0	0	0	0
CNSW							2540	2320	0	0	0	0
SNW								0	0	0	0	0
SNSW									400	0	0	0
VIC										462	650	220
TAS											0	0
SESA												650
CSA												

The development of the generation and storage capacities and the acronyms for the regions are shown in **Error! Not a valid bookmark self-reference.** The minor variations between scenarios are due to variations in the regional capacities for utility-scale and roof-top solar and the locations of centralised and decentralised storage.

[75] https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-transmission-expansion-options-report.pdf

[76] https://www.apa.com.au/our-services/other-energy-services/electricity-interconnectors/murraylink/#:~:text=Murraylink%20has%20capacity%20to%20deliver,AC%20network%20in%20either%20state.&text=Murraylink%20is%20a%20single%20DC,to%20Berri%20in%20South%20Australia

[77] https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-transmission-expansion-options-report.pdf

Table 25: Generation and storage capacities by NEM regions and scenarios

GENERATION AND STORAGE CAPACITIES PER REGION		[GW]	CP_CS	CP_DS	DP_CS	CP_CS
Region	Code	2020	2030	2030	2030	2030
Northern Queensland	NQ	2.3	9.6	9.7	9.5	9.6
Central Queensland	CQ	3.3	10.0	9.6	10.6	10.1
Southern Queensland	SQ	9.9	34.2	35.6	33.1	34.5
Northern New South Wales	NNSW	2.2	11.8	11.2	12.0	11.5
Central New South Wales	CNSW	10.3	41.0	40.8	41.8	41.6
Sydney, Newcastle, Wollongong	SNSW	6.0	19.3	18.6	21.4	20.7
Southern New South Wales	VIC	14.8	46.2	46.9	45.2	45.9
Victoria	SA	4.9	21.1	20.1	21.1	20.0
Tasmania	TAS	2.7	9.0	8.2	8.8	8.0
Total NEM		56.4	202.2	200.6	203.6	202.0

Table 26: Interconnector capacities of the NEM (in MW) calculated for 2030 under the *Necessary Ambition Pathway*

2030 (MW)	NQ	CQ	GG	SQ	NNSW	CNSW	SNW	SNSW	VIC	TAS	SESA	CSA
NQ		1200	0	0	0	0	0	0	0	0	0	0
CQ			700	2100	0	0	0	0	0	0	0	0
GG				0	0	0	0	0	0	0	0	0
SQ					685	0	0	0	0	0	0	0
NNSW						910	0	0	0	0	0	0
CNSW							2540	2320	0	0	0	0
SNW								0	0	0	0	0
SNSW									**2069**	0	0	**800**
VIC										**1212**	650	220
TAS											0	0
SESA												650
CSA												

6.2 AUSTRALIA: DEVELOPMENT OF POWER PLANT CAPACITIES

The overall power generation capacity will increase significantly in power systems with high shares of solar photovoltaic and onshore wind power generation due to the lower average capacity factors of the technologies.

Under the ***Necessary Ambition Pathway*** (*NP*), solar photovoltaic capacity will grow fastest, from 36 GW in 2023 to 79 GW in 2030. The second largest total capacity will come from onshore wind, with an increase from 10 GW in 2023 to 69 GW in 2030. Offshore wind is also expected to enter the Australian power grid just before 2030 as a new renewable electricity generation with high 'base-load-like' capacity factors. Hydro power and bio-energy are projected to grow only moderately and according to the current project development pipeline, with an additional 2 GW of hydro power and 1 GW of bio-energy until 2030.

Table 27: Australia—average annual changes in installed power plant capacity

		2020–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050
Total change in generation capacity	[GW/yr]	23	68	48	24	15	9
Fossil	[GW/yr]	−10	−20	−13	0	0	0
Hard Coal	[GW/yr]	−1	−13	0	0	0	0
Lignite	[GW/yr]	−12	−3	0	0	0	0
Gas	[GW/yr]	−1	0	−13	0	0	0
Oil & Diesel	[GW/yr]	0	0	0	0	0	0
Diesel	[GW/yr]	0	0	0	0	0	0
Renewables	[GW/yr]	33	87	60	25	15	9
Hydro	[GW/yr]	1	0	0	0	0	1
Wind	[GW/yr]	9	51	19	7	9	5
(Offshore wind)	[GW/yr]	0	5	4	5	3	3
Photovoltaic	[GW/yr]	24	34	40	16	5	2
Biomass	[GW/yr]	0	1	0	0	0	0
Geothermal	[GW/yr]	1	1	1	1	1	1
Concentrated Solar Power	[GW/yr]	0	0	0	0	0	0
Variable solar and wind	[GW/yr]	33	86	59	24	14	7

The annual installation rates for solar photovoltaic installations must increase by around 12 GW between 2024 and 2030 under *NP*, whereas onshore wind must increase from around 1.5 GW per year to around 8 GW per year in the same time frame. Furthermore, offshore wind must come into the power system before 2030, with annual capacity additions of 1 GW until 2050.

Solar photovoltaic is the key renewable energy technology for Australia, but diversity is required to keep the storage demand low and the security of supply high. All renewable power technologies—on- and offshore wind, geothermal power, and concentrated solar power plants—are important for the successful decarbonization of Australia's power sector.

6.3 AUSTRALIA: REGIONAL UTILISATION OF POWER GENERATION CAPACITIES

The division of Australia into 11 sub-regions reflects the current structure of the Australian power market. It is assumed that the sub-regions of the NEM will be interconnected with increasing interconnector capacities over time, whereas Western Australia and the Northern Territory will remain independent power markets.

Table 28 shows the system-relevant technical characteristics of the various generation types. Future power systems must be structured according to the generation characteristics of each technology to maximize their synergy. Power utilities can encourage sector coupling—between industry, transport, and heating—to utilise various demand-side management possibilities and to maximize the cross-benefits.

The integration of large shares of variable power generation will require a more flexible market framework. Power plants requiring high capacity factors because of their technical limitations regarding flexibility ('base-load power plants') will not be desirable to future power system operators. Therefore, capacity factors will become more of a technical characteristic than an economic necessity. Flexibility is a commodity that will increase in value over time.

Table 29 shows the regional distribution of power generation and storage capacities in percentages of the total installations in Australia. It is assumed that shares will remain the same in 2025 and 2030.

Table 28: System-relevant generation types

Generation type	Fuel	Technology
Limited dispatchable	Fossil, uranium	Coal, brown coal/lignite, (including co-generation)
	Renewable	Hydro power, bio-energy and synthetic fuels, geothermal, concentrated solar power (including co-generation)
Dispatchable	Fossil	Gas, oil, diesel (including co-generation)
		Storage systems: batteries, pumped hydro power plants, Hydrogen- and synthetic-fuelled power and co-generation plants
	Renewable	Bio-energy, hydro, hydrogen- and synthetic-fuelled power and co-generation plants
Variable	Renewable	Solar photovoltaic, onshore and offshore wind

Table 29: Regional shares of national power generation and storage capacities

Regional shares of national capacities [%]		National Electricity Market									Independent Power Grids	
		NQ	CQ	SQ	NNSW	CNSW	SNSW	Vic	SA	TAS	NT	WA
Gas	Limited Dispatchable	2%	0%	19%	0%	17%	5%	17%	11%	3%	9%	19%
Lignite	Limited Dispatchable	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%
Coal	Limited Dispatchable	0%	19%	28%	0%	45%	0%	0%	0%	0%	0%	9%
Oil & Diesel	Limited Dispatchable	57%	0%	0%	0%	0%	0%	0%	14%	0%	11%	18%
Photovoltaic—roof-top	Variable Renewables	3%	3%	19%	4%	21%	4%	22%	9%	1%	1%	12%
Photovoltaic—utility-scale	Variable Renewables	3%	6%	17%	5%	23%	12%	18%	8%	1%	1%	7%
Wind—onshore	Variable Renewables	8%	5%	14%	8%	17%	6%	22%	10%	7%	0%	3%
Wind—offshore	Variable Renewables	0%	0%	0%	0%	0%	0%	42%	0%	0%	0%	58%
Concentrated solar power	Variable Renewables	0%	0%	0%	0%	12%	0%	0%	88%	0%	0%	0%
Battery-distributed	Distributed Storage	3%	3%	15%	5%	23%	5%	23%	11%	1%	0%	11%
Electric vehicle—V2G	Distributed Storage	2%	2%	16%	3%	26%	5%	25%	7%	2%	1%	11%
Hydro Power	Dispatch Generation	2%	0%	7%	0%	3%	30%	29%	0%	28%	0%	0%
Geothermal	Dispatch Generation	1%	77%	9%	0%	1%	0%	4%	7%	0%	0%	0%
Bio-energy	Dispatch Generation	14%	29%	17%	2%	0%	3%	0%	2%	0%	0%	33%
Gas—additional	Dispatch Generation	2%	0%	19%	0%	17%	5%	17%	11%	3%	9%	19%
Lignite—additional	Dispatch Generation	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%
Coal—additional	Dispatch Generation	0%	19%	28%	0%	45%	0%	0%	0%	0%	0%	9%
Ocean	Dispatch Generation	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%
Oil & Diesel—additional	Dispatch Generation	57%	0%	0%	0%	0%	0%	0%	14%	0%	11%	18%
Co-Gen Bio	Dispatch Generation	0%	25%	16%	31%	0%	0%	28%	0%	0%	0%	0%
Co-Gen Geothermal	Dispatch Generation	1%	77%	9%	0%	1%	0%	4%	7%	0%	0%	0%
Co-Gen Gas	Dispatch Generation	0%	0%	0%	5%	8%	45%	3%	0%	1%	0%	37%
Co-Gen Coal	Dispatch Generation	0%	19%	28%	0%	45%	0%	0%	0%	0%	0%	9%
Co-Gen Lignite	Dispatch Generation	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%
Co-Gen Oil	Dispatch Generation	57%	0%	0%	0%	0%	0%	0%	14%	0%	11%	18%
Co-Gen Fuel Cell	Dispatch Generation	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%
Fuel Cell	Dispatch Generation	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%	9%
Battery—utility-scale	Storage	2%	3%	12%	6%	21%	10%	25%	15%	1%	1%	3%
Hydro Pump—storage	Storage	3%	9%	28%	7%	17%	24%	0%	3%	9%	0%	0%
H_2	Storage	0%	0%	50%	0%	0%	0%	0%	50%	0%	0%	0%

Table 30 shows the installed capacities for all power generation and storage technologies included in this analysis. The distributions are based on current regional installed capacities, regional solar and wind potentials, and the regional electricity demand. The further breakdown of decentralised (roof-top) and utility-scale solar photovoltaic and storage technologies are the only values that will change with the different scenario narratives, as defined in Table 21.

The significant regional differences in coal, gas, and oil power generation and hydro power are based on current and projected regional installations. Table 30 and Table 32 show the regional distribution of the assumed capacities under the *Necessary Ambition Pathway* for 2025 and 2030.

Table 30: Australia—regional capacities (in GW) in 2025 under the *NP* scenario

2025—Regional Capacities [GW]		National Electricity Market										
		NQ	CQ	SQ	NNSW	CNSW	SNSW	Vic	SA	TAS	NEM Total	Australia Total
Gas	Baseload Generation	0.2	0.0	2.4	0.0	2.2	0.6	2.2	1.5	0.4	9.5	13.2
Lignite	Baseload Generation	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	3.3	3.3
Coal	Baseload Generation	0.0	3.3	4.9	0.0	7.7	0.0	0.0	0.0	0.0	15.9	17.4
Oil & Diesel	Baseload Generation	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.5	0.7
		Centralised Generation scenario										
Photovoltaic—roof-top	Variable Renewables	0.6	0.7	4.2	0.9	4.7	1.0	5.0	2.0	0.3	19.5	22.4
Photovoltaic—utility-scale	Variable Renewables	0.7	1.4	3.7	1.1	5.1	2.8	4.0	1.7	0.2	20.6	22.5
		Decentralised Generation scenario										
Photovoltaic—roof-top	Variable Renewables	0.8	0.9	5.3	1.1	5.9	1.2	6.2	2.5	0.4	24.3	27.9
Photovoltaic—utility-scale	Variable Renewables	0.5	1.5	2.0	1.0	4.4	3.7	2.2	1.2	0.0	16.6	16.9
Wind—onshore	Variable Renewables	1.7	1.0	3.0	1.8	3.7	1.4	4.7	2.2	1.4	20.9	21.5
Wind—offshore	Variable Renewables	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Concentrated Solar Power	Variable Renewables	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Battery—distributed	Distributed	0.3	0.3	1.8	0.6	2.7	0.5	2.7	1.3	0.2	10.3	11.6
Electric Vehicle—V2G	Distributed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro Power	Dispatch Generation	0.1	0.0	0.6	0.0	0.2	2.2	2.2	0.0	2.1	7.5	7.5
Geothermal	Dispatch Generation	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4
Bio-energy	Dispatch Generation	0.2	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.1
Ocean	Dispatch Generation	0.1	0.0	0.6	0.0	0.2	2.2	2.2	0.0	2.1	7.5	7.5
Co-Gen Bio	Dispatch Generation	0.0	0.1	0.1	0.2	0.0	0.0	0.2	0.0	0.0	0.6	0.6
Co-Gen Geothermal	Dispatch Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Gas	Dispatch Generation	0.0	0.0	0.0	0.1	0.2	1.1	0.1	0.0	0.0	1.5	2.4
Co-Gen Coal	Dispatch Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Lignite	Dispatch Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Oil	Dispatch Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Fuel Cell	Dispatch Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Cell	Dispatch Generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Battery—utility-scale	Storage	0.4	0.5	1.9	1.0	3.5	1.7	4.1	2.5	0.2	15.8	16.4
Hydro Pump storage	Storage	0.2	0.6	1.8	0.5	1.1	1.5	0.0	0.2	0.6	6.4	6.4
H_2	Storage	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.4	0.4
Total		4.41	8.27	23.00	5.62	29.35	12.75	25.96	10.74	5.05	125	138

Over time, the proportion of variable power generation will increase (Table 32) under all scenarios. The regions with large utility-scale solar power plants and offshore wind capacities will have the highest shares of variable power generation in the grid and will require greater interconnection with neighbouring regions than those with smaller shares of variable electricity.

Difference between '*centralised*' and '*decentralised*' generation scenarios

The Australia-wide breakdown of decentralised roof-top photovoltaic and centralised utility-scale photovoltaic as a percentage of all solar photovoltaic across Australia (the NEM plus Western Australia and the Northern Territory) varies in the centralised and decentralised generation scenarios:

- *Centralised Power Generation* (CP) scenario: 49.9% roof-top photovoltaic and 50.1% utility-scale photovoltaic
- *Decentralised Power Generation* (DP) scenario: 62.3% roof-top photovoltaic and 37.7% utility-scale photovoltaic

This breakdown assumes that the total solar capacity in 2030 will stay the same across both scenarios. In the centralised generation scenario, utility-scale solar will reach its 2030 potential according to AEMO's *Green Energy Export* scenario[78] and thus roof-top photovoltaic will be ~50% of the total solar capacity, whereas in the distributed generation scenarios, roof-top photovoltaic will retain its current proportion of ~62% of total solar. Therefore, total decentralised photovoltaic is consistent with the value expected in 2035 under the *Step Change* scenario[79,80]. The total capacity in the *NP* scenario is higher than the value forecasted in the AEMO *Step Change* scenario, by ~25% (when scaled to Australia-wide values). This accounts for the facts that the *NP* scenario will have a higher annual demand, and that in a grid with higher shares of variable renewable capacity and less dispatchable power, some level of overbuilding is required.

- Centralised scenario (CP): Utility-scale solar will be 100% of forecast value based on the 2030 *Green Energy Export* scenario, roof-top photovoltaic will be 105% of the Australia-wide forecast based on the *Step Change* scenario.
- Decentralised scenario (DP): Utility will be 75% of forecast value based on the 2030 *Green Energy Export* scenario, roof-top photovoltaic will be 100% of forecast value based on the 2035 *Step Change* scenario (which is 132% of the 2030 forecast under the *Step Change* scenario).

Whereas the overall Australian solar photovoltaic capacity will remain the same in the CP and DP scenarios, the regional distribution is assumed to change in order to better differentiate the different regional distributions of decentralised and centralised generation for the analysis of the power grid and storage capacities. Table 31 shows the regional distribution of utility-scale solar photovoltaic under the centralised and decentralised power generation scenarios.

Table 31: Regional distribution of utility-scale solar photovoltaic under the CP and DP scenarios

	NQ	CQ	SQ	NNSW	CNSW	SNSW	Vic	SA	Tas	NT	WA
CP case	3%	6%	17%	5%	23%	12%	18%	8%	1%	1%	7%
DP case	3%	9%	12%	6%	26%	22%	13%	7%	0%	1%	1%

[78] https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/a3-renewable-energy-zones.pdf

[79] 2023 IASR Workbook, https://aemo.com.au/en/consultations/current-and-closed-consultations/2023-inputs-assumptions-and-scenarios-consultation

[80] Forecasts of photovoltaic uptake based on AEMO, CSIRO, and Green Energy Markets data. Refer to '2023 IASR reference materials' at: https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp/current-inputs-assumptions-and-scenarios

Table 32: Australia—regional capacities (in GW) in 2030 under the *NP* scenario

2030—Regional Capacities [GW]		National Electricity Market NQ	CQ	SQ	NNSW	CNSW	SNSW	VIC	SA	TAS	NEM Total	Australia Total
Gas	Baseload Generatio	0.2	0.0	2.4	0.0	2.2	0.6	2.2	1.5	0.4	9.5	13.2
Lignite		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil & Diesel		0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.5
Centralised Generation scenario	Variable Renewables											
Photovoltaic—roof-top		1.1	1.2	7.4	1.6	8.3	1.7	8.8	3.6	0.6	34.3	39.3
Photovoltaic—utility-scale		1.2	2.4	6.5	1.9	9.0	4.9	7.0	3.0	0.4	36.3	39.5
Decentralised Generation scenario												
Photovoltaic—roof-top		1.3	1.5	9.3	2.0	10.4	2.1	11.0	4.5	0.7	42.8	49.1
Photovoltaic—utility-scale		0.9	2.7	3.6	1.8	7.7	6.5	3.9	2.1	0.0	29.1	29.7
Wind—onshore		5.0	2.9	8.9	5.2	11.0	4.0	13.9	6.5	4.3	61.7	63.4
Wind—offshore		0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	2.2	5.3
Concentrated Solar Power		0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.5	0.0	0.6	0.6
Battery—distributed	Distr ibut	0.3	0.3	1.8	0.6	2.7	0.5	2.7	1.3	0.2	10.3	11.6
Electric Vehicle V2G		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydropower	Dispatch Generation	0.1	0.0	0.6	0.0	0.2	2.2	2.2	0.0	2.1	7.5	7.5
Geothermal		0.0	1.2	0.1	0.0	0.0	0.0	0.1	0.1	0.0	1.5	1.5
Bio-energy		0.3	0.6	0.3	0.0	0.0	0.1	0.0	0.0	0.0	1.3	1.9
Ocean		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.6
Co-Gen Bio		0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.2	0.2
Co-Gen Geothermal		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Gas		0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.3
Co-Gen Coal		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Lignite		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Oil		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Co-Gen Fuel Cell		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Cell		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2	1.5
Battery—utility-scale	Storag e	0.6	0.8	3.1	1.6	5.7	2.8	6.7	4.1	0.3	25.7	26.8
Hydro Pump storage		0.3	0.8	2.4	0.6	1.4	2.0	0.0	0.3	0.8	8.4	8.4
H_2		0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.4	0.4

6.4 AUSTRALIA: DEVELOPMENT OF LOAD, GENERATION, AND RESIDUAL LOAD

Table 33 shows the maximum, minimum, and average loads (in GW) for the 11 calculated regions for the year 2020. The NEM consists of nine regions plus the two unconnected regions of Western Australia and the Northern Territory. These loads have been calculated on the basis of the available statistics and with the calculated synthetic load curves generated by the [R]E 24/7 model (see also Section 3).

The recalculation of the load curves for 2020 allows the calibration of the model. The calculated values deviate from the published historical data by ±10%.

Table 33: Australia and the NEM—calculated maximum, minimum, and average loads (in GW)

	2020		
Region Names	Max. Demand [GW]	Min. Demand [GW]	Average Demand [GW]
North and Far North Queensland	0.574	0.322	0.393
Central Queensland	0.654	0.375	0.459
Southern Queensland	4.127	2.215	2.827
North NSW	0.764	0.42	0.531
Central NSW & Sydney	8.372	4.748	6.097
Southern NSW	1.41	0.789	1.123
Victoria	7.252	3.972	5.649
South Australia	2.019	1.11	1.526
Tasmania	0.593	0.32	0.479
NEM-Australia	25.765	14.271	19.084
Northern Territory	0.267	0.146	0.188
Western Australia	3.133	1.729	2.248
Australia	29.165	16.146	21.52

Based on the recalculated historical loads and generation, the maximum load (= demand), power generation, and residual load have been calculated for 2025 and 2030 with the projected electricity demand and supply development under the '*Necessary Ambition*' scenario (see 4.1.2).

Table 34 shows the results under the *centralise*d and *decentralised* generation pathways. The calculated maximum loads under both scenarios lead to identical results. The actual power demand is not influenced by the different distributions of generation.

However, the calculated values for maximum generation showed minor differences between the decentralised and centralised generation pathways—even though identical total installed capacities were assumed. The difference can be explained by the regional variations in the solar and wind power generation shares and the available interconnections and storage capacities, which influence the curtailment rate—the forced shut-down of generation capacity when there is no local demand and the surplus electricity can neither be stored nor transported to points of demand.

The residual load describes the difference between the required load (= demand) and the available supply. The higher the share of decentralised power generation—roof-top photovoltaic—the lower is the residual load. Solar photovoltaic supplies the residential power demand close to the point of demand. However, the differences are relatively small and additional research that includes different voltage levels is required. It is worth noting that no differences in the maximum residual load could be calculated in the two regions that are not connected to the NEM.

Table 34: Projections of load, generation, and residual load until 2030

Development of Load and Generation		Necessary Ambition Pathway Centralised				Necessary Ambition Pathway Decentralised			
		Max. Demand [GW/h]	Max. Generation [GW/h]	Max. Residual Load [GW/h]	Peak Load Increase [%]	Max. Demand [GW/h]	Max. Generation [GW/h]	Max. Residual Load [GW/h]	Peak Load Increase [%]
North and Far North Queensland	2020	0.76	1.19	0.63	100%	0.76	1.18	0.63	100%
	2025	0.84	2.05	0.84	110%	0.84	2.05	0.83	110%
	2030	1.12	4.25	1.69	148%	1.12	4.24	1.71	148%
Central Queensland	2020	0.87	2.40	0.77	100%	0.87	2.40	0.76	100%
	2025	0.96	3.22	0.97	110%	0.96	3.36	0.97	110%
	2030	1.28	4.16	1.47	147%	1.28	4.96	2.50	147%
Southern Queensland	2020	5.37	5.58	5.09	100%	5.37	5.45	5.11	100%
	2025	5.94	10.49	5.33	111%	5.94	10.17	5.36	111%
	2030	7.96	16.29	7.16	148%	7.96	16.05	7.16	148%
North NSW	2020	0.69	1.45	0.64	100%	0.69	1.51	0.64	100%
	2025	0.77	2.77	0.67	111%	0.77	2.79	0.67	111%
	2030	1.03	5.63	0.92	150%	1.03	5.65	0.92	150%
Central NSW & Sydney	2020	7.49	8.60	7.42	100%	7.49	8.60	7.42	100%
	2025	8.34	12.73	8.25	111%	8.34	12.92	8.25	111%
	2030	11.16	19.88	11.06	149%	11.16	19.88	11.06	149%
Southern NSW	2020	1.26	2.08	1.25	100%	1.26	2.55	1.25	100%
	2025	1.41	4.35	1.39	111%	1.41	4.68	1.39	111%
	2030	1.88	7.84	1.87	149%	1.88	9.12	1.87	149%
Victoria	2020	6.40	9.61	6.37	100%	6.40	9.51	6.37	100%
	2025	7.15	11.47	7.08	112%	7.15	11.10	7.08	112%
	2030	9.59	18.85	9.42	150%	9.59	18.67	9.42	150%
South Australia	2020	1.73	2.32	1.70	100%	1.73	2.32	1.70	100%
	2025	1.93	4.60	1.90	112%	1.93	4.60	1.90	112%
	2030	2.59	9.10	2.90	150%	2.59	9.00	2.91	150%
Tasmania	2020	1.11	1.11	1.59	100%	1.11	1.11	1.49	100%
	2025	1.22	1.82	1.35	110%	1.22	1.73	1.37	110%
	2030	1.62	4.43	1.91	146%	1.62	4.36	2.30	146%
Australia—NEM	2020	25.68	34.34	25.46	100%	25.68	34.63	25.38	100%
	2025	28.55	53.49	27.76	111%	28.55	53.39	27.81	111%
	2030	38.23	90.43	38.39	149%	38.23	91.93	39.84	149%
Northern Territory	2020	0.35	0.35	0.35	100%	0.35	0.35	0.35	100%
	2025	0.39	0.39	0.37	110%	0.39	0.39	0.37	110%
	2030	0.52	0.55	0.49	147%	0.52	0.53	0.49	147%
Western Australia	2020	3.13	3.13	3.08	100%	3.13	3.13	3.08	100%
	2025	3.48	4.19	3.38	111%	3.48	3.83	3.38	111%
	2030	4.66	6.62	4.28	149%	4.66	6.62	4.29	149%
Australia	2020	29.17	37.83	28.89	100%	29.17	38.12	28.80	100%
	2025	32.43	58.07	31.51	111%	32.43	57.62	31.57	111%
	2030	43.41	97.60	43.16	149%	43.41	99.09	44.63	149%

Figure 29 shows the same data as Table 34, but focuses on the centralised generation and centralised storage scenario. The graphs visualise the increasing differences between the maximum generation and the maximum load (demand). These differences are due to the higher installed capacities for systems with high shares of solar photovoltaic and wind because their capacity factors are lower than those of fuel-based and dispatchable-generation-based systems.

The difference between supply and demand must be transported to other regions with higher demand, stored, or curtailed. Demand-side management can also reduce the gap between demand and supply over a certain time period. Therefore, a renewable power generation system requires a different network operation concept than those based on dispatchable generation. The overall system must be far more flexible, both in terms of the demand and of generation management.

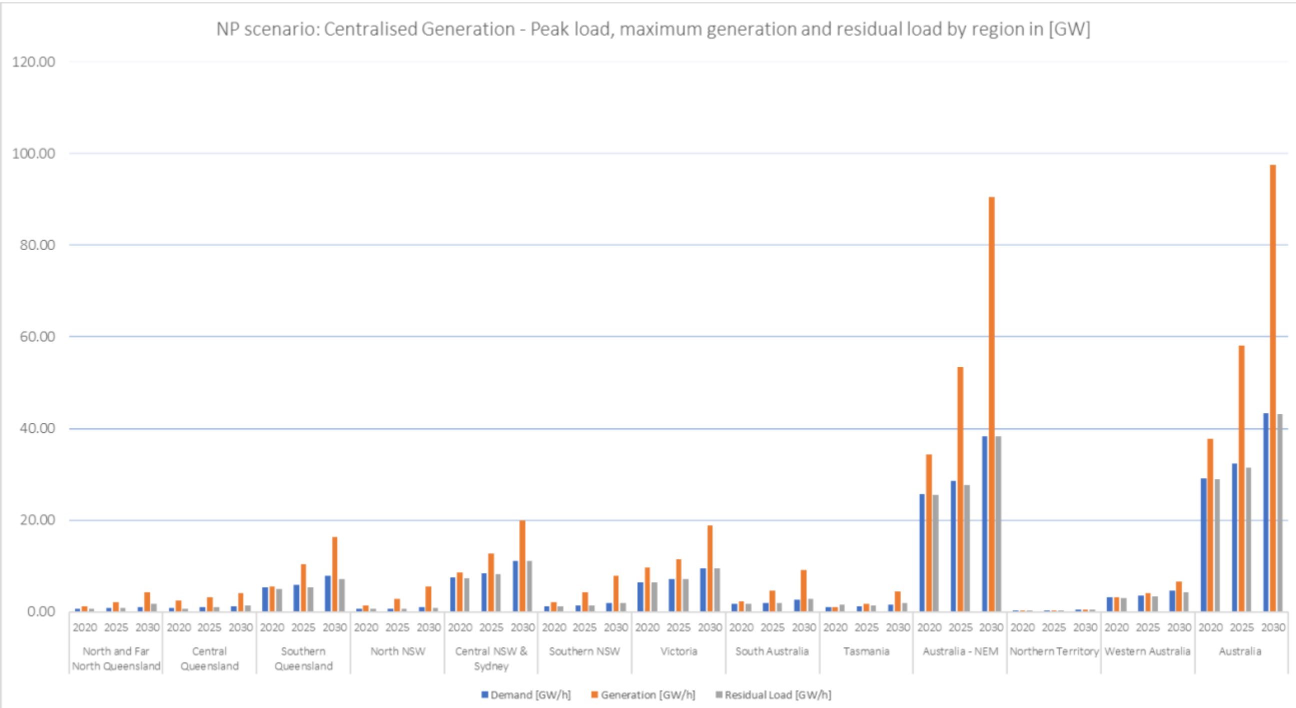


Figure 29. *NP* scenario: centralised generation—peak load, maximum generation, and residual load by region (in GW)

Peak load and peak generation events do not appear at the same time, so their values cannot simply be added. Moreover, peak loads can vary across all regions and appear at different times. Therefore, summing all the regional peak loads will only provide an indication of the peak load for the whole power system. The maximum residual load[81] shows the maximum undersupply in a region and indicates the maximum load imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. Optimizing the interconnections for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be serviced by the following options:

- imports from other regions through interconnections;
- charged storage facilities providing additional load;
- available back-up capacities, such as gas peaking plants;
- load and demand-side management.

In practice, security of supply can be achieved with a combination of several measures and will require an in-depth analysis of the regional technical possibilities, e.g., whether or not a cable connection is possible.

[81] Residual load is the load remaining after local generation within the analysed region is exhausted. There could be a shortage of load supply due to the operation and maintenance of a coal power plant or reduced output from wind and solar power plants.

6.5 AUSTRALIA: DEVELOPMENT OF INTER-REGIONAL EXCHANGE OF CAPACITY

The increasing electricity load in all regions, shown in Table 34, will require increases in the transmission and distribution networks in Australia. This analysis assumes that those network upgrades will be implemented as the demand increases and are based on ISP assumptions. Because it is a technical requirement, Australia must increase its grid capacity proportionally to the increasing demand. This technical requirement to expand the grid capacity as demand increases is largely independent of the type of power generation. The outcomes in this section are based on the aforementioned assumptions (particularly the interconnection limits), and the proportions of the demand and supply technology. As can be seen when Figures 24 and 25 are compared, the scenario parameters are not the key drivers of the dynamics of regional interconnection. CNSW will remain a large importer of energy across scenarios given the high demand driven by industry, population, and transport—and a correspondingly smaller amount of generation capacity in this region.

Conversely, regions such as NQ, CQ, NNSW, SA, and Tas, will act as net exporters of energy throughout the year given their proportionally higher levels of generation capacity relative to demand. Their proximity to large loads in SQ, CNSW, and VIC—together with sufficient interconnection capacity—will allow the flow of renewable energy between regions to enhance system balancing and to avoid further supply gaps when the need for additional gas generation is beyond what is outlined in section 6.8.

Limitations: The calculated loads are not optimised in the regard to local storage, the self-consumption of decentralised producers of solar photovoltaic electricity and demand-side management. Therefore, the calculated loads may be well below the actual values. The utilisation of the interconnector is highly dependent on the geographical distribution of generation and storage, and the degree of correlation between the demand (= load profile) and the generation profiles.

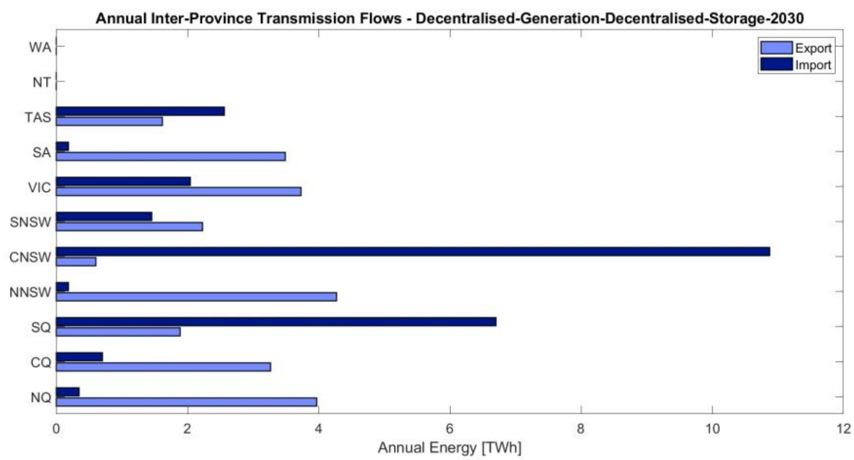


Figure 30. ***Decentralised*** generation and ***decentralised*** storage scenario: annual inter-regional transmission flows across nine NEM regions

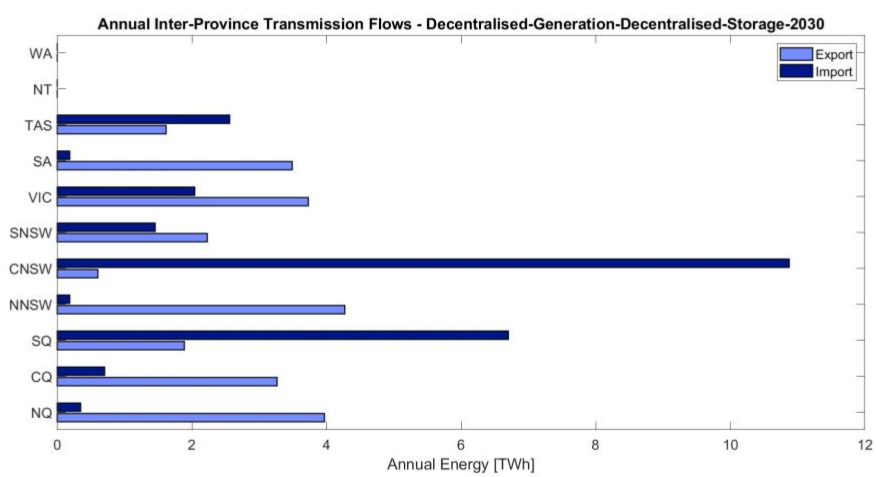


Figure 31. ***Centralised*** generation and ***centralised*** storage scenario: annual inter-regional transmission flows across nine NEM regions

6.6 STORAGE REQUIREMENTS

The quantity of storage required is largely dependent on the storage costs, grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands (Wendong 2016)[82]. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt–hour than storage costs. Cebulla et al. (2018)[83] reported that "in general terms, photovoltaic-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage, power, and energy capacities if grid expansion is unlimited or cheap". They also found, in an analysis of 400 scenarios for Europe and the USA, that once the share of variable renewables exceeds 40% of the total generation, the increase in electrical energy storage power capacity is about 1–2 GW for each percentage of variable renewable power generation in wind-dominated scenarios and 4–9 GW in solar-photovoltaic-dominated scenarios.

Over the past decade, the cost of batteries, especially lithium batteries, has declined significantly. However, solar photovoltaic costs have also declined significantly. Storage is economic when the cost per kilowatt–hour is equal to or lower than the cost of generation. Therefore, if storage costs are high, curtailment could be economic. However, there are various reasons for curtailment, including transmission constraints, system balancing, and economic reasons (NREL 2014)[84]. The California Independent System Operator (CISO)[85] defines economic curtailment during times of oversupply as a market-based decision. "During times of oversupply, the bulk energy market first competitively selects the lowest cost power resources. Renewable resources can "bid" into the market in a way to reduce production when prices begin to fall. This is a normal and healthy market outcome. Then, self-scheduled cuts are triggered and prioritized using operational and tariff considerations. Economic curtailments and self-scheduled cuts are considered "market-based"."

Table 35: Storage requirements under four different scenarios

	Storage utilisation (charge)				Comparison with CP_CS		
	CP_CS	CP_DS	DP_CS	DP_DS	CP_DS	DP_CS	DP_DS
	[GW/h]	[GW/h]	[GW/h]	[GW/h]			
North and Far North Queensland	−1,519.6	−1,080.9	−1,503.2	−1,071.7	71.13%	98.93%	70.53%
Central Queensland	−3,136.6	−1,544.1	−3,243.3	−1,540.1	49.23%	103.40%	49.10%
Southern Queensland	−8,556.5	−8,911.1	−7,724.5	−8,069.0	104.14%	90.28%	94.30%
North NSW	−3,379.4	−1,489.7	−3,500.6	−1,497.3	44.08%	103.59%	44.31%
Central NSW & Sydney	−9,056.7	−7,562.2	−9,555.9	−7,932.8	83.50%	105.51%	87.59%
Southern NSW	−7,573.9	−6,625.5	−8,713.9	−7,325.6	87.48%	115.05%	96.72%
Victoria	−8,725.2	−7,158.0	−8,485.8	−6,949.1	82.04%	97.26%	79.64%
South Australia	−6,095.6	−3,515.2	−6,161.7	−3,528.2	57.67%	101.09%	57.88%
Tasmania	−1,821.9	−129.9	−1,794.5	−129.4	7.13%	98.50%	7.10%
Australia-NEM	−49,865.3	−38,016.6	−50,683.5	−38,043.1	76.24%	101.64%	76.29%
Northern Territory	−22.4	−22.4	−13.5	−13.5	100.00%	60.19%	60.19%
Western Australia	−1,699.9	−2,107.1	−1,538.5	−1,817.4	123.96%	90.50%	106.91%
Australia	−51,587.5	-40,146.1	−52,235.5	−39,873.9	77.82%	101.26%	77.29%

CP_CS: Centralised power generation and centralised storage | CP_DS: Centralised power generation and decentralised storage
DP_CS: Decentralised power generation and centralised storage | DP_DS: Decentralised power generation and decentralised storage

[82] Wendong et al. (2016) Regional study on investment for transmission infrastructure in China based on the State Grid data, 10.1007/s11707-016-0581-4, Frontiers of Earth Science, June 2016

[83] Cebulla et al. (2018) How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, Journal of Cleaner Production, February 2018, https://www.researchgate.net/publication/322911171_How_much_electrical_energy_storage_do_we_need_A_synthesis_for_the_US_Europe_and_Germany/link/5a782bb50f7e9b41dbd26c20/download

[84] Bird, Cochran, and Wang (2014) Wind and Solar Energy Curtailment: Experience and Practices in the United States; National Renewable Energy Laboratory (NREL), March 2014, https://www.nrel.gov/docs/fy14osti/60983.pdf

[85] Impacts of renewable energy on grid operations, factsheet, https://www.caiso.com/Documents/CurtailmentFastFacts.pdf

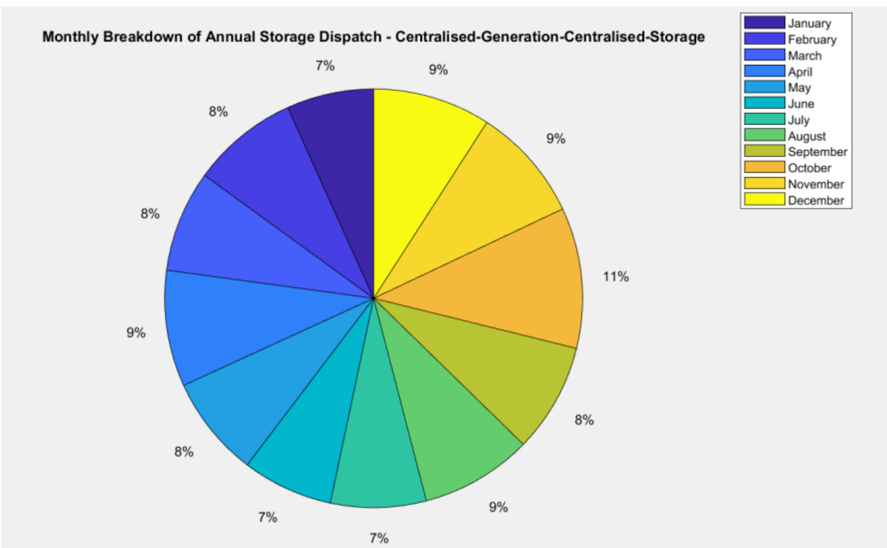
In the *NP*, the share of variable generation will exceed 30% by 2025 in all 11 Australian regions.

In this analysis, we assume that a curtailment rate of 5% for the annual generation (in GWh/yr) by solar photovoltaics and onshore and offshore wind will be economically viable by 2030. Curtailment rates over 10% indicate that additional grid integration measures are required to increase the economic performance of the overall power system. However, economic curtailment rates are dependent upon the available grid capacities and can vary significantly, even within Australia. Curtailment will be economic when the power generated from a wind turbine or photovoltaic power plant exceeds the demand for only a few hours per day and this event occurs rarely across the year. Therefore, grid expansion will not be justifiable.

Table 35 shows the storage utilisation in GWh per year by region under the four different scenarios. The decentralised storage scenarios achieve slightly lower utilisation rates than the centralised storage scenarios—even though the overall installed storage capacity in GW is identical in all four scenarios. The combination of decentralised generation and centralised storage achieves the highest utilisation rates. This is due to the chosen dispatch order—decentralised storage is charged first with roof-top photovoltaic generation, whereas centralised storage also has access to surplus wind power generation, but is also constrained by transport capacities (interconnections power grid).

Figure 32 shows the storage demand by month across the whole of Australia. All four scenarios showed identical distributions of storage demand per month. The storage demand is fairly equally distributed over the year, which indicates a lower demand for seasonal storage than, for example, in the northern hemisphere, such as in Europe or North America.

Figure 32. Storage demand by month



In the next step, the week with the highest and lowest solar and wind generation in the year analysed (here 2030) is plotted against the demand to show the extreme situations, either the over- or undersupply of demand at a specific hour.

Figure 33 shows the week with the highest generation surplus under the centralised generation and decentralised storage scenario and Figure 34 under the decentralised generation and decentralised storage scenario.

The time of the highest surplus renewable electricity production in the centralised generation and storage scenario, and in the decentralised generation and storage scenario was in January. The two red lines (dotted line at 40 GW load and full line at 80 GW, respectively) are included for better orientation. The decentralised scenario utilises roof-top solar generation better and has less surplus electricity, whereas the centralised scenario has less surplus generation in utility-scale solar plants. The total solar generation is almost identical in both cases. Centralised storage lead to lower overall curtailment rates, because surplus wind energy has access to more storage capacity than with decentralised storage. However, decentralised storage leads to less curtailment of roof-top solar photovoltaic.

Figure 35 shows the week with the lowest generation under the centralised generation and decentralised storage scenario and Figure 36 under the decentralised generation and decentralised storage scenario. For both scenarios, the event was in July, in the middle of winter. Even on the day of lowest generation, the solar generation peaks during mid-day exceeded the demand and could be utilised with a further increase in storage capacity. However, additional storage would be required to avoid a supply gap. Because this event would only occur on a very limited number of days, only existing gas power plants have been used as gas back-up systems.

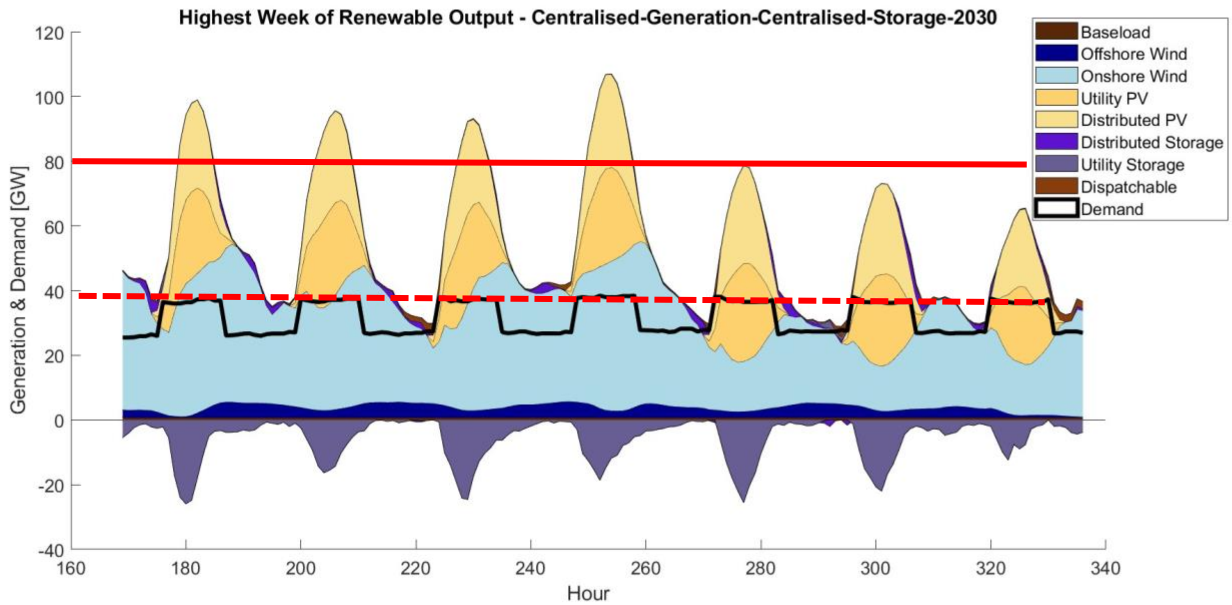


Figure 33. Week with highest power generation under the centralised generation and decentralised storage scenario

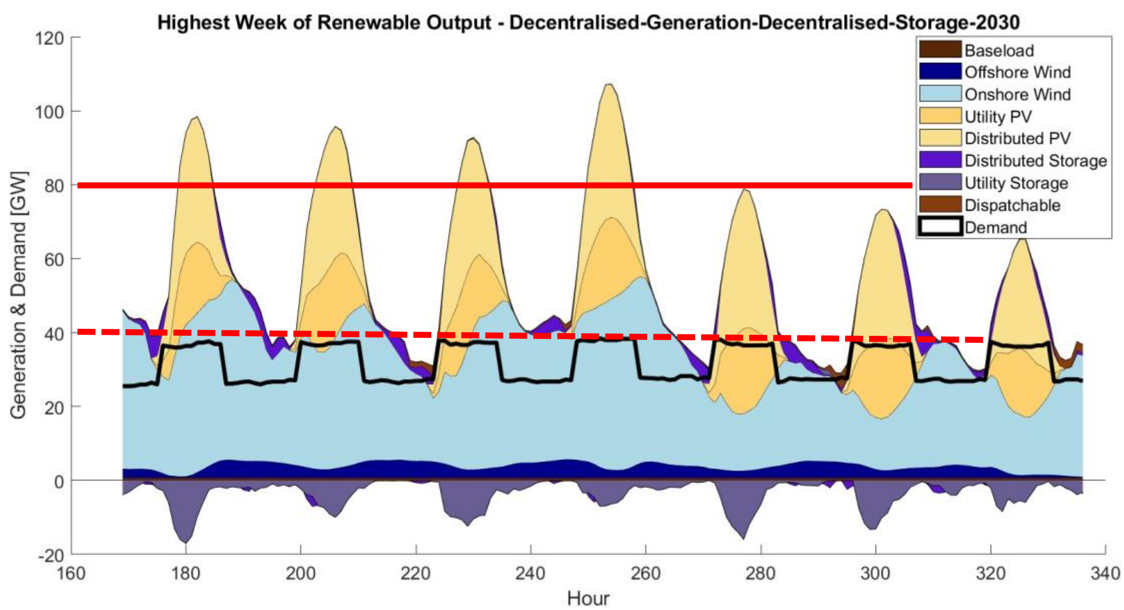


Figure 34. Week with highest power generation under the decentralised generation and decentralised storage scenario

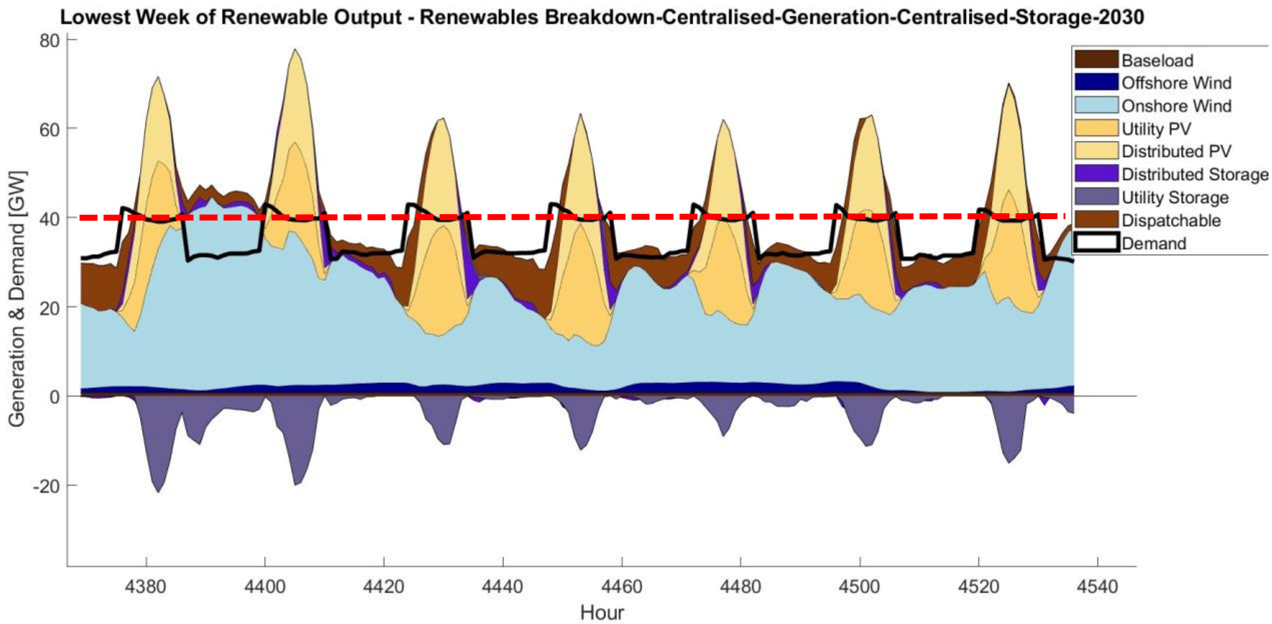


Figure 35. Week with lowest power generation under the centralised generation and decentralised storage scenario (white fields = gas back-up)

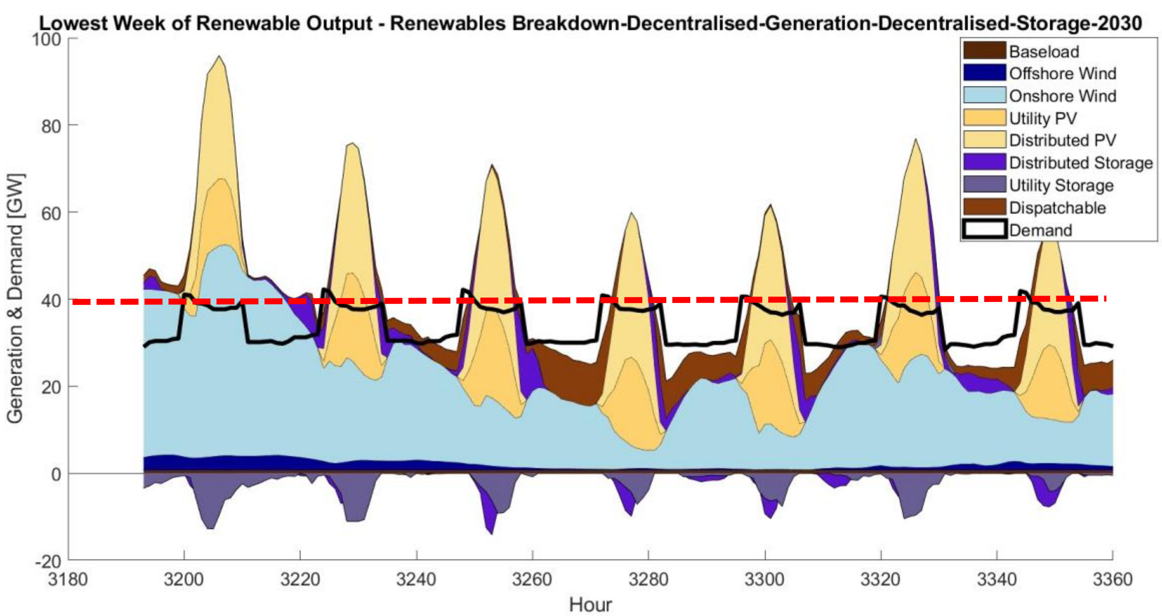


Figure 36. Week with lowest power generation under the decentralised generation and decentralised storage case (white fields = gas back-up)

6.7 CURTAILMENT AND SECURITY OF SUPPLY

The four scenarios with combinations of centralised and decentralised storage technologies have been calculated with solar and wind data for the year 2012 to make them comparable to the ISP, which uses that year. Our analysis for the year 2030 with hourly resolution (8760 hours per year) showed that the chosen electricity generation mix produced between 22% to 17% more electricity than required. However, the chosen storage capacities were insufficient absorb the surplus electricity generated. The times of over- and undersupply were several months apart, so the surplus electricity stored in batteries was no longer available at the time of undersupply.

The following options can fill this supply gap:

- Gas-generated supply;
- Increased interconnection;
- Increased demand-side management.

Based on the current projections for the increased interconnection and storage projects, gas back-up was the option chosen in all four scenarios.

Table 36 shows the results for curtailment rates, total gas electricity generation, the requirement for natural-gas-based back-up generation, and the resulting CO_2 emissions that can be avoided, if additional storage capacities were available.

Table 36: Over- and underproduction results for the four scenarios

Scenario	Percentage curtailment	Total gas generation [GWh/a]	Gas peaker demand in [GWh/a]	Additional CO_2 emissions of gas peaker [$MtCO_2$/yr]
Centralised generation, centralised storage	17.15%	16,736	5,064	3.71
Centralised generation, decentralised storage	21.69%	15,870	4,852	3.52
Decentralised generation, centralised storage	17.01%	16,897	5,061	3.75
Decentralised generation, decentralised storage	21.79%	16,217	4,698	3.60

6.8 SUMMARY: POWER SECTOR ANALYSIS FOR AUSTRALIA

All four scenarios lead to a secure power supply for the NEM and Australia. This in itself is a significant finding, because it demonstrates that with sufficiently ambitious policy support for the energy transition, it will be possible to decarbonize Australia's electricity production faster than currently expected. An example of this, AEMO's *Step Change* scenario in the 2022 ISP, utilises a total of ~7 GW across the NEM in 2030[86], whereas the *NP* scenario assumes a retirement of all coal capacity across the NEM and SWIS grids—with no expansion of the gas capacity beyond current levels. The supply of all regions is secure under all four generation/storage scenarios, and the results of this analysis do not indicate any technical barriers to the *NP* pathway or the assumed power generation mix.

Due to the modelling methodology and scenario assumptions used, negligible differences between the centralised and decentralized generation parameters were observed. With a higher-resolution modelling method, further differences could be detected when the ratio of distributed to utility solar is altered, e.g., distributed network hosting capacity limits, other network constraints, and export limits, etc. (this is beyond the scope of this report). Therefore, our modelling supports a need for the continued uptake of both roof-top solar and utility-scale projects together with storage in order to accelerate the decarbonization of electricity production in Australia. It should be noted that the scenarios also require an expansion of wind generation (onshore and offshore) beyond current forecasts, to ensure sufficient supply outside solar hours.

Both the decentralized and centralised storage scenarios produced similar results, with the centralised storage scenarios reducing curtailment relative to the decentralized storage scenarios. This is because centralised storage scenarios have greater GWh, because the duration of storage with pumped hydro and utility-scale batteries is greater than that of distributed batteries. Furthermore, utility-scale storage has the added ability to store and dispatch power to neighbouring regions, thus further reducing the curtailment of surplus renewable energy.

Because this effect was slight, it can be said that neither an entirely centralised power generation and storage system nor an entirely decentralised generation and storage system is preferable. Ultimately, a combination of renewable generation and storage type is required to achieve the *NP* scenario, although a noticeable increase in uptake across both centralised and decentralised technologies relative to the current forecasts is required if the *NP* is to be achieved

These results suggest that the greatest security of supply with the lowest curtailment rates can be achieved with a high supply share of decentralised roof-top solar systems combined with decentralised storage for the residential sector and centralised utility-scale solar combined with onshore wind, offshore wind, and utility-scale storage that are connected to high-voltage lines to serve industrial consumers.

[86] https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/2022-integrated-system-plan-isp.pdf

7 CONCLUSIONS

The aim of this research was to develop an ambitious energy transition plan to bridge the substantial gap between what the climate science says is necessary for decarbonization and the plans that are already underway or proposed in Australia. This report *Aim High, Go Fast: Why Emissions Need to Plummet this Decade* underpins the Climate Council's science-based vision for what Australia's effort should look like: a 75% reduction in GHG emissions relative to 2005 levels by 2030, reaching net zero by 2045.

The key answers to the research questions are:

4. Australia can reduce its energy-related CO_2 emissions by 75% relative to 2005 levels by 2030. The *Necessary Ambition Pathway* scenario will lead to energy-related CO_2 emissions of 82 $MtCO_2$ in 2030 and 43 $MtCO_2$ in 2035.
   The energy sector will be entirely decarbonized just before 2050.
5. The overall carbon budget for Australia until full decarbonization is calculated to be 3 $GtCO_2$ between 2020 and 2050. In this analysis, we developed a sector-specific carbon budget for 15 sectors (see Table 37). The research indicates that there are no technical barriers to the achievement of full decarbonization in all the sectors analysed.
6. To achieve those ambitious decarbonization pathways, a wide spectrum of technologies is required, and policies to implement those pathways must be comprehensive and long-term.

a. For the power sector, solar photovoltaics is the key renewable energy technology for Australia, but diversity is required to keep the storage demand low and the security of supply high. All renewable power technologies—on- and offshore wind, geothermal power, and concentrated solar power plants—are important for the successful decarbonization of Australia's power sector.

b. For the industry sector, the generation of electrical process heat and thermal process heat based on hydrogen and synthetic fuels will be among the most important new technology developments.

c. For the transport sector, electrification of road and rail transport vehicles, increased active transport (such as cycling and walking), and consistent policies are the key measures and among the most challenging for Australia given the geography of the country.

d. For the building sector, significant improvement in building efficiency in terms of the building envelope and double glazing is key.

To conclude, Australia can decarbonize its economy with existing technologies, but not with existing policies.

Table 37: *Necessary Pathway* – energy-related CO_2 emissions (in $MtCO_2$/year)

Necessary Pathway—energy-related CO_2 emissions [$MtCO_2$/year]						Cumulative energy-related CO_2 emissions [$MtCO_2$]			Share of Carbon Budget
Sector	Industry	2020	2030	2035	2050	2020–2030	2031–2050	2020–2050	
Cement	Industry	6	3	2	0	51	25	76	2%
Steel	Industry	6	3	2	0	46	32	80	3%
Chemical Industry	Industry	6	2	1	0	46	13	59	2%
Textile & Leather	Industry	0	0	0	0	5	2	6	0%
Aluminium	Industry	30	6	4	0	188	44	232	8%
Buildings—commercial, residential, & construction	Services	148	14	12	0	1,012	144	1,156	38%
Agriculture & Food Processing	Services	18	1	1	0	104	10	115	4%
Forestry & Wood	Services	6	0	0	0	41	4	45	1%
Water Utilities	Services	0	0	0	0	2	0	2	0%
Aviation—Transport Services	Transport	9	7	3	0	91	31	122	4%
Aviation Industry—direct	Transport	0	0	0	0	2	0	2	0%
Navigation Transport Services	Transport	2	2	2	0	20	15	36	1%
Navigation Industry—direct	Transport	0	0	0	0	2	0	2	0%
Road Transport—Transport Services	Transport	64	27	14	0	506	175	680	22%
Road Transport Industry—direct	Transport	4	1	0	0	20	0	20	1%
All other sectors	Other	60	12	3	0	412	34	443	14%
Sum		360	79	43	0	2,547	530	3,077	100%

8 APPENDIX

8.1 DATA OVERVIEW

Data sheets

Name	Content	Comment - UTS
Australian Overview	All country-relevant energy scenarios on one page—summary over the following six sheets	
EG	Electricity Generation	Data 2005–2020 IEA - 2021–2050 projection
IC	Installed Capacity (power generation)	Data 2005–2020 IEA - 2021–2050 projection
H	Heating (Residential and Commercial/Industry)	Data 2005–2020 IEA - 2021–2050 projection
T	Transport	Data 2005–2020 IEA - 2021–2050 projection
FE	Final Energy by Sector	Data 2005–2020 IEA - 2021–2050 projection
PE	Primary energy	Data 2005–2020 IEA - 2021–2050 projection
CO_2 annual	Calculated annual CO_2 emission	
CO_2_Budget	Calculated cumulative CO_2 emission 2020–2050 by sector	
Assumptions	Overview—key technical input parameters	
Water	Water Utilities	Key assumptions, technical parameters, and key results
Agri & Food	Agriculture and Food Industry	Key assumptions, technical parameters, and key results
Forestry & Wood	Forestry and Wood Products	Key assumptions, technical parameters, and key results
Chemical Industry	Chemical Industry	Key assumptions, technical parameters, and key results
Tex & Lea	Textile & Leather Industry	Key assumptions, technical parameters, and key results
Alu	Aluminium Industry (including bauxite mining)	Key assumptions, technical parameters, and key results
Buildings	Commercial and Residential Buildings	Key assumptions, technical parameters, and key results
Steel	Iron & Steel Industry (including iron ore mining)	Key assumptions, technical parameters, and key results
Transport	Aviation, Shipping, and Road transport	Key assumptions, technical parameters, and key results

8.2 ASSUMPTIONS SHEET

The *Assumptions Sheet* provides the three different types of parameters for each of the sectors studied and for the Australia scenario for the years 2020, 2025, 2030, and 2050.

1. Market development: Current and assumed development of demand by sector, such as cement produced, passenger–kilometres travelled, or assumed market volume in $GDP.
2. Energy intensity: Energy use per unit of service and/or product, e.g., in megajoules (MJ) per passenger–kilometre (MJ/pkm) travelled, MJ per tonne of steel (MJ/tonne steel), aluminium, or cement, or MJ per $GDP contributed by the chemical industry (MJ/$GDP), etc.
3. Carbon intensity: Current and future carbon intensity per unit (see above) in tonnes of CO_2 (e.g., tCO_2/tonne steel).

Table 38 shows the parameters provided for the cement industry in Australia.

IMPORTANT: The parameters for market development and energy intensity are INPUTS, the values for 2025–2050 are assumptions. Carbon intensities are calculated values based on the current energy supply. Historical values are used to calibrate the model; the values for 2025–2050 are calculated—based on the assumed supply mix—and are therefore RESULTS. Therefore, emission intensities (except process emissions) can never be INPUTS into an energy scenario.

Table 38: Assumptions sheet—example: Cement Industry

Total Materials / Cement		Australia	2017	2018	2019	2020	2025	2030	2035	2040	2045	2050
Market Development	Cement—production volume	[Mt/yr]	10	10	10	11	12	12	12	12	13	13
	Deviation from 2019	[%]				0%	13%	16%	19%	22%	25%	28%
	Clinker—production volume (based on clinker to cement ratio)	[Mt/yr]	8	8	8	9	9	8	8	8	8	8
	Deviation from 2019	[%]				0%	8%	0%	−1%	−4%	−6%	−7%
Energy Intensity	Thermal energy intensity—per tonne of clinker	[GJ/tonne]	3.50	3.5	3.5	3.5	3.40	3.30	3.25	3.20	3.15	3.10
	Thermal energy intensity—clinker: deviation from 2019	[%]					−3%	−6%	−7%	−9%	−10%	−11%
	Cement production—electricity intensity	[kWh/tonne]	116	116	116	116	103	87	85	83	81	79
	Cement production—electricity intensity: deviation from 2019	[%]					−11%	−25%	−27%	−28%	−30%	−32%
	Thermal energy intensity—per tonne of cement (final energy)	[GJ/tonne]	5.17	5.40	5.23	4.74	4.00	3.50	3.00	2.07	2.04	2.01
	Thermal energy intensity—cement: deviation from 2019	[%]					−24%	−33%	−43%	−61%	−61%	−62%
	Product Energy Intensity (thermal + electricity)	[GJ/tonne cement]	5.59	5.82	5.65	5.15	4.37	3.81	3.31	2.36	2.33	2.29
	Deviation from 2019	[%]					−23%	−33%	−42%	−58%	−59%	−59%
Carbon Intensity	Specific ENERGY-RELATED CO_2 emissions per tonne of clinker	[tCO_2/tonne clinker]	0.36	0.39	0.38	0.34	0.21	0.12	0.07	0.02	0.01	0.00
	Deviation from 2019	[%]					−45%	−68%	−81%	−93%	−97%	−100%
	Specific ENERGY-RELATED CO_2 emissions per tonne of cement	[tCO_2/tonne cement]	0.66	0.69	0.68	0.63	0.43	0.33	0.23	0.14	0.05	0.00
	Deviation from 2019	[%]					−37%	−51%	−67%	−79%	−93%	−100%
	Specific CO_2 emissions per tonne of cement (including process emissions)	[tCO_2/tonne cement]	1.42	1.48	1.60	1.51	1.18	0.93	0.72	0.53	0.36	0.24
	Deviation from 2019	[%]					−26%	−42%	−55%	−67%	−78%	−85%

8.3 LITERATURE

Publications: One Earth Climate Model Methodology

Publisher & Link	Title
Springer Book (Open Access):	The 'Global Stocktake' and the remaining carbon budgets for G20 countries to limit global temperature rise to +1.5 °C
Springer Book (Open Access):	A Net-zero 1.5 °C sectorial pathways for G20 countries: energy and emissions data to inform science-based decarbonisation targets
Springer Book (Open Access):	Achieving the Paris Climate Agreement Goals—Part 2: Science-based Target Setting for the Finance Industry—Net-Zero Sectorial 1.5˚C Pathways for Real Economy Sectors
Springer Nature (Open Access):	Global sector-specific Scope 1, 2, and 3 analyses for setting net-zero targets: agriculture, forestry, and processing harvested products
Springer Nature (Open Access):	1.5 °C pathways for the Global Industry Classification (GICS) sectors chemicals, aluminium, and steel
Journal (Open Access):	One Earth Climate Model—Integrated Energy Assessment Model to Develop Industry-Specific 1.5 °C Pathways with High Technical Resolution for the Finance Sector
Journal (Open Access):	It Is Still Possible to Achieve the Paris Climate Agreement? Regional, Sectorial, and Land-Use Pathways
Springer Book (Open Access):	Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C

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