Australia's National
Science Agency

The State of Energy Transition Technologies

Electricity

TECHNICAL APPENDIX

December 2025

Citation and authorship

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Acknowledgement

CSIRO acknowledges the Traditional Owners of the land, sea, and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

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Contents

Unit conversions

UNITS	
GJ	Gigajoule (1 000 000 000 joules)
PJ	Petajoules (1 000 000 gigajoules)
GW	Gigawatt (1 000 megawatts)
GWh	Gigawatt hour (a gigawatt of power used in an hour)
kL	Kilolitres (1 000 litres)
Km	kilometre (1 000 metres)
kW	Kilowatt (1000 watts of electrical power)
MJ	Megajoule (1 000 000 joules)
Mwe	Megawatt electric (1 000 000 watts of electrical energy)
MWh	Megawatt hour (1 000 000 watts of power used in an hour)
MWth	Megawatt thermal (1 000 000 watts of thermal energy)
TWh	Terawatt hour (1 000 000 megawatt hours)

1 Executive summary

Electricity

RD&D that reduces the cost of electricity will underpin Australia’s cross-sectoral decarbonisation objectives and have a significant impact on the financial viability of several abatement pathways.

Challenge

Electrification and the use of renewables underpin many of Australia’s cross-sectoral decarbonisation strategies and will require the deployment and integration of technologies and infrastructure at an accelerated pace. However, Australia's electricity system is unique, spanning both interconnected and isolated grids, with relatively low density compared to international regions. The transition of Australia’s electricity supply must be carefully planned to ensure it occurs seamlessly while continuing to provide reliable energy services to consumers and industry.

Scope of analysis

This analysis highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia’s decarbonisation efforts of large-scale electricity generation in Australia, as well as energy storage solutions for short, medium and long duration grid scale demands:

- **Electricity generation** analyses electricity generation technologies that can be centralised and produce electricity at grid-scale with the capacity to operate reliably. Identifying decarbonisation technologies in the context of this use case is considered essential for achieving net-zero targets by 2050. Three technologies were explored in more detail to identify RD&D opportunities.
- **Electricity storage** analyses storage technologies across three discharge durations: short, medium and long. These durations represent how long a storage technology can sustain its maximum discharge rate, which allows them to service different demand sectors and markets. Short duration storage can respond within hours, providing frequency regulation and peak shaving during high demand periods. Longer duration storage solutions offer a way to store energy during low demand times, and can provide reliable energy supply for extended periods, such as during times of low energy generation. Seven technologies were explored in more detail to identify RD&D opportunities.

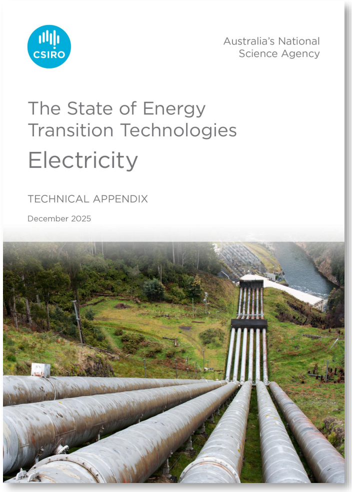
2 Electricity overview

Research, development and demonstration (RD&D) will be pivotal in informing and driving the change required to achieve the energy transition and Australia’s net zero ambitions. However, with limited resources and a broad array of emerging low emissions technologies, Australia faces the important task of strategically and collaboratively optimising its RD&D efforts to maximise national benefit.

This study, *The State of Energy Transition Technologies*, highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia’s decarbonisation efforts. It is not intended to prescribe research strategies for Australia or any individual organisation. Rather, it serves as a resource to support constructive dialogue and help navigate the energy transition by leveraging the nation’s RD&D strengths.

2.1 This report

The State of Energy Transition Technologies consists of a Synthesis report and five technical appendices spanning a range of Australian energy supply and demand related sectors. This report, focused on electricity supply, is to be considered alongside the other reports, and aims to evaluate a diverse range of technologies to help explore opportunities for RD&D across the vast and rapidly growing low emissions technology landscape. It leverages global literature and CSIRO expertise, designing and applying a technology analysis framework to explore RD&D opportunities.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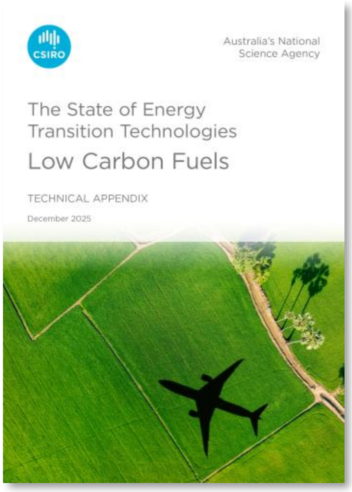
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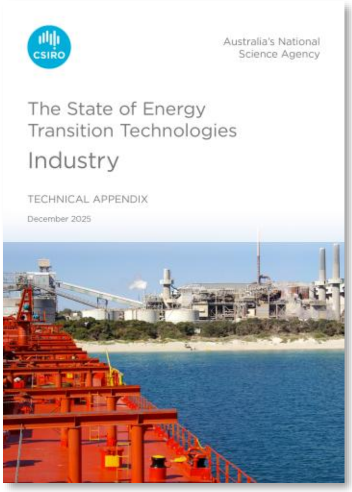
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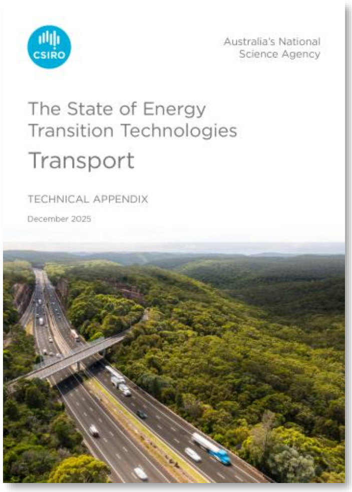
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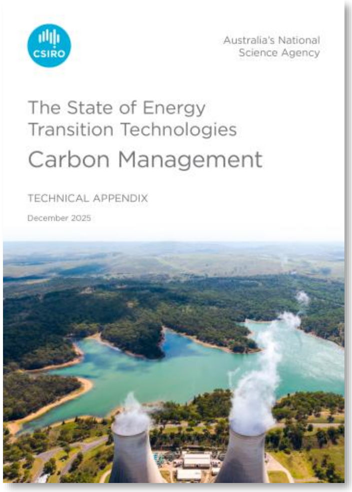
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2.2 Australia’s electricity needs

Australia's electricity system is unique. It services both interconnected and isolated grids serving various states and territories. It includes one of the world's longest interconnected markets, the National Electricity Market (NEM), and has one of the longest submarine power cables, connecting Victoria and Tasmania. It supplies power to a wide range of sectors including commercial, industrial, transport, agriculture and residential. Compared to international regions, Australia's grids are relatively low density, with only six interconnectors linking five states which limits Australia's ability to easily share energy across regions.

Australia’s electricity generation mix is transforming from a centralised system of large fossil fuel generation towards distributed networks with increasing levels of variable renewable energy (VRE), mainly in the form of wind and solar technologies. In 2023, fossil fuels accounted for 65% of Australia’s total electricity generation, with coal contributing 46%, gas 17% and oil 2%. This marks a continued decline in fossil fuel use, coinciding with a record high of 35% grid scale VRE generation.[1] Australia’s renewable capacity has increased from 10.5% in 2010 to 34% in 2022-2023.[2]

Despite Australia's growing renewable energy capacity, there is a need to rapidly increase renewable energy generation and integration to support decarbonisation and greater levels of electrification across the economy. There is potential for electricity to replace fossil fuels in industry processes such as industrial heating or electrochemical processes in chemical manufacturing. Moreover, battery electric vehicles are already emerging as a key technology for achieving decarbonisation of the road sector and are projected to be cost competitive with internal combustion vehicles in the long-term. However, these technologies can only reduce emissions if Australia’s energy capacity is able to keep pace with increasing electricity demand.

As Australia decarbonises and renewable energy deployment increases, it will be important to ensure that Australia optimises how energy is transmitted, distributed and stored. For example, traditional electricity grids were designed to transfer power from large, centralised generation assets. However, Australia’s rapid adoption of renewables (particularly related to rooftop solar) requires more sophisticated approaches and technologies. Network transformation will be coupled with increasing amounts of large-scale electricity storage technologies to firm generation, address demand, and overcome geographical constraints.[3]

The transition of Australia’s electricity supply must be carefully planned to ensure it occurs seamlessly while continuing to provide reliable energy services to consumers and industry. Accelerating the most relevant and cost-effective technologies will require careful consideration.

2.3 Scope of this report

This report highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia’s decarbonisation efforts for electricity generation and storage.

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[1] Department of Climate Change, Energy, the Environment and Water (2023) Australian Energy Statistics, Table O Electricity generation by fuel type 2022-2023. <table-o-australian-energy-statistics-2024.xlsx>

[2] Australian Government Department of Climate Chane, Energy, the Environment and Water (2024) Australian Energy Update. <https://www.energy.gov.au/sites/default/files/2024-08/australian_energy_update_2024.pdf>

[3] CSIRO (2023) Renewable Energy Storage Roadmap.

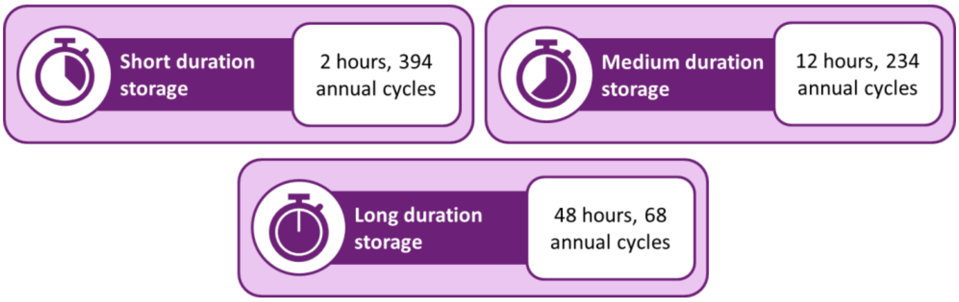
Overview of electricity generation

Large-scale electricity generation refers to the centralised production of electricity at a significant scale with the capacity to operate reliably without supply constraints. Large-scale electricity generation is required to support Australian industries, manufacturing, commercial facilities and regional, national and interstate transmission networks. In 2022-2023, total electricity generation was around 274 terawatt hours, with fossil fuels contributing to 65% of total generation.[4] Given large-scale electricity generation is a major source of Australia's emissions, this analysis focuses on exploring low emissions technologies and RD&D opportunities in the context of this use case for large scale electricity generation and storage.

Overview of electricity storage

This analysis also aims to explore key storage technologies across three discharge durations, short, medium and long (see Figure 1). These durations represent how long a storage technology can sustain its maximum discharge rate, which allows them to service different demand sectors and markets. Short duration storage can respond within hours, providing frequency regulation and peak shaving during high demand periods. Longer duration storage solutions offer a way to store energy during low demand times, and can provide reliable energy supply for extended periods, such as during times of low energy generation. Although there is no universal definition for short, medium and long duration storage, these values are considered a useful proxy for analysing the cost competitiveness of various energy storage solutions.

Figure 1: Use case characteristics of short, medium and long duration electricity storage technologies



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[4] Department of Climate Change, Energy, the Environment and Water (2023) Australian Energy Statistics, Table O Electricity generation by fuel type 2022-2023. <table-o-australian-energy-statistics-2024.xlsx>

3 General methodology

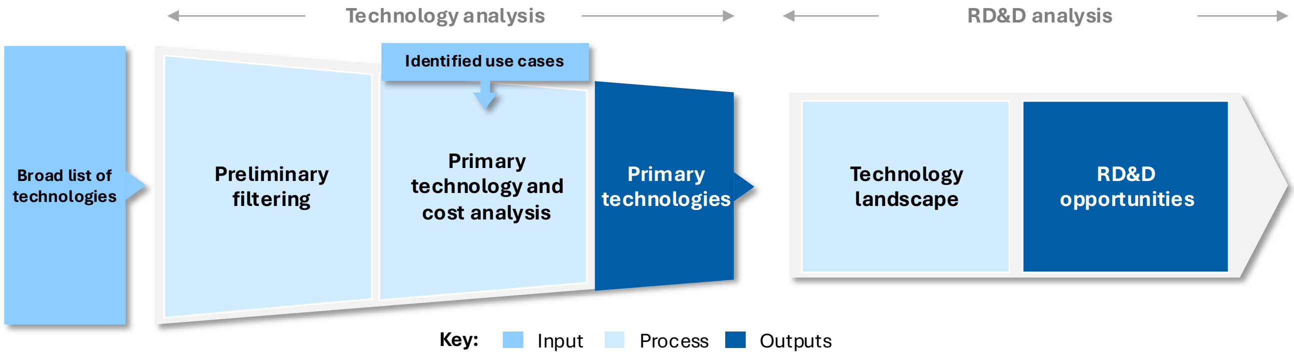
The State of Energy Transition Technologies report methodology was designed to highlight RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. The methodology adopts a multi-stage approach, where prospective technology solutions were identified from a broad list through a technology analysis framework. This formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

The framework uses a structured approach to consistently filter technologies, while retaining flexibility to adapt criteria to a broad range of sectors and sub-sectors. This helps ensure technologies are fit-for-purpose and can meet the expected requirements for indicative energy- and emissions-intensive Australian use cases, while capturing a diverse range of technologies and RD&D opportunities to support Australia's sectoral and economy-wide 2050 net zero objectives.

The analysis derives technology specific RD&D opportunities that could address the technical, economic, and operational requirements of different sector applications. While extremely important, non-technical RD&D is outside of the scope of this study. This includes research related to policy and regulation, social licence and participation, communication and engagement and governance to support the energy transition.

The following Figure 2 is a high-level summary of the methodology and framework applied in this report.

Figure 2: Summary of framework



Inputs

The broad list of technologies was compiled from most recent Australian and global literature and assigned to key (sub)sectors (see *Appendix A.3* for sources). As the level of detail varied across sources, only technologies that directly contribute to emissions reduction efforts were considered as inputs to the framework.

Use cases were defined based on energy and emissions intensive applications identified for the sector/subsector. These use cases were developed to ensure technologies were fit-for-purpose for the specific (sub)sector, and focus on opportunities with the highest abatement impact. These use cases aim to capture a diverse range of applications where possible to ensure the technologies explored provide a portfolio of solutions that align with Australia's sectoral and economy-wide decarbonisation needs.

Technology analysis

The technology broad list was filtered through a two-stage process to explore their suitability for the chosen use case(s). Filtering has been conducted on a knock-out basis, ensuring that only technologies meeting all relevant conditions progressed through the analysis. The order of filters is not indicative of a relative importance of criteria.

Preliminary filtering: Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:

(1) Relevance to Australia;
(2) Technology maturity; and
(3) Abatement potential.[5]

Primary technology and cost analysis: Specific criteria were applied to determine each technology's suitability for use case applications, followed by levelised cost analysis to provide a relative comparison of the long-term feasibility of technology options and to support RD&D opportunity analysis.

(1) The specific criteria used to evaluate suitability differed by subsector. For more detail on the criteria used across each (sub)sector in *The State of Energy Transition Technologies* reports, please refer to *Appendix A.3*.
(2) Levelised cost analysis was conducted for each use case to identify technologies that are relatively more cost competitive and therefore likely to play a role in advancing Australia's decarbonisation efforts. Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis.*

At each filter, technologies were assigned one of three ratings (see Figure 3) based on their ability to meet the criteria. Where conditions or limitations were identified but deemed surmountable for a given technology, a 'meets criteria with caveats' rating was applied.

The subset of technologies that met all filtering criteria are described as *Primary technologies*, and inform the technology landscape development and RD&D opportunity analysis.

Figure 3: Technology assessment rating criteria

🟦 Meets filter criteria
🟦 Meets criteria with caveats
⬛ Does not meet criteria
▨ Not assessed further

Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the exploration of RD&D opportunities. The identified *Primary technologies* cannot exist in isolation and form one part of a broader technology landscape that must be developed in parallel. This landscape includes technologies essential for the deployment or enhanced performance of the primary technologies, described in *The State of Energy Transition Technologies* reports as *Auxiliary technologies* (see Figure 4).

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[5] Considers Scope 1 emissions arising from the direct use of a technology, as well as Scope 2 (indirect) emissions generated from the production of key energy inputs. Some Scope 3 emissions are considered on a case-by-case basis. See the relevant section for further detail.

Figure 4: Technology landscape components

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding *Energy efficiency solutions*, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across *Primary and/or Auxiliary technologies*. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

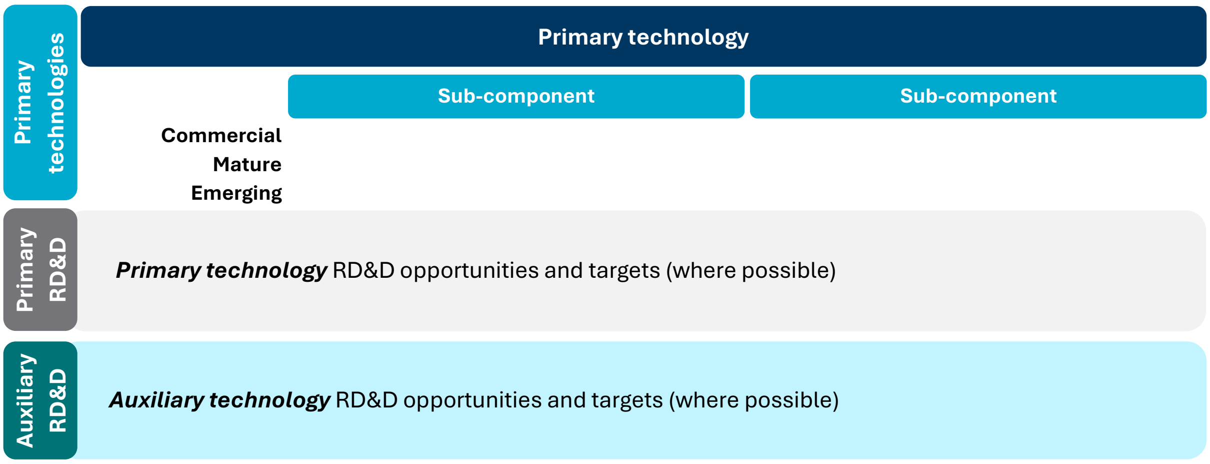
RD&D opportunity analysis

Following the development of the technology landscape, RD&D opportunities were explored. These RD&D opportunities reflect broad workstreams that are likely to help scale-up, de-risk and accelerate the deployment of low emissions technologies.

The analysis is designed to inform constructive dialogue around the role of RD&D in navigating Australia's energy transition. As such, the identified opportunities are not exhaustive of all RD&D areas for the technologies explored. Where possible, cost projections or quantitative targets for technology development were also identified, informed by model cost projections, literature reviews, and the input of subject matter experts. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of the explored low emission technologies.

Primary technologies were categorised based on their technological maturity and disaggregated into their key components where relevant. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9). Literature and stakeholder experts were consulted to determine detailed RD&D opportunities related to the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies (Figure 5).

Figure 5: Technology RD&D opportunity overview



4 Electricity generation

4.1 Executive summary

RD&D can enhance the cost, efficiency, and performance of solar, wind, and concentrated solar power (CSP) technologies, and will be essential to developing the tools required to ensure grid stability and reliability in a high variable renewable energy (VRE) future.

Technology landscape: Large-scale electricity generation

Solar PV, wind, and CSP can provide scalable low emissions solutions for Australia's large-scale electricity generation needs, however, the increased penetration of VRE generation will require careful management to address challenges regarding power quality, grid stability, and reliability.

Solar photovoltaics (PV)	Wind	Concentrated solar power (CSP)
• Grid-scale storage • Transmission and distribution infrastructure		• Grid-scale storage • Transmission and distribution infrastructure • Thermal energy storage media

RD&D Opportunities

Solar photovoltaics	• RD&D can lower solar costs through modular and automated deployment, cost-efficient materials like perovskites, and advanced cell architectures such as silicon-perovskite tandems that capture more of the solar spectrum.
Wind	• There are RD&D opportunities to reduce turbine costs and boost efficiency through new materials, and innovative design and approaches to manufacturing. These efforts can also help develop novel turbine designs suited to decentralised or urban settings. • For offshore wind, RD&D can lower foundation costs and improve floating platform designs.
Concentrated solar power	• For CSP, RD&D can reduce costs, improve efficiency, and enhance combined generation and storage opportunities through advanced heat transfer fluids, and development of high-temperature, corrosion-resistant materials to enhance CSP system durability and longevity.

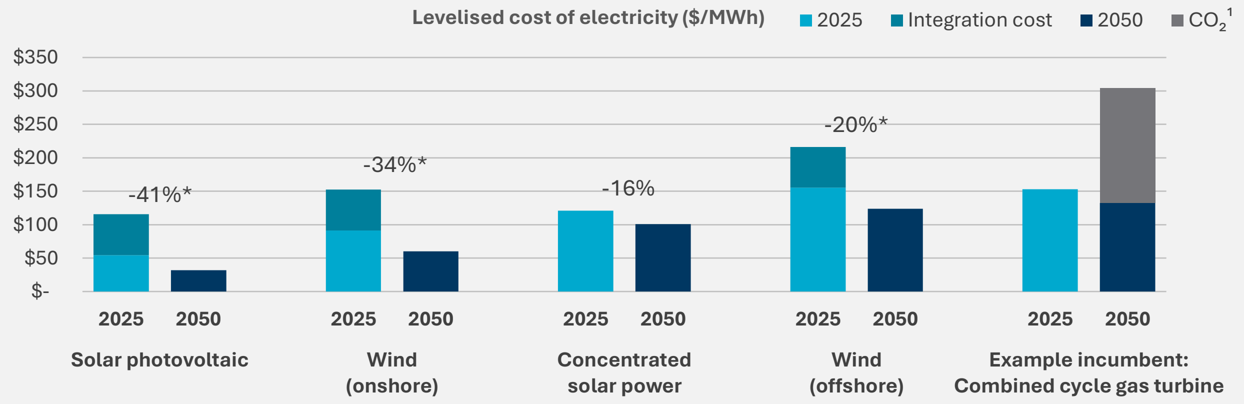
Auxiliary

- The increased penetration of VRE generation can lead to systemwide challenges regarding power quality, grid stability, and reliability, making RD&D on auxiliary technologies essential. RD&D opportunities span new inverter designs, tools and methods to support stability, planning, and restoration, technologies and business model innovations to optimise the use of distributed energy resources, and the development of new technologies for power system operator control rooms.
- *See Electricity – Electricity storage for RD&D opportunities associated with thermal energy storage media.*

Levelised cost analysis

Large-scale electricity generation

Solar and wind technologies are projected to have the lowest levelised costs of electricity in 2025 and 2050, even with the inclusion of integration costs associated with VRE technologies in 2025.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

4.2 Introduction

Large-scale electricity generation refers to the centralised production of electricity at a significant scale with the capacity to operate reliably without supply constraints. Large-scale electricity generation projects typically cover a large area (e.g., solar farms, wind farms or hydroelectric plants) and are connected to major electricity markets (i.e. the National Electricity Market (NEM) and the Wholesale Electricity Market (WEM)) as well as regional and isolated grids to meet the energy demands of Australia's population, industries and infrastructure.

At present, fossil fuels contribute to 65% of total electricity generation, including 46% from black and brown coal, 17% from gas and 2% from oil.[6] While there are 45-coal fired units across 13 power stations in the NEM,[7] the last coal fired plant was commissioned in 2007 and, according to the Australian Energy Market Operator's (AEMO) Integrated System Plan, all are estimated to close by 2038.[8] As a result, there has been a significant shift towards building out Australia's renewable energy capacity. Illustrating this, Australia's capacity rose from 10.5% in 2010 to 34% in 2022-2023.[9] Australia's abundant natural resources such as solar and wind, as well as significant amounts of land make it ideal for large-scale projects and off-grid solutions.

Wind energy and solar PV are the leading types of renewable power generation technologies installed in Australia and considered some of the most mature low emissions electricity generation technologies. Wind accounts for 11% of Australia's total electricity generation, while solar PV accounts for 15%.[9] Wind farm capacities in Australia typically range from 300 MW to 500 MW, although new projects are anticipated to reach up to 1000 MW. In terms of solar PV, investment is significant with several farms >200 MW under development and as of June 2022, Australia had over 3.1 million solar PV systems and 424 wind systems.[8]

In addition to wind energy and solar PV, there is a variety of commercial and emerging renewable technologies that are being used internationally that could be deployed or demonstrated in Australia. These systems could be scaled to support or meet utility-scale demands, supported by RD&D.

Transitioning Australia's energy supply will require replacing lost generation capacity with renewables while addressing key challenges like high infrastructure costs, transmission network upgrades, and potential land-use conflicts. Despite Australia's growing renewable capacity, the gap between potential renewable energy capacity and grid penetration highlights the need for improvements to transmission networks and grid infrastructure. AEMO's Quarterly Energy Dynamics Report contends that while the potential energy from VRE met 99.7% of the NEMs total energy demand in 2023, the highest penetration achieved was 72.1%.[10]

The complex nature of large-scale electricity generation and its significant contribution to Australia's emissions presents challenges to decarbonisation. This chapter presents an analysis of low emissions technologies for large-scale electricity generation to identify technically feasible and cost competitive solutions. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

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[6] Department of Climate Change, Energy, the Environment and Water (2023) Australian Energy Statistics, Table O Electricity generation by fuel type 2022-2023. <table-o-australian-energy-statistics-2024.xlsx>

[7] Australian Energy Market Operator, Aurecon (2023) 2023 Costs and Technical Parameter Review. < https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2023/2024-forecasting-assumptions-update-consultation-page/aurecon---2023-cost-and-technical-parameters-review.pdf?la=en>

[8] Australian Energy Market Operator (2024) Integrated System Plan: For the National Electricity Market. < https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en>

[9] Australian Government Department of Climate Chane, Energy, the Environment and Water (2024) Australian Energy Update. <https://www.energy.gov.au/sites/default/files/2024-08/australian_energy_update_2024.pdf>

[10] Australian Energy Market Operator (2024) Quarterly Energy Dynamics Q4 2023. < https://aemo.com.au/-/media/files/major-publications/qed/2023/quarterly-energy-dynamics-q4-2023.pdf?la=en>

4.2.1 Electricity generation use case(s)

To explore low emissions technologies in the electricity generation subsector, a single use case has been defined, reflecting centralised large-scale generation (see Table 1). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use cases.

This use case is representative of large-scale electricity generation required to support Australian operations and economic sectors, including industrial users (e.g., power plants), industrial manufacturing, and large-scale commercial facilities. Although not evaluated here, small-scale solutions should be recognised for the role that they may play in distributed generation models and in accelerating progress towards scalable solutions for the sector.

Australian transmission and distribution networks are also vital and require distinct consideration given the diversity of Australia's electricity network infrastructure needs. Brief discussion of transmission and distribution technologies is included in *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure,* in recognition that these technologies will need to be adopted in tandem.

This use case is illustrative and presents requirements that technologies must be able to meet to service Australia's electricity generation subsector. In reality, operations in Australia are diverse and will differ in their scale.

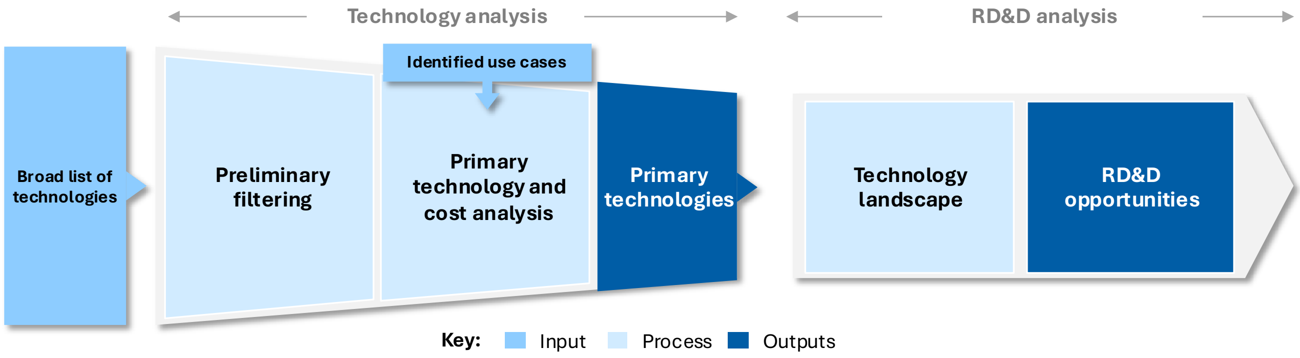
Table 1: Use case(s) – Electricity generation

Use case(s)	**Large-scale generation**
Description:	Centralised generation for power availability with capacity to operate without supply constraints. Primarily for industrial users, including power plants, industrial manufacturing, and large-scale commercial facilities.

4.3 Methodology: Electricity generation inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies with the potential to contribute to decarbonisation for large-scale electricity generation. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 6).

Figure 6: Technology RD&D analysis framework for electricity generation



4.3.1 Broad technology list

A broad technology list comprised of 12 technologies has been developed (see Table 2). These technologies were then passed through three preliminary filters: relevance to Australia, technological maturity, and abatement potential. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case(s).

Table 2: Technology category definitions – Electricity generation

Technology	Definition
Biomass	The conversion of organic materials, such as wood, agricultural residues, or dedicated energy crops, to produce electricity through combustion or biochemical processes.
Bioenergy with carbon capture and storage (BECCS)	Combines biomass energy production with the capture and storage of CO_2.
Coal with carbon capture and storage (CCS)	Utilises coal as a fuel source while employing CCS technologies to capture and store CO_2 emissions.
Concentrated solar power (CSP)	Concentrates sunlight to a receiver with a heat-transfer fluid (such as molten salts), producing heat to drive turbines for electricity generation.
Gas with CCS	Uses natural gas to generate electricity, coupled with CCS systems to mitigate CO_2 emissions.
Geothermal energy	Harnesses heat from the Earth's interior to generate steam, which drives turbines to produce electricity.
Hydrogen reciprocating	Uses hydrogen in internal combustion engines to generate electricity with water vapor as the primary by-product.
Hydroelectricity	Generates electricity by harnessing the energy of flowing or falling water (including run-of-the-river) to spin turbines connected to generators.
Nuclear power	Produces electricity using nuclear fission or fusion reactions in reactors. This category considers both large-scale reactors and small modular reactors (SMRs).
Ocean energy	This category includes ocean, wave and tidal technologies. Uses the movements of the ocean, including surface waves (wave energy) and the effect of the gravitational pull of the sun and moon (tidal energy) to generate electricity.
Solar photovoltaics (PV)	Converts sunlight directly into electricity using photovoltaic cells.
Wind	Converts wind energy into power using turbines on land or sea.

4.3.2 Primary technology parameters

Technology assessment involved evaluating the technologies identified through preliminary filtering against singular performance parameters for large-scale electricity generation (Table 3). The lowest cost mitigation technologies able to meet the scale of generation required were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in *Section 4.4.2 Primary technology analysis*

Table 3: Technology filtering criteria – Electricity generation

Subsector	**Electricity generation**
Use case(s)	**Large-scale generation**
Preliminary filtering criteria	**Relevance to Australia** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions. *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources*
	Technology maturity Technology has a TRL greater than 3. The TRL index can be found in *Appendix A.2.*
	Abatement potential

	Technology options have been compared against a ‘zero-emissions’ benchmark. This was established to reflect the anticipated availability of zero emissions technology solutions with significant abatement potential by 2050, and in accordance with long term decarbonisation targets which acknowledge supply-side technology impacts on downstream emissions.
Primary technology analysis	**Levelised Cost of Electricity (LCOE) in 2050** Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOE relative to other assessed technologies (in $ per MWh).
	Note: A second performance parameter was not included. An assessment of each technology’s ability to address use case requirements has already been made, given that the broad technology list was created from GenCost’s technology list.[11]

4.4 Technology analysis

This chapter outlines the process of identifying *Primary technologies* for Australia’s electricity generation subsector. Following the technology analysis framework process, **concentrated solar power (CSP), solar photovoltaics (PV), and wind emerged as *Primary technologies* for further RD&D exploration.** These were able to service the designated use case and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in the decarbonisation of electricity generation, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. The results of the technology analysis for electricity generation are provided in Table 4.

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[11] Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia.

Table 4: Technology analysis results – Electricity generation[12]

🟦 Meets criteria ◻ Meets with caveats ⬜ Does not meet ★ Primary technology ▨ Not assessed further

1. Preliminary filtering

2. Primary technology analysis

Large-scale generation

Technologies	**Relevance to Australia**	**Maturity** *TRL > 3*	**Abatement threshold** *≥100%*	**LCOE (2050)**	
Biomass	🟦	CRI 4-6	86%	▨	▨
Biomass with carbon capture and storage (BECCS)	Geo-dependent (CCS)	TRL 5 - CRI 2	≥100%	$529/MWh	▨
Coal with carbon capture and storage (CCS)	Geo-dependent (CCS)	TRL 6-8	73%	▨	▨
Concentrated solar power (CSP)	🟦	CRI 2-6	100%	$101/MWh	★
Gas with CCS	Geo-dependent (CCS)	TRL 6-8	73%	▨	▨
Geothermal energy	🟦	TRL 5 - CRI 6	100%	Inconclusive	▨
Hydrogen reciprocating	🟦	TRL 9 - CRI 2	100%	$488/MWh	▨
Hydroelectricity	No new sites			▨	▨
Nuclear power	🟦	TRL 2 – CRI 6	100%	$310/MWh (SMR) $210/MWh (large-scale reactor)	▨
Ocean energy[13]	Environmental constraints	TRL 5 - CRI 2	100%	$582/MWh	▨
Solar photovoltaics (PV)	🟦	TRL 4 - CRI 6	100%	$32/MWh[14]	★
Wind (on, offshore)	🟦	TRL 8 - CRI 6	100%	$60/MWh (onshore)[14] $124/MWh (offshore, fixed)[14]	★

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[12] Details for these figures, including sources/assumptions, are found in Table 5 (maturities), and under ‘Abatement potential’, ‘Levelised cost analysis’ and *Technical Appendix: Levelised cost analysis*.

[13] Includes ocean, wave and tidal technologies.

[14] For variable renewable energy (VRE) technologies solar and wind, integration costs such as costs representing transmission, spillage and synchronous condensers have been included. These have been taken from GenCost's 2030 modelled case on 90% VRE adoption for electricity generation. Integration costs were not estimated for ocean.

4.4.1 Preliminary filtering

Key information – Preliminary filtering

Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:

- **Relevance to Australia:** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- **Technology maturity*:*** Technology has a TRL greater than 3.
- **Abatement potential:** Technology demonstrates the potential to meet a nominated abatement threshold. The threshold for this sector is distinguished in the relevant filtering section, below.

Relevance to Australia

Most of the technologies for the given use case meet this criterion as they can be reasonably deployed in the Australian context. Explanations for technologies that have not met this criterion, or that meet this criterion with caveats, are provided below.

CCS-coupled pathways

Pathways reliant on CCS meet the criteria with caveats, as they are dependent on appropriate subsurface formations for permanent geological storage.

CCS-coupled pathways rely on point-source carbon capture along the production route, which is then permanently stored in deep, geological formations. This requires the identification of subsurface structures that possess acceptable injectivity, capacity and seal characteristics for permanent CO_2 storage. For further detail, please refer to the *Carbon Management* technical appendix*.*

Hydroelectricity

Hydroelectricity does not meet the criterion, due to geographic limits preventing new large-scale sites.

Although Australia has several large-scale hydro sites, which are expected to remain operational,[15] Australia also has lower levels of rainfall compared to other countries, and experiences significant fluctuations in rainfall and temperatures annually, leading to constrained and inconsistent surface water resources. The dry climate, low runoff (reduced water flow over land) and limited water availability limit any significant expansion of existing hydroelectric power infrastructure. For these reasons, no new large-scale hydro sites are currently expected in Australia.[16] For more details, refer to the Box 2: Hydroelectricity RD&D case study and *Section 5.6.3 Pumped hydro energy storage (PHES).*

Ocean energy

Ocean energy technologies meet the criterion with caveats, due to reliance on geographic features, seasonal factors and hydrological patterns. These technologies include tidal, wave, and thermal energy systems that harness the kinetic and thermal properties of ocean water. Their viability in Australia is constrained by limited geographic features suitable for tidal energy, seasonal variations in wave intensity, and inconsistent thermal gradients, making deployment challenging.

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[15] ARENA (2018) Australian Energy Resource Assessment. <https://arena.gov.au/assets/2018/08/australian-energy-resource-assessment.pdf> (accessed 10 December 2024).

[16] Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia.

Technological maturity

All technologies were found to include technologies with a TRL greater than 3 (see Table 5). Maturity ratings are based on the IEA Clean Energy Technology Guide and supplemented with additional literature when needed.[17]

Table 5: Technology maturities – Electricity generation

Technology category	TRL
Biomass	• CRI 4-6
Bioenergy with carbon capture and storage (BECCS)	• Overall: TRL 5 - CRI 2 ○ Carbon capture separation technologies: [18] ○ Biomass capture pathways[19] ○ Industrial applications with BECCS[20] ○ Demonstration and pilot scale BECCS facilities[21]
Coal with CCS	• TRL 6-8[22]
Concentrated solar power (CSP)	• CRI 2-6
Gas with CCS	• TRL 6-8[23]
Geothermal energy	• Overall: TRL 5 - CRI 6 ○ Dry steam, flash process, organic Rankine cycle: CRI 6 ○ Direct lithium extraction (brine): TRL 7 ○ Enhanced geothermal systems, Kalina process: TRL 6 ○ Closed-loop / hybrid closed loop systems: TRL 5
Hydrogen reciprocating	• TRL 8-9
Hydroelectricity[24]	• CRI 6
Nuclear power	• Overall: TRL 2 - CRI 6 ○ Generation II-III+ fission reactors: CRI 4-6

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[17] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[18] Osman A, Hefny M, Abdel Maksoud M, et al (2021) Recent advances in carbon capture storage and utilisation technologies: a review. Environ Chem Lett 19, 797–849 <https://doi.org/10.1007/s10311-020-01133-3>; Garcia J, Villen-Guzmen M, Rodriguez-Maroto J, Paz-Garcia J (2022) Technical analysis of CO2 capture pathways and technologies. Journal of Environmental Chemical Engineering. <https://doi.org/10.1016/j.jece.2022.108470>; Almena A, Thornley P, Chong K, Roder M (2022) Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass and Bioenergy <https://doi.org/10.1016/j.biombioe.2022.106406>; International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[19] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology>.

[20] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology>.

[21] Two pilot plants for power generation have been piloted and are now currently in development planning see; Almena A, Thornley P, Chong K, Roder M (2022) Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass and Bioenergy <https://doi.org/10.1016/j.biombioe.2022.106406> Toshiba Energy Systems and Solutions Cooperation (2020) Toshiba Starts Operation of Large-Scale Carbon Capture Facility. <https://www.global.toshiba/ww/news/energy/2020/10/news-20201031-01.html>

[22] As of November 2023, four coal-fired plants with CCS are operational worldwide: two in China, one in the United States, and one in Canada. However, these plants are typically used for enhanced oil recovery and not power generation. Coal with CCS technologies are still under development and testing, resulting in a TRL of 6-8. For more information on coal fired plants for industrial uses see, Rempel Z, Cameron L, Bois von Krusk O (2023) Unpacking Carbon Capture and Storage: The technology behind the promise. <https://www.iisd.org/articles/insight/unpacking-carbon-capture-storage-technology>

[23] There are no commercial scale natural gas plants with CCS for power generation. Gas with CCS technologies are still under development and testing, resulting in a TRL of 6-8. For more information see, Cameron L, Carter A (2023) Why Carbon Capture and Storage Is Not a Net-Zero Solution for Canada's Oil and Gas Sector. <https://www.iisd.org/system/files/2023-02/bottom-line-carbon-capture-not-net-zero-solution.pdf>; Soepyan F, Habib M, Zhang Z, Nemetx L, Haque M, Esquino A, Rivero J, Bhattacharyya D, Lipscomb G, Matuszewski M, Hornbostel K (2024) Optimization of a Natural Gass Power Plant with Membrane and Solid Sorbent Carbon Capture Systems. Carbon Capture Science and Technology. <https://doi.org/10.1016/j.ccst.2023.100165>

[24] While hydroelectricity does not meet the requirements of the relevance to Australia criterion, it is included here for informational purposes.

	○ Generation IV fission reactors: TRL 4-9 ○ Fusion: TRL 2-3 ○ SMRs: TRL 5-7
Ocean energy	• Overall: TRL 5 - CRI 2 ○ Tidal range / ocean current: CRI 2 ○ Ocean wave: TRL 6-7 ○ Ocean thermal: TRL 5 ○ Salinity gradient: TRL 4
Solar photovoltaics (PV)	• Overall: TRL 4 - CRI 6 ○ First generation cells: CRI 6 (crystalline)[25] ○ Second generation cells: CRI 2-6 (thin film)[26] ○ Third generation cells: TRL 4-9[27]
Wind	• Overall: TRL 8- CRI 6 ○ Onshore: CRI 2-5 ○ Fixed offshore: CRI 2 ○ Floating offshore: TRL 8

Abatement potential

Key information – Abatement potential

The abatement potential criterion identifies technologies that meet or exceed a nominated abatement threshold. Emissions estimates reflect full fuel cycle emissions, including:

- Scope 1 (direct) emissions: arising from the direct use of a technology from the combustion or use of its fuel, including fugitives in some instances.
- Scope 2 (indirect) emissions: arising the production of a given energy input.
- Some Scope 3 emissions: For biofuels, indirect land-use change (ILUC) have been included for completeness; however, other Scope 3 emissions, such as embodied emissions have been excluded due to a lack of available data and low likelihood of impacting the relative results of the filtering criteria.

For more details, please refer to *Appendix A.4*.

A ‘zero emissions’ threshold has been set for this subsector, reflecting the expected availability of zero emissions technology solutions with significant abatement potential by 2050. This approach aligns with that taken in other supply-side assessments where an absolute threshold is applied in accordance with long term decarbonisation targets, acknowledging that supply-side technology choices largely determine the emissions intensity of downstream energy use.

The emissions factors, in CO_2 equivalents, for each technology are sourced from a report to the Australian Energy Market Operator’s (AEMO) by ACIL Allen Consulting and are reported in Table 6. These factors include the global warming impacts of carbon dioxide, methane, nitrous oxides and synthetic gases.

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[25] Pastuszak J, Węgierek P (2022) Photovoltaic cell generations and current research directions for their development. Materials 15(16), 5542. https://doi.org/10.3390/ma15165542; Zhao J (2004) Recent advances of high-efficiency single crystalline silicon solar cells in processing technologies and substrate materials. Solar Energy Materials and Solar Cells 82(1–2), 53–64. https://doi.org/10.1016/j.solmat.2004.01.005. For TRL, see, e.g., IEA (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[26] See, e.g., Wijewardane S, Kazmerski LL (2023) Inventions, innovations, and new technologies: Flexible and lightweight thin-film solar PV based on CIGS, CdTe, and a-Si:H. Solar Compass 7, 100053. https://doi.org/10.1016/j.solcom.2023.100053; Solak EK, Irmak E (2023) Advances in organic photovoltaic cells: A comprehensive review of materials, technologies, and performance. RSC Advances 13, 12244–12269. https://doi.org/10.1039/D3RA01454A

[27] Some of these technologies are also sometimes referred to as fourth generation cells / technologies. For the upper TRL provided for the range (i.e. TRL 9 for multi-junction cells), see IEA (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024). For the lower TRL provided for the range, see, e.g., Fraunhofer Institute for Solar Energy Systems (2024) Photovoltaics Report. <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html> (accessed 10 December 2024); Du T, Xu W, Xu S, Ratnasingham SR, Lin C-T, Kim J, Briscoe J, McLachlan MA, Durrant JR (2020) Light-intensity and thickness dependent efficiency of planar perovskite solar cells: charge recombination versus extraction. Journal of Materials Chemistry C 36, 12244–12269. https://doi.org/10.1039/D3RA01454A; Shi P, Xu J, Yavuz I, Huang T, Tan S, Zhao K, Zhang X, Tian Y, Wang S, Fan W, Li Y, Jin D, Yu X, Wang C, Gao X, Chen Z, Shi E, Chen X, Yang D, Xue J, Yang Y, Wang R (2024) Strain regulates the photovoltaic performance of thick-film perovskites. Nature Communications 15, 2579. https://doi.org/10.1038/s41467-024-25479-9

Table 6: Abatement potentials (fuel cycle) – Electricity generation[28]

Technology	Combustion	Fugitives	Total fuel cycle	Abatement potential	Source/assumption
	gCO_2e/kWh	*gCO_2e/kWh*	*gCO_2e/kWh*	*Threshold: zero emissions*	
Conventional baseload gas	**363**	**50**	**414**		**ACIL Allen (2016)**
Biomass	57	0	57	Positive	ACIL Allen (2016)
BECCS	*Assumed zero or negative*		≤0.0	Zero or negative	Zero or negative combustion and fugitive emissions
Coal with CCS	94	16	110	Positive	ACIL Allen (2016)
Concentrated solar power (CSP)	0	0	0	Zero	ACIL Allen (2016)
Gas with CCS	59	54	113	Positive	ACIL Allen (2016)
Geothermal energy	0	0	0	Zero	Zero combustion and fugitive emissions
Hydrogen reciprocating	0	0	0	Zero	Zero combustion and fugitive emissions
Hydroelectricity[29]	0	0	0	▨	Acil Allen (2016)
Nuclear power	0	0	0	Zero	Zero combustion and fugitive emissions
Ocean energy	0	0	0	Zero	Zero combustion and fugitive emissions
Solar photovoltaics (PV)	0	0	0	Zero	Acil Allen (2016)
Wind	0	0	0	Zero	Acil Allen (2016)

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[28] See tables 3.2 and 3.3, ACIL Allen Consulting (2016) AEMO Emissions Factors. Australian Energy Market Operator (AEMO). <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/ntndp/2016/data_sources/acil-allen---aemo-emissions-factors-20160511-pdf-document.pdf?la=en&hash=AB233ACCECC78768D7C236E307433C10>. See also, Oh K-Y, Nam W, Ryu M-S, Kim J-Y, Epureanu BI (2018) A review of foundations of offshore wind energy converters: Current status and future perspectives. Renewable and Sustainable Energy Reviews 88, 16–36. https://doi.org/10.1016/j.rser.2018.02.005

[29] While hydroenergy does not meet the requirements of the relevance to Australia criterion, it is included here for informational purposes.

A majority of the technologies meet the ‘zero emissions’ abatement criteria. Biomass, coal with CCS, and gas with CCS do not meet this criterion, as shown in Table 6.

Fossil fuels with CCS

While fossil fuels with CCS do not meet this threshold, they could still play a role in the energy transition as a transitionary technology. CCS pathways can provide a continuous supply of electricity with lower emissions than conventional fossil fuels, potentially providing support for VRE generation and storage.[30]

Natural gas is expected to play an important role as a firming technology. As such, gas peaker plants are used as a reference in the electricity storage cost analysis for other energy storage options. For more detail, please see the levelised cost discussion in *Section 5.4.2 Primary technology analysis*.

Biomass

Based on the sourced emissions factors, electricity derived from the combustion of biomass does not meet the abatement criteria.

4.4.2 Primary technology analysis

Key information – Primary technology analysis

A single criterion was employed to ensure the suitability and feasibility of each technology for the use case:

- **Levelised cost of electricity:** Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Unlike the other sectors, additional performance parameters beyond cost were not included as suitability was an implicit consideration in the broad technology list. The broad technology list was derived from GenCost analysis in which only utility scale technologies were considered, rendering additional assessment unnecessary.[31]

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[30] See, e.g., Energy Council (2024) Gas Outlook Highlights Peaking Plant Role in Transition. <https://www.energycouncil.com.au/analysis/gas-outlook-highlights-peaking-plant-role-in-transition/> (accessed 17 January 2025).

[31] Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia.

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Electricity (LCOE) was estimated to determine the viability of each technology considered. LCOE is defined as the average net present cost per unit of output (in $/MWh) over the lifetime of the system.

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis.*

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs of new deployments are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from the levelised cost analysis are outlined in Figure 7. CSP, solar PV and wind (onshore and offshore) were projected to be the most cost competitive, distinguished by a cost differential in LCOE relative to other assessed technologies, suggesting areas of promise for further RD&D activity**.** There is a cost differential between hydrogen reciprocating engines and ocean technology above CSP, solar PV and wind, while geothermal technology remains inconclusive due to insufficient data for LCOE modelling. These technologies were not identified as *Primary technologies*.

Levelised costs are distinct to market prices, which are driven by both aggregate demand and aggregate supply (generation) across an energy market. For a description of how electricity pricing works, please refer to The Australian Energy Regulators State of the Energy Market 2024 report.[32] Wholesale electricity prices of the NEM[33] and WEM[34] have been included to aid interpretation.

Assumptions have been designed to broadly align with the AEMO 2024 ISP IASR Step Change scenario. They have been sourced from GenCost 2024-25 except where indicated.[35] The midpoint of the GenCost low and high assumptions for capacity factor and fuel price have been used. Refer to *Technical Appendix: Levelised cost analysis* for detailed cost assumptions.

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[32] See Box 2.1: The Australian Energy Regulators (2024) State of the Energy market 2024 – National Electricity Market. <https://www.aer.gov.au/system/files/2024-11/State%20of%20the%20energy%20market%202024%20-%20Chapter%202%20-%20National%20Electricity%20Market_0.pdf>

[33] Average of Controlled Load 1 wholesale costs for 2023-2024 Default Market Offer 5 Final Determination. <https://www.aer.gov.au/system/files/Default%20market%20offer%20prices%202023-24%20final%20determination.pdf>

[34] Average Market Price for FY25 (Sep-24 – Jun-25). < https://aemo.com.au/energy-systems/electricity/wholesale-electricity-market-wem/data-wem/data-dashboard>

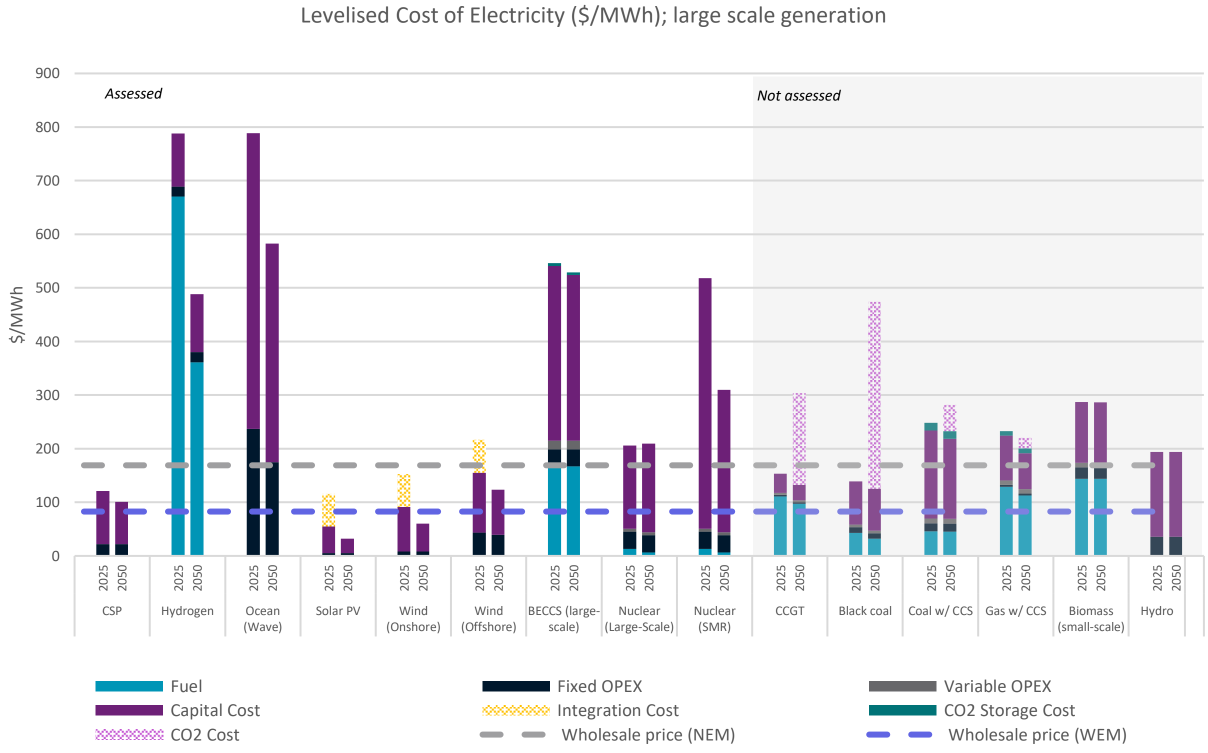
[35] Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia.

The fixed cost component includes insurance, operating and maintenance labour costs, and miscellaneous fixed charges.[36] The variable cost component includes scheduled maintenance and spare parts.[37]

Further sensitivity analysis was conducted to quantify the impact of applying the CO_2 emission price as a rebate for negative emissions and is outlined in Box 1.

Additional technologies included in Figure 7 include BECCS, coal with CCS, gas with CCS, hydroelectricity and nuclear power (large-scale, SMR). These technologies did not meet the earlier filtering criteria, respectively, with cost analysis conducted for reference only. In these instances, the cost of storing CO_2 was also captured.

Figure 7: Levelised cost of electricity ($/MWh) – Electricity generation



CSP, solar PV, wind (onshore and offshore)

CSP, solar PV and wind technologies are estimated to have the lowest LCOEs in 2025 and 2050 of all assessed technologies, even with the inclusion of integration costs in 2025.

Solar PV and wind technology integration costs (additional costs associated with storage, transmission, spillage and synchronous condensers) have been included for 2025. These are sourced from GenCost's 2024-25 modelled case on preparing for 90% VRE adoption.[38] Integration costs for 2050 were excluded based on the

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[36] Aurecon (2024) Cost and Technical Parameters Review Report for the Australian Energy Market Operator (AEMO). <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2024/aurecon-2024-cost-and-technical-parameters-review-report.pdf?la=en> (accessed 10 December 2024).

[37] Aurecon (2024) Cost and Technical Parameters Review Report for the AEMO. <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2024/aurecon-2024-cost-and-technical-parameters-review-report.pdf?la=en> (accessed 10 December 2024).

[38] Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia. Integration costs were derived from GenCost and calculated as the midpoint of the integration costs for the Low and High scenarios.

recognition that, by the 2040s, if variable renewable generation technologies are widely adopted, the majority of renewable integration resources will already be established.

Hydrogen reciprocating engines

This technology was estimated to have a much higher levelised cost compared to wind and solar, rendering it less competitive than these systems. Hydrogen reciprocating engines tend to have lower capital costs than other dispatchable technologies. However, fuel costs associated with the procurement and use of hydrogen fuel offsets these reductions and results in a higher overall levelised cost.

Ocean energy

Wave generation has been modelled as a representative of ocean energy technologies for this levelised cost analysis, given there is inconclusive data for ocean and tidal technologies.

Ocean (wave) energy exhibits the highest modelled levelised cost out of all modelled options due to its significantly high capital and variable costs. The levelised costs of wave generation are further inflated by the technology's low-capacity factor assumption relative to other technologies considered in this analysis (see the *Technical Appendix: Levelised cost analysis*).

Nuclear

The nuclear technologies modelled, large-scale reactor and SMR, were found to be less competitive compared to lowest cost technologies identified. Both options share similar fuel and operational costs. Large-scale plants are projected to be more cost competitive than SMRs due to substantially lower capital costs (per MW capacity), particularly in 2025.[39] See GenCost 2024-25 for information regarding other potential barriers to deployment.

Geothermal energy

Cost results for geothermal technology were inconclusive due to insufficient data for LCOE modelling. Capital costs are a significant driver of the LCOE for geothermal energy.[40] Geothermal energy in Australia faces unique challenges due to the country's low geothermal gradient and lack of active volcanoes, which make conventional geothermal systems unfeasible.[41] Unlike regions with active volcanoes and high geothermal gradients, Australia's resources require enhanced geothermal systems (EGS) or hot sedimentary aquifers (HSA) to extract heat from deep underground, with temperatures suitable for energy production (>160°C) only accessible at depths of over 3 kilometres. These depths increase drilling costs significantly, and the conductive thermal processes characteristic of most Australian geothermal reserves, where heat flows without fluid

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[39] See GenCost 2024-25 for other considerations related to deployment. Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia.

[40] Huddlestone-Holmes C (2014) Geothermal energy in Australia, prepared for the ARENA International Geothermal Energy Group. CSIRO. <https://www.arena.gov.au/assets/2017/02/Geothermal-Energy-in-Australia.pdf> (accessed 10 December 2024).

[41] Note that at a small scale, there may a role for low grade or low enthalpy (hot aquifer) geothermal resources in direct low temperature process heat use cases (e.g. swimming pools, food processing), and in geothermal heat and geothermal storage (ATES) for long duration applications. While technically suitable, there are limits to their applicability and impact, including: geological suitability (groundwater flow, borehole geometry), engineering precision (demand matching, renewable integration), economic factors (cost, financing, subsidies), and social considerations (public acceptance, groundwater conflicts): Sheldon HA, Wilkins A, Green CP (2021) Recovery efficiency in high-temperature aquifer thermal energy storage systems. Geothermics. <https://doi.org/10.1016/j.geothermics.2021.102173>

movement, further complicate accessibility.[42] Costs can be exacerbated by the significant distances between many of Australia's prospective geothermal resources, and transmission and distribution infrastructure.[43]

While geothermal energy has yet to become commercially viable in Australia,[44] advancements in international technology suggest potential for future development, offering a possibility to overcome these economic and technical hurdles.

Biomass, BECCS

While not assessed, the LCOE of biomass and BECCS have been modelled for informational purposes.

The projected cost competitiveness of large-scale biomass and BECCS is highly subject to the cost of biogenic feedstocks, which is in turn influenced by availability and competition. The additional capital and operational costs associated with CCS renders BECCS to be less cost competitive than biomass. However, the modelled levelised cost of BECCS does not include any credits for the net removal of CO_2 that this process could deliver as a co-benefit. Refer to Box 1 for further analysis.

Hydroelectricity

While not assessed, the LCOE of hydroelectricity has been modelled for informational purposes.

Dispatchable generation sources, such as hydroelectricity, have higher capital costs than wind and solar, driving up their overall levelised cost. Although the presence of commercial hydroelectric plants demonstrates their viability, this analysis is centred on the construction of new plants.

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[42] Geoscience Australia (2024), Australia's Energy Commodity Resources 2024 – Geothermal. <https://www.ga.gov.au/aecr2024/geothermal> (accessed 31 March 2025).

[43] ARENA (2018) Australian Energy Resource Assessment. <https://arena.gov.au/assets/2018/08/australian-energy-resource-assessment.pdf> (accessed 10 December 2024).

[44] See, e.g., Australia's sole geothermal energy plant in Birdsville, Queensland, which went out of operation in 2018 to shift focus to solar PV and storage due to 'changing energy market dynamics': ThinkGeoEnergy (2023) Birdsville in Australia Abandons Plans for Renewal of Geothermal Plant. <https://www.thinkgeoenergy.com/birdsville-in-australia-abandons-plans-for-renewal-of-geothermal-plant/> (accessed 10 December 2024).

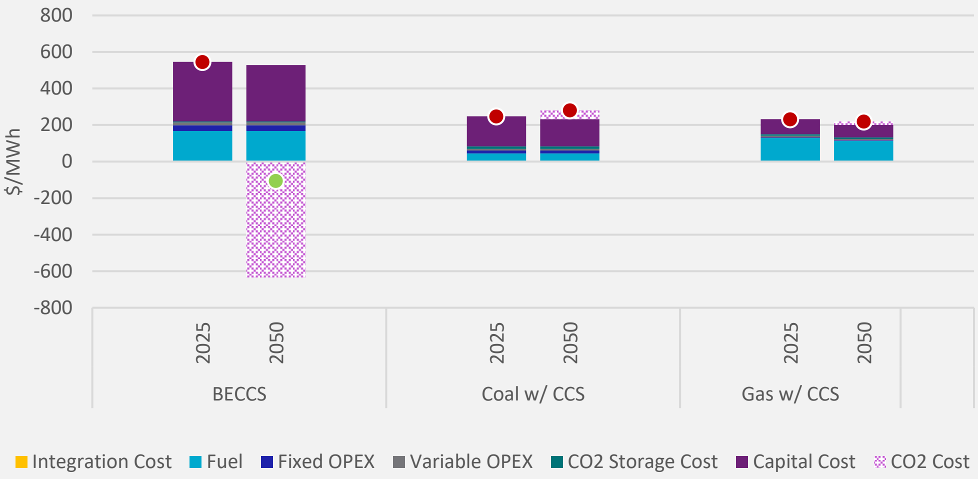
Box 1: Impact of carbon removals on electricity generation (BECCS, coal with CCS, gas with CCS)

Carbon credits could improve the economics of electricity generation processes that also remove CO_2 from the atmosphere and durably store it. The generation of carbon credits would create an additional revenue stream for the operator of a BECCS plant that would offset generation costs. In some cases**,** this could lead to a net-negative levelised cost of energy. This would allow the operator to bid into the electricity market at very competitive prices.

While BECCS has a relatively high levelised cost of electricity, as shown in Figure 8, it has the potential to deliver a co-benefit of durable carbon removal. In 2050, assuming a CO_2 cost of $435/t$CO_2$ and a biomass price of $11.43/GJ, this would lead to a positive cashflow (i.**e.** a negative cost) of $106/MWh generated (see Figure 8).[45] The value of the CO_2 rebate reflects the CO_2 cost that has been applied elsewhere in this analysis for fossil-based, carbon emitting processes.

Note that this outcome is highly sensitive to the assumed carbon price and the availability and cost of biogenic feedstock, both of which are highly uncertain.

Figure 8: Levelised cost of electricity for BECCS with a carbon credit



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[45] The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

4.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

Primary technologies directly contribute to emissions reduction within a given sector.

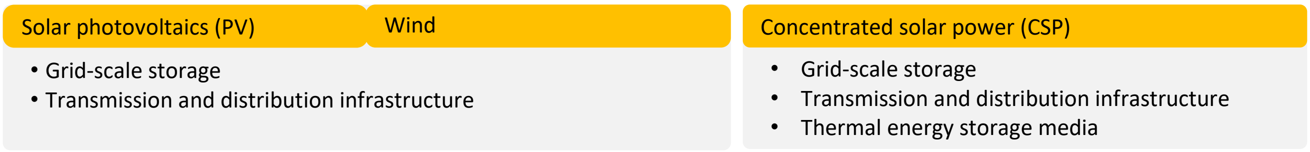
Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

The technology analysis framework identified solar PV, CSP and wind as *Primary technologies* for a large-scale generation use case (Figure 9).

Although not explored further, the other low emissions technologies evaluated in this report could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the electricity generation subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

Figure 9: Technology landscape identification – Electricity generation



The associated *Auxiliary technologies* and *Energy efficiency solutions* identified for analysis are outlined in Table 7 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

Solar PV, CSP and wind cannot exist in isolation and their successful use and deployment is dependent on a range of *Auxiliary technologies*, summarised in Table 7. *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure* notes RD&D opportunities required for transmission and distribution infrastructure, for all primary electricity generation technologies.

Table 7: Auxiliary technologies – Electricity generation

Primary technology	Auxiliary technology	Description
Solar photovoltaics (PV)	**Grid-scale storage**	Large-scale energy storage systems that are essential for balancing supply and demand, improving grid stability, and integrating renewable energy sources into the electricity network.

	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.
Concentrated solar power (CSP)	**Grid-scale storage**	Large-scale energy storage systems that are essential for balancing supply and demand, improving grid stability, and integrating renewable energy sources into the electricity network.
	Thermal energy storage (TES) media	TES media, such as molten salts and graphite, are often used as storage systems, where captured heat from CSP is not immediately converted into electricity.
	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.
Wind	**Grid-scale storage**	Large-scale energy storage systems that are essential for balancing supply and demand, improving grid stability, and integrating renewable energy sources into the electricity network.
	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.

Energy efficiency solutions

No explicit *Energy efficiency solutions* were identified for electricity generation; rather, a range of storage, transmission and distribution *Auxiliary technologies* will be a core focus of RD&D efforts across all *Primary technologies.*

4.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the identified technology landscape, spanning P*rimary, Auxiliary and Energy efficiency technologies*.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include non-technical RD&D opportunities. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 8. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Please note, levelised cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system.

Table 8: Summary of RD&D opportunities – Electricity generation[46]

Primary technologies		Solar PV			Concentrated solar power (CSP)	Wind (onshore, offshore)	
		1st gen	2nd gen	3rd gen	CSP collector	Turbines	Foundations
	Commercial	Crystalline silicon	Thin film	-	Parabolic trough collectors, solar power towers, parabolic dish collectors	*Onshore:* Horizontal axis wind turbines (HAWTS), vertical axis wind turbines (VAWTs) *Offshore:* HAWTs	*Onshore:* monopile, concrete, gravity *Offshore (fixed)*: monopile, jacket
	Mature	-	-	Multi-junction cells	Linear fresnel reflectors	-	*Onshore:* hybrid, pile, rock anchor *Offshore (floating):* Tension leg platform, spar-submersible, spar-buoy, suction caisson
	Emerging	-	-	Perovskites, dye-sensitised, organic PV, quantum dots	-	*Onshore:* Multi-rotor, adaptive, guy-wire supported *Offshore (floating)*: X-rotor	-

	Solar PV	Concentrated solar power (CSP)	Wind (onshore, offshore)
Primary RD&D	• Reduce system costs **(LCOE forecast: $32/MWh cf. $55, excluding integration)** through: - E.g. Improving commercial cell efficiencies **(Target: 30, 35% for commercial dual- and triple-junction cells respectively, cf. 24% for commercial silicon cells)**[47] - E.g. Developing cost efficient materials with less energy-intensive processing requirements, such as perovskites - E.g. Unlocking co-benefits through dual-use applications. • Improve durability through: - E.g. Enhancing thermal management and developing thermally stable materials	• Reduce system costs **(LCOE forecast: $101/MWh cf. $121),** through: - E.g. Enhancing thermal efficiency by incorporating novel heat transfer fluids (HTFs) with improved heat capacities - E.g. Improving system conversion efficiency, by incorporating advanced working fluids and high-performance materials • Develop improved high-temperature, corrosion-resistant materials to enhance CSP system durability	• Reduce system costs **(LCOE forecast: $60 & $124/MWh cf. $91 & $155 for onshore and offshore respectively, excluding integration),** through: - E.g. Enhancing turbine capacities and efficiencies by improving design and manufacturing processes - E.g. Optimising foundation systems designs • Expand deployment opportunities through novel turbine configurations
Auxiliary RD&D	• Establish sufficient grid-scale storage infrastructure to improve the stability of energy supply (refer to *Section 5: Electricity storage*) • Establish sufficient reliable generation, transmission and distribution infrastructure to support the energy network through: • E.g. enhancing inverter-based resources, new stability tools, better real-time visibility, innovative planning methods, black start procedures, system restoration, technical service quantification, future power system architectures, and managing high levels of distributed energy resources		

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cf. – Compare.

[46] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6.

[47] These targets refer to layered cells, that will use Si-based dual-junction solar cells with a bottom cell of silicon and a higher bandgap material on top of that (e.g. III-V semiconductors, Perovskite, silicon quantum dots): Fraunhofer Institute for Solar Energy Systems (2017) Current Status of Concentrator Photovoltaic (CPV) Technology. <https://www.ise.fraunhofer.de/en/publications/studies/studie-current-status-of-concentrator-photovoltaic-cpv-technology.html> (accessed 10 December 2024).

4.6.1 Solar photovoltaics (PV)

Solar PV cells transform sunlight directly into electricity. When sunlight photons strike the cells, they dislodge electrons from their atoms, generating an electric current. These cells are typically combined into solar panels, which can then be further configured into arrays and systems to generate significant amounts of electricity. There are three generations of solar PV cell technologies:

- **First generation cells** (CRI 6) are made primarily from monocrystalline and polycrystalline silicon.[48] They have been widely used due to their reliable performance and well-established manufacturing processes. Monocrystalline cells can reach up to 24% efficiency, making them among the most efficient types of solar cells commercially available.[49]
- **Second generation cells** include thin-film technologies like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) (CRI 2-6) and reach efficiencies of around 10-20%.[50] They require fewer active materials than first-generation cells and can be produced on flexible substrates.
- **Third generation cells** further develop the second-generation innovations of thin active layers and flexible substrates. They are characterised by their use of novel materials such as perovskites, dye-sensitised cells, and organic photovoltaics (TRL 4-9).[51] They also leverage advanced designs such as concentrated, multi-junction and tandem configurations, and quantum dots, offering potential for greater efficiencies and lower production costs.

In 2023, first generation cells constituted accounted for nearly 98% of total global PV production, with second generation cells comprising the remaining portion.[52]

While out of scope for this report, there are broad RD&D opportunities across the solar PV value chain, including pathways to low emissions polysilicon production and opportunities for greater recovery of high-quality minerals through downstream solar PV recycling. Further details on these opportunities can be found in CSIRO's *From Minerals to Materials: Assessment of Australia's Critical Mineral Mid-stream Processing Capabilities* report.[53]

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[48] Pastuszak J, Węgierek P (2022) Photovoltaic cell generations and current research directions for their development. Materials 15(16), 5542. https://doi.org/10.3390/ma15165542; Zhao J (2004) Recent advances of high-efficiency single crystalline silicon solar cells in processing technologies and substrate materials. Solar Energy Materials and Solar Cells 82(1–2), 53–64. https://doi.org/10.1016/j.solmat.2004.01.005. For TRL, see, e.g., IEA (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[49] Pastuszak J, Węgierek P (2022) Photovoltaic cell generations and current research directions for their development. Materials 15(16), 5542. https://doi.org/10.3390/ma15165542

[50] See, e.g., Wijewardane S, Kazmerski LL (2023) Inventions, innovations, and new technologies: Flexible and lightweight thin-film solar PV based on CIGS, CdTe, and a-Si:H. Solar Compass 7, 100053. https://doi.org/10.1016/j.solcom.2023.100053; Solak EK, Irmak E (2023) Advances in organic photovoltaic cells: A comprehensive review of materials, technologies, and performance. *RSC Advances* 13, 12244–12269. https://doi.org/10.1039/D3RA01454A

[51] Some of these technologies are also sometimes referred to as fourth generation cells / technologies. For the upper TRL provided for the range (i.e. TRL 9 for multi-junction cells), see IEA (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024). For the lower TRL provided for the range, see, e.g., Fraunhofer Institute for Solar Energy Systems (2024) Photovoltaics Report. <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html> (accessed 10 December 2024); Du T, Xu W, Xu S, Ratnasingham SR, Lin C-T, Kim J, Briscoe J, McLachlan MA, Durrant JR (2020) Light-intensity and thickness dependent efficiency of planar perovskite solar cells: charge recombination versus extraction. Journal of Materials Chemistry C 36, 12244–12269. https://doi.org/10.1039/D3RA01454A; Shi P, Xu J, Yavuz I, Huang T, Tan S, Zhao K, Zhang X, Tian Y, Wang S, Fan W, Li Y, Jin D, Yu X, Wang C, Gao X, Chen Z, Shi E, Chen X, Yang D, Xue J, Yang Y, Wang R (2024) Strain regulates the photovoltaic performance of thick-film perovskites. Nature Communications 15, 2579. https://doi.org/10.1038/s41467-024-25479-9

[52] Fraunhofer Institute for Solar Energy Systems (2024) Photovoltaics Report. <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html> (accessed 10 December 2024).

[53] CSIRO (2024) From minerals to materials: assessment of Australia's critical mineral mid-stream processing capabilities. CSIRO, Canberra

Primary technologies

RD&D is critical for driving continued cost reductions through solar cell efficiency and materials performance.

Forecast cost reductions to $32/MWh by 2050 (from $55/MWh in 2025, excluding integration costs) can be realised through a combination of innovative cell designs and the development of novel materials and coatings to improve conversion efficiencies and reduce materials intensity.

Crystalline silicon solar cells have a theoretical efficiency limit of 29.4% due to the fundamental properties of silicon as an indirect semiconductor, with today's commercial modules achieving up to 24%.[54] However, practical issues like recombination losses ensure that this maximum will never be achieved.[55]

Cost reductions can be achieved through improved efficiencies from innovative cell designs and materials. Multi-junction and tandem cell architectures improve efficiency by capturing a broader spectrum of sunlight and reducing thermalisation losses.[56] Dual- and triple-junction cells expected to achieve respective efficiencies of around 30% and 35%, by 2050. Notably, perovskite solar cells have achieved up to 28.6% efficiency in commercial-sized tandem configurations when layered atop conventional silicon cells, showing their high efficiency potential.[57] At laboratory scale, four-junction concentrated PV (CPV) cells have exceeded efficiencies of 40%.[58]

Scaling next-generation solar PV begets low-cost, manufacturing materials and streamlined processing techniques.

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[54] Fraunhofer Institute for Solar Energy Systems (2017) Current Status of Concentrator Photovoltaic (CPV) Technology. <https://www.ise.fraunhofer.de/en/publications/studies/studie-current-status-of-concentrator-photovoltaic-cpv-technology.html> (Accessed 10 December 2024). See also, Agora Energiewende (2015) Current and Future Cost of Photovoltaics. February 2015. <https://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf> (accessed 10 December 2024). These targets refer to layered cells, that will use Si-based dual-junction solar cells with a bottom cell of silicon and a higher bandgap material on top of that (e.g. III-V semiconductors, Perovskite, silicon quantum dots).

[55] Agora Energiewende (2015) Current and future cost of photovoltaics. <https://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf> (accessed 12 December 2024); Richter A, Hermle M, Glunz SW (2013) Reassessment of the limiting efficiency for crystalline silicon solar cells. IEEE Journal of Photovoltaics 3(4), 1184–1191. https://doi.org/10.1109/JPHOTOV.2013.2270351; Glunz SW (2014) Crystalline silicon solar cells with high efficiency. In Advanced Concepts in Photovoltaics. (Eds. AJ Nozik, G Conibeer, MC Beard) 1–29. The Royal Society of Chemistry, Cambridge, UK. Recombination losses are the energy losses that occur when electrons and holes recombine before they can contribute to electric current. In photovoltaic cells, these losses are a significant factor that limits their efficiency.

[56] See, e.g., Agora Energiewende (2015) Current and Future Cost of Photovoltaics. February 2015. <https://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf> (accessed 12 December 2024); Li Q, Li T, Kutlu A, Zanelli A (2024) Life cycle cost analysis and life cycle assessment of ETFE cushion integrated transparent organic/perovskite solar cells: Comparison with PV glazing skylight. Journal of Building Engineering 87, 109140. https://doi.org/10.1016/j.jobe.2024.109140; Xie G, Li H, Qiu L (2024) Recent advances on monolithic perovskite-organic tandem solar cells. Interdisciplinary Materials 3(1), e12142, 113-132. https://doi.org/10.1002/idm2.12142. Thermalisation loss occurs when the energy from photons hitting the solar cells is higher than the cell's bandgap. The excess energy is released as heat, which reduces the efficiency of the cells: Wang A, Xuan Y (2018) A detailed study on loss processes in solar cells. Energy 144, 490-500. https://doi.org/10.1016/j.energy.2017.12.058 https://www.sciencedirect.com/science/article/pii/S0360544217320911

[57] Renewables Now (2024) Oxford PV touts 28.6% efficiency for commercial-sized tandem cell. https://renewablesnow.com/news/oxford-pv-touts-28-6-percent-efficiency-for-commercial-sized-tandem-cell-824012> (10 December 2024). https://renewablesnow.com/news/oxford-pv-touts-286-efficiency-for-commercial-sized-tandem-cell-824012/At smaller scales, efficiencies of up to 33.9% have been achieved and theoretically tandem configurations can achieve efficiencies above 40%: World Economic Forum (2024) Tandem solar cells: A key to accelerating the energy transition. <https://www.weforum.org/agenda/2024/01/tandem-solar-cells-energy-transition/> (accessed 12 December 2024); National Renewable Energy Laboratory (NREL) (2024) Best research-cell efficiencies chart. <https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf> (accessed 12 December 2024).

[58] Fraunhofer Institute for Solar Energy Systems (2017) Current Status of Concentrator Photovoltaic (CPV) Technology. <https://www.ise.fraunhofer.de/en/publications/studies/studie-current-status-of-concentrator-photovoltaic-cpv-technology.html> (Accessed 10 December 2024); Fraunhofer Institute for Solar Energy Systems (2024) Photovoltaics Report. <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html> (accessed 10 December 2024). Cell efficiencies have reached 47.6%, and module efficiencies have reached 38.9%. Efficiencies of commercially available concentrator PV (CPV) modules exceed 30%.

There is further opportunity for research focused on developing cells from materials that have lower and more cost-efficient processing requirements. For example, perovskites, which require about 600 times less active material and require more simple processing techniques including lower temperature processing (<150°C).[59] However, these cells require significant RD&D to improve their stability and longevity, and to improve manufacturing processes for scale. As an example of this, CSIRO is working to develop scalable manufacturing processes for perovskites and organic PVs, including by using roll-to-roll processing.[60]

Identifying dual-use PV applications can expand the value of solar PV through the unlocking of co-benefits.

Co-benefits such as land-use efficiency, diversified revenue, and lower soft costs can be unlocked through RD&D into dual-use systems tailored to agricultural, urban, and industrial contexts. For example, agrivoltaics, the co-location of agricultural production with ground based solar photovoltaic systems, can be used to optimise energy and agricultural production, can increase land-use efficiency and yield, provide additional revenue streams for farmers and lower soft costs of solar systems.[61] Another example can be seen with building-integrated PV, where solar materials aim to be incorporated into conventional building materials such as shading in carports and parking structures, skylights, awnings and facades.[62]

Maintaining PV performance over time necessitates the use of reliable materials and thermal management systems.

Improving the reliability and lifespan of emerging solar technologies, particularly perovskites and organics, can be achieved through the management of thermal stress and material degradation. Extended exposure to high temperatures can lead to accelerated aging, decreased reliability, and reduced lifespan, especially in second- and third-generation cells.[63] Current RD&D is focused on developing more thermally stable material

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[59] For instance, the active layer of a perovskite may have a thickness of 250-750nm, relative to a typical silicon wafer with a thickness of 150,000nm. Perovskite sources: see, e.g., Qin Z, Wang Z, Huang Y, Wang J, Zhang Y, Wang Y, Lu X, Tang B, Yang S (2020) High-performance organic semiconductors for field-effect transistors through a molecular design approach. Journal of Materials Chemistry C 8(33), 11436–11444. https://doi.org/10.1039/D0TC03390A; Huo Y, Zhang X, Liu L, Wang M, Li Y, Wei H, Wang Z, Wang Y, Liu X, Chen X (2024) Advanced nanomaterials for sustainable energy applications: Challenges and perspectives. Nature Communications 15, 47019. https://doi.org/10.1038/s41467-024-47019-8. Silicon wafer source: Fraunhofer Institute for Solar Energy Systems (2024) Photovoltaics Report. <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html> (accessed 10 December 2024). Regarding processing techniques, for instance, perovskite materials can be manufactured using solution processing, where they are dissolved in a solvent and then applied to a substrate through methods like printing, spraying, or spinning. This facilitates quick production and requires less capital investment in manufacturing equipment compared to conventional silicon cell production. See, e.g., Min Y, Chen L, Zhao X, Wang Y, Li H, Liu Z, Zhang T (2022) Local nanoscale phase impurities are degradation sites in halide perovskites. Nature 610, 345–352. https://doi.org/10.1038/s41586-022-04872-1. Regarding processing temperature, see, e.g., Wang R, Sun J, Li F, Liu Z, Chen Y (2013) Low-temperature processed meso-superstructured to thin-film perovskite solar cells. Energy & Environmental Science 6(8), 1739-1743. https://doi.org/10.1039/C3EE40810H; Kahandal SS, Tupke RS, Bobade DS, Kim H, Piao G, Sankapal BR, Said Z, Pagar BP, Pawar AC, Kim JM, Bulakhe RN (2024) Perovskite solar cells: Fundamental aspects, stability challenges, and future prospects. Progress in Solid State Chemistry 74, 100463. https://doi.org/10.1016/j.progsolidstchem.2024.100463

[60] See, e.g., Weerasinghe HC, Macadam N, Kim JE, Sutherland LJ, Angmo D, Ng LWT, Scully AD, Glenn F, Chantler R, Chang NL, Dehghanimadvar M, Shi L, Ho-Baillie AWY, Egan R, Chesman ASR, Gao M, Jasieniak JJ, Hasan T, Vak D (2024) The first demonstration of entirely roll-to-roll fabricated perovskite solar cell modules under ambient room conditions. Nature Communications 15, 1656. https://doi.org/10.1038/s41467-024-38559-7. See also, more generally, Han X, Li B, Zhao Y, Tian C, Li K, Hou C, Li Y, Wang H, Zhang Q (2024) Dual-meniscus-assisted roller-coating for scalable and patterned perovskite solar cells. Solar Energy 271, 112454. https://doi.org/10.1016/j.solener.2024.112454

[61] Barron-Gafford G, Pavao-Zuckerman M, Minor R, Sutter L (2019) Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands. Nature Sustainability 2 (9). <https://doi.org/10.1038/s41893-019-0364-5>

[62] US DOE (n.d) Dual-Use Photovoltaic Technologies. Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/solar/dual-use-photovoltaic-technologies

[63] Solak EK, Irmak E (2023) Advances in organic photovoltaic cells: a comprehensive review of materials, technologies, and performance. RSC Advances 13, 12244–12269. https://doi.org/10.1039/D3RA01454A

combinations[64] and integrating passive and active cooling strategies to reduce operating temperatures.[65] Continuing these efforts can play a central role in preserving efficiency and reducing replacement costs over a system's operational life.

Auxiliary technologies

The distribution of generated electricity will be reliant on the availability of storage infrastructure and distribution networks.

Grid-scale electricity storage systems, discussed further in *Section 5: Electricity storage*, play a crucial role in stabilising the supply of electricity sourced from variable renewable energy technologies. For example, systems that store excess energy generated during peak sunlight hours for use during low sunlight hours.

Transmission and distribution infrastructure will be required to enable reliable generation, transmission and distribution throughout the energy network. Refer to *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure* for more information.

4.6.2 Concentrated solar power (CSP)

Concentrated solar power (CSP) uses mirrors or lenses to gather direct solar irradiation and create high-temperature heat stored in a heat transfer fluid (HTF). When required, this HTF drives a thermodynamic cycle with a generator to produce electricity. Concentrated solar thermal (CST) specifically refers to the initial generation and storage of thermal energy in CSP electricity generation (see also *Section 5.6.2: Thermal energy storage with electricity output (TESe)*).

CSP technologies are distinguished by how they focus solar radiation onto the receiver: parabolic trough collectors, solar power towers, parabolic dish collectors, and linear fresnel reflectors (TRL 7 - CRI 6).[66]

Primary technologies

Reducing CSP costs could be achieved through increased thermal efficiency, including RD&D on improved thermal media.

Achieving the forecasted reduction in CSP's LCOE from $121/MWh in 2025 to $101/MWh by 2050, will likely require gains in thermal efficiency and durability. These gains hinge on the development of next-generation heat transfer and storage materials that can operate at higher temperatures with reduced degradation. Researchers are advancing novel HTFs and storage materials that have improved heat capacities, addressing thermal losses.[67] Conventional nitrate-based molten salts are widely used as HTFs for temperatures up to

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[64] See, e.g., Li S, Ma R, Zhao X, Guo J, Zhang Y, Wang C, Ren H, Yan Y (2020) Enhanced photovoltaic performance and stability of planar perovskite solar cells by introducing dithizone. Solar Energy Materials and Solar Cells 206, 110290. https://doi.org/10.1016/j.solmat.2019.110290https://www.sciencedirect.com/science/article/pii/S0927024819306191; Tian C, Han X, Zhao Y, Sun Z, Hou C, Wang H, Qi J, Li Y, Jia W, Zhang Q (2021) Anion effect on properties of Zn-doped $CH_3NH_3PbI_3$ based perovskite solar cells. Solar Energy Materials and Solar Cells 233, 111400. https://doi.org/10.1016/j.solmat.2021.111400; Zhao Y, Zhang X, Han X, Hou C, Wang H, Qi J, Li Y, Zhang Q (2021) Tuning the reactivity of PbI_2 film via monolayer $Ti_3C_2T_x$ MXene for two-step-processed $CH_3NH_3PbI_3$ solar cells. Chemical Engineering Journal 417, 127912. https://doi.org/10.1016/j.cej.2020.127912

[65] In the context of CPVs, see, e.g., Yang Q, Zhang P, Zhang T, Wang L, Ding Y (2024) Enhancing concentrated photovoltaic power generation efficiency and stability through liquid air energy storage and cooling utilization. Solar Energy 280, 112875. https://doi.org/10.1016/j.solener.2024.112875 https://www.sciencedirect.com/science/article/pii/S0038092X2400570X

[66] IEA (2023) Clean Technology Guide. International Energy Agency. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024); Zhang HL, Baeyens J, Degrève J, Cacères G (2013) Concentrated solar power plants: Review and design methodology. Renewable and Sustainable Energy Reviews 22, 466–481. https://doi.org/10.1016/j.rser.2013.01.032

[67] Vignarooban K, Xu X, Arvay A, Hsu K, Kannan AM (2015) Heat transfer fluids for concentrating solar power systems – A review. Applied Energy 146, 383-396. https://doi.org/10.1016/j.apenergy.2015.01.125

800°C but are constrained by high freezing points, corrosiveness at elevated temperatures and associated increases in maintenance costs due to thermal stress on CSP infrastructure.[68] Alternative HTFs, including novel chloride, fluoride or carbonate-based molten salts, are being researched. These options offer thermal stability at elevated temperatures and are more cost-effective, although they maintain high freezing points and may exhibit heighted corrosiveness. Falling particle systems, involving free-flowing fine ceramic media, are being validated at pilot-scale (TRL 4-6) (see *Section 5.6.2: Thermal energy storage with electricity output (TESe),* for further discussion on thermal media).[69] These systems offer the dual benefit of functioning as both HTF and thermal storage medium, capable for storing solar energy at temperatures of up to 800°C.[70]

Improvements in thermal media can be leveraged to optimise CSP's core advantage in its ability to combine generation and storage, and contribute to cost reduction efforts to improve commercial viability.

Improving the cost competitiveness of CSP could be achieved through increases in system conversion efficiency, enabled by innovations in working fluids and high-performance materials.

To reach a levelised cost of $101/MWh by 2050, CSP systems can benefit from higher heat-to-electricity conversion efficiencies. This could be achieved by advancing working fluids and high-performance materials that allow for operation at high temperatures and pressures without compromising durability.

CSP plants conventionally use subcritical water or steam, functioning at high temperatures but lower pressures, constraining thermodynamic efficiency. Researchers are exploring advanced working fluids like supercritical CO_2, which operate at increased pressures and temperatures (600-750°C) to achieve conversion efficiencies of around 50%.[71] Supercritical CO_2 can be used as an advanced working fluid, with the increase pressure improving carbon dioxide's heat transfer properties and reducing the energy required for compression. It also allows for the use of smaller turbomachinery and heat exchangers by a factor of 10, significantly reducing equipment size and cost.[72] Supercritical CO_2 systems introduce new challenges, such as the increased risk of corrosion in the presence of water; these may be overcome with materials advancements.

Unlocking higher-temperature operation and system life requires corrosion-resistant materials that can be developed through RD&D.

Researchers are developing high-temperature, corrosion-resistant materials to enhance CSP system durability and longevity. Advanced alloys and ceramics can enable infrastructure to withstand temperatures beyond the range of conventional steel alloys. High-temperature ceramics and nickel-based superalloys are engineered to operate at 700°C or higher, facilitating more efficient cycles. These cycles require the use of advanced HTFs

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[68] Baigorri J, Zaversky F, Astrain D (2023) Massive grid-scale energy storage for next-generation concentrated solar power: A review of the potential emerging concepts. Renewable and Sustainable Energy Reviews 185, 113633. https://doi.org/10.1016/j.rser.2023.113633

[69] Baigorri J, Zaversky F, Astrain D (2023) Massive grid-scale energy storage for next-generation concentrated solar power: A review of the potential emerging concepts. Renewable and Sustainable Energy Reviews 185, 113633. https://doi.org/10.1016/j.rser.2023.113633

[70] CSIRO (2024) Australian Solar Thermal Research Initiative (ASTRI). <https://www.csiro.au/en/research/technology-space/energy/Solar-thermal/ASTRI> (assessed 10 December 2024).

[71] The Australian Solar Thermal Research Institute (ASTRI) have used CSP demonstration facilities to run supercritical CO_2 Brayton cycle at up to 700°C. CSIRO achieved a world record in 2013 with the highest temperature supercritical steam produced from solar energy, at 591 ºC at 23.1 MPa. See, e.g., CSIRO (2024) Australian Solar Thermal Research Initiative (ASTRI). <https://www.csiro.au/en/research/technology-space/energy/Solar-thermal/ASTRI> (assessed 10 December 2024); CSIRO. Solar thermal. <https://www.csiro.au/en/research/technology-space/energy/Solar-thermal> (accessed 10 December 2024); Baigorri J, Zaversky F, Astrain D (2023) Massive grid-scale energy storage for next-generation concentrated solar power: A review of the potential emerging concepts. Renewable and Sustainable Energy Reviews 185, 113633. https://doi.org/10.1016/j.rser.2023.113633

[72] CORDIS (2024) Results of the project: 640905. <https://cordis.europa.eu/project/id/640905/results> (accessed 10 December 2024); Baigorri J, Zaversky F, Astrain D (2023) Massive grid-scale energy storage for next-generation concentrated solar power: A review of the potential emerging concepts. Renewable and Sustainable Energy Reviews 185, 113633. https://doi.org/10.1016/j.rser.2023.113633

such as higher-temperature molten salts, which may exhibit increased corrosiveness.[73] Researchers are developing corrosion mitigation strategies, such as applying graphite or nanoparticle coatings, to mitigate against the corrosive effects of molten salts.[74] These solutions aim to protect critical components, allow CSP systems to operate at higher temperatures and extend the lifespan of CSP infrastructure.

Auxiliary technologies

The distribution of generated electricity will be reliant on the availability of storage infrastructure and distribution networks.

Refer to *Section 5: Electricity storage* for discussion on grid-scale electricity storage systems, vital for maintaining a steady supply of power from variable renewable energy technologies such as CSP. TES media such as molten salts and graphite are often used for energy storage with CSP, where captured heat is not immediately converted into electricity: refer to *Section 5.6.2: Thermal energy storage with electricity output (TESe),* for detail on TESe storage options.

Transmission and distribution infrastructure will be required to enable reliable generation, transmission and distribution throughout the energy network. Refer to *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure* for more information.

4.6.3 Wind

Wind energy harnesses the natural movement of air to generate electricity. Wind generation equipment is comprised of two key sub-components: the turbine, including the rotor blades, nacelle (gears and generator), and tower, and the foundation on which the wind turbine is located. The foundation (and location) distinguishes onshore and offshore systems.

Wind farms can be located onshore or offshore. Onshore wind farms are typically constructed in less populated regions where obstacles like buildings do not obstruct airflow. Offshore wind farms are located on fixed and floating foundations off the coast, where the wind quality is often superior, characterised by stronger and more consistent wind speeds. This reduces turbulence, lessening turbine fatigue and extending the lifespan of offshore turbines.[75]

Primary technologies

The costs of turbines can be reduced by improving system performance and manufacturing processes, enabled through developments in turbine design and materials.

Onshore and offshore wind RD&D is primarily focused on reducing costs and improving the performance of turbines, which represent up to 75% of total wind project expenditure.[76] LCOE forecasts indicate that wind generation could cost $60-124/MWh by 2050 for onshore and offshore respectively, compared to $91-

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[73] Bell S, Steinberg T, Will G (2019) Corrosion mechanisms in molten salt thermal energy storage for concentrating solar power. Renewable and Sustainable Energy Reviews 114, 109328. < https://doi.org/10.1016/j.rser.2019.109328.>; Mortazavi A, Zhao Y, Esmaily M, Allanore A, Vidal J, Birbilis N (2022) High-temperature corrosion of a nickel-based alloy in a molten chloride environment – The effect of thermal and chemical purifications. Solar Energy Materials and Solar Cells 236, 111542. < https://doi.org/10.1016/j.solmat.2021.111542.>

[74] González-Fernández L, Weiss J, Haas F, Serrano A, Azpiazu A, Anagnostopoulos A, Gaddam A, Dimov S, Bondarchuk O, Chorążewski M, Fluri T, Ding Y, Palomo E, Fernandez A. G, Grosu Y (2025) Large-scale testing of corrosion mitigation strategies for molten salts at concentrated solar power plants. Journal of Energy Storage 108, 11500. < https://doi.org/10.1016/j.est.2024.115060 >

[75] Esteban M.D., Diez J.J., López J.S., Negro V. (2011) Why offshore wind energy? Renewable Energy 36(2), 444–450. https://doi.org/10.1016/j.renene.2010.07.009

[76] Esteban M.D., Diez J.J., López J.S., Negro V. (2011) Why offshore wind energy? Renewable Energy 36(2), 444–450. https://doi.org/10.1016/j.renene.2010.07.009

155/MWh in 2025. Turbines larger than 1 MW offer greater stability and reliability, and their use reduces the number of units needed for a given wind farm capacity, lowering costs and land use impacts per MW installed.[77]

RD&D efforts are enabling improvements in turbine capacity factors and efficiencies through advanced turbine materials, aerodynamic designs and approaches to manufacturing. Current areas of research centre on the use of lightweight materials and novel blade designs that enhance wind capture across a broad range of speeds, improve erosion resistance, extend blade lifespan. These design enhancements contribute to lower drivetrain costs and longer operational life.[78]

In addition, computational fluid dynamics that incorporate 3D-aerodynamics also serve to improve turbine efficiency. New manufacturing approaches, such as 3D printing and adaptive spiral welding, can further reduce turbine weight, improve quality and lower manufacturing costs.[79]

Large, onshore turbines, now with commercial capacities around 6MW, are being refined to overcome transport, noise and efficiency challenges. Outside the Australian context there are projects pursuing the development of adaptive turbines, alongside advanced noise prediction tools and advanced structural and dynamic models to address these challenges.[80] Emerging designs, such as flexible-bladed, oversized rotors, could improve turbine capacity factors by 10% or more compared to typical land-based turbines.[81]

Reducing offshore wind energy costs can be enabled through advanced foundation systems that lower costs, enhance stability and ease installation.

Offshore turbines currently achieve over double the capacity of their onshore counterparts, but face distinct challenges due to harsh marine environments, installation complexity, and transmission costs. Offshore projects must ensure foundation stability under extreme weather and while achieving sufficient height for their blades to clear the highest wave crests while managing higher mechanical loads.[82]

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[77] IRENA (2019) The Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects. International Renewable Energy Agency. <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf?rev=c324896ba0f74c99a0cde784f3a36dff> (accessed 10 December 2024); Zhang Y., Li J., Li W., Liao Q., Liu J., Cheng J., Wang Z. (2023) A new perspective on the future of wind energy integration in smart grids. Nature Energy, 8(7), 848–860. https://doi.org/10.1038/s41560-023-01266-z; Akhtar, N., Geyer, B., & Schrum, C. (2024). Larger wind turbines as a solution to reduce environmental impacts. Scientific Reports, 14, Article 6608. https://doi.org/10.1038/s41598-024-27944-w

[78] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Next Generation Wind Technology. <https://www.energy.gov/eere/wind/next-generation-wind-technology> (accessed 10 December 2024); University of Newcastle, Australia. Wind Energy Research Centre. <https://www.newcastle.edu.au/research/centre/wind-energy> (accessed 10 December 2024); Bortolotti P, Branlard E, Gupta A, Johnson N, Jonkman J, Moriarty P, Paquette J, Snowberg D, Veers P (2024) The Wind Turbine Rotors of the Future: A Research Agenda from the Big Adaptive Rotor Project. Golden, CO: National Renewable Energy Laboratory <https://www.nrel.gov/docs/fy24osti/86097.pdf.>

[79] Bortolotti P et al. (2024) The Wind Turbine Rotors of the Future: A Research Agenda from the Big Adaptive Rotor Project. Golden, CO: National Renewable Energy Laboratory <https://www.nrel.gov/docs/fy24osti/86097.pdf.>;

[80] U.S. Department of Energy (2021) Flexing the Limits of Land-Based Wind Turbine Rotor Growth. <https://www.energy.gov/sites/default/files/2021/01/f82/bar-fact-sheet-2021.pdf>

[81] U.S. Department of Energy (2021) Flexing the Limits of Land-Based Wind Turbine Rotor Growth. <https://www.energy.gov/sites/default/files/2021/01/f82/bar-fact-sheet-2021.pdf>

[82] See e.g. Gevernova. Cypress Platform. <https://www.gevernova.com/wind-power/onshore-wind/cypress-platform> (accessed 10 December 2024); Gevernova. Haliade-X Offshore Turbine. <https://www.gevernova.com/wind-power/offshore-wind/haliade-x-offshore-turbine> (accessed 10 December 2024). See also, Esteban, M. D., Diez, J. J., López, J. S., & Negro, V. (2011). Why offshore wind energy? Renewable Energy, 36(2), 444–450. https://doi.org/10.1016/j.renene.2010.07.009; IRENA (2019) Future of Wind: Deployment, investment, technology, grid integration, and socio-economic aspects. <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf> (10 December 2024); UNEP Finance Initiative (2020) Global Trends in Renewable Energy Investment 2020. UNEP, Nairobi. <https://www.fs-unep-centre.org/wp-content/uploads/2020/06/GTR_2020.pdf> (accessed 10 December 2024).

RD&D into foundational systems is important for reducing offshore wind costs and improving deployment feasibility.[83] By 2025, LCOE analysis indicates that offshore wind energy will be 120% more expensive than onshore, though technology advancements could reduce this gap to 50% by 2050. Improving foundation materials and structural designs, simplifying logistics, and reducing material inputs are important RD&D areas to achieve this.[84]

Floating foundation designs are a key focus. These systems, anchored to the seabed with cables rather than fixed structures, may allow for lower costs through engineering to reduce steel requirements and allow for standardised, rather than site-specific, designs. Floating platforms also allow turbines to be assembled onshore and towed to their final location, reducing the cost and complexity of marine construction and installation.[85]

Deploying wind energy in space-constrained or decentralised contexts depends on novel turbine configurations tailored to site conditions.

In addition to utility-scale wind development, RD&D in turbine configurations can further enable deployments in decentralised, off-grid, or urban contexts. These environments present spatial and energy constraints that differ from large-scale onshore or offshore farms. Multirotor turbines that use multiple smaller rotors on a single structure, are being explored for their potential to improve wind capture in low wind or urban locations. Likewise, vertical axis wind turbines, which feature a singular vertical rotor, are smaller, cheaper to manufacture and can harness wind from any direction, making them promising candidates for urban locations.[86]

Auxiliary technologies

The distribution of generated electricity will be reliant on the availability of storage infrastructure and distribution networks.

Wind variations affect grid operations, including cost, power quality, power imbalances, and transmission planning.[87] In addition transmission and distribution infrastructure (refer to *section 4.6.4: Auxiliary technology: Transmission and distribution infrastructure*), wind generation will require support from electricity storage systems to improve the stability of energy supply (refer to *Section 5: Electricity storage*).

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[83] Esteban M.D., Diez J.J., López J.S., Negro V. (2011) Why offshore wind energy? Renewable Energy 36(2), 444–450. https://doi.org/10.1016/j.renene.2010.07.009; Wu X., Hu Y., Li Y., Yang J., Duan L., Wang T., Adcock T., Jiang Z., Gao Z., Lin Z., Borthwick A., Liao S. (2019) Foundations of offshore wind turbines: A review. Renewable and Sustainable Energy Reviews 104, 379–393. https://doi.org/10.1016/j.rser.2019.01.012

[84] Wu X., Hu Y., Li Y., Yang J., Duan L., Wang T., Adcock T., Jiang Z., Gao Z., Lin Z., Borthwick A., Liao S. (2019) Foundations of offshore wind turbines: A review. Renewable and Sustainable Energy Reviews 104, 379–393. https://doi.org/10.1016/j.rser.2019.01.012

[85] UN Environment Programme (2020) Global Trends in Renewable Energy Investment 2020. UNEP, Nairobi. <https://www.fs-unep-centre.org/wp-content/uploads/2020/06/GTR_2020.pdf> (accessed 10 December 2024).

[86] Bortolotti P et al. (2024) The Wind Turbine Rotors of the Future: A Research Agenda from the Big Adaptive Rotor Project. Golden, CO: National Renewable Energy Laboratory <https://www.nrel.gov/docs/fy24osti/86097.pdf.>;

[87] Georgilakis, P. S. (2008) Technical challenges associated with the integration of wind power into power systems. Renewable and Sustainable Energy Reviews, 12(3), 852–863. https://doi.org/10.1016/j.rser.2006.10.007

Case study: Hydroelectricity

Box 2: Hydroelectricity RD&D case study

Hydroelectricity is generated by harnessing the kinetic energy of moving water. Traditional hydropower facilities utilise a reservoir created by a dam, flexibly releasing water as needed to flow through turbines, which then propel generators to transform mechanical energy into electricity. Some hydroelectricity designs can act as combined hydroelectric and pumped hydroelectric storage (PHES) plants by using reservoirs at different heights (see *Section 5.6.3: Pumped hydro energy storage (PHES)).*

The distribution of generated electricity will be reliant on the availability of transmission networks and infrastructure. Transmission systems and smart grid technologies are essential to facilitate, regulate and optimise energy distribution within the grid; for more detail, see *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure.*

Many large-scale hydroelectricity plants currently in operation in Australia will soon require refurbishment, with many having been in use for over 50 years.

Primary technologies

Modernising turbine infrastructure through uprating and materials research can extend plant life and enhance performance.

There are a range of refurbishment strategies to extend operational life, restore performance and adapt to changing hydrological conditions. RD&D is focused on optimising replacement of aged turbines with turbines of higher power (known as 'uprating') and investigating durable materials to extend the lifespan of hydroelectric components going forward.

Hydroelectric plant flexibility and safety can be enhanced by leveraging digital tools.

Advanced control systems and the digitalisation of plant management systems can support increased plant flexibility, allowing for improved performance and safety in line with Australian regulations.[88]

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[88] IEA (n.d.) Hydroelectricity. International Energy Agency, Paris. <https://www.iea.org/energy-system/renewables/hydroelectricity> (accessed 10 December 2024).

Case study: Nuclear fission

Box 3: Nuclear fission RD&D case study

Nuclear fission involves splitting heavy atoms such as uranium-235 or plutonium-239 in a pressurised core, releasing significant heat. This heat is used to make steam, driving turbines to generate electricity. A coolant and moderator are necessary alongside the fuel for a controlled, sustained reaction. There are varying generations of large-scale generators:

- **Conventional fission reactors** (generations II-III+) are widely used technologies with commercial maturity (CRI 4-6), harnessing water as a coolant and low-enriched uranium (LEU) as fuel. Generation III+ designs are the latest commercial models, offer improved efficiency and operational flexibility. These designs also feature advanced safety mechanisms, such as passive safety systems that minimise operator intervention and do not require AC emergency power.
- **Advanced generation IV fission reactors** are in earlier stages of development (TRL 4-9) and explore the utilisation of novel fuels such as high-assay, low-enriched uranium (HALEU) and tri-structural isotropic particle fuel (TRISO) fuel particles, and advanced coolants such as liquid metal, gas, and molten salts.

Most commercial reactors today operate at GW capacity, however there is interest in exploring small modular reactors (SMRs) (~50-300 MW per unit) that can be quicker to build with repeatable 'product-based' processes.[89] These reactors can be deployed in tandem to reach capacities similar to large-scale plants and are being demonstrated using conventional fission reactor designs (generation II-III+).

In Australia, nuclear power is currently prohibited for electricity generation. At a national level, the *Australian Radiation Protection and Nuclear Safety Act 1998* (Cth) and the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) expressly prohibit the approval, licensing, construction, or operation of a nuclear fuel fabrication plant; a nuclear power plant; an enrichment plant; or a reprocessing facility.[90] Further legislation at a state level reinforces the prohibition, for example, South Australia introduced the *Nuclear Waste Storage Facility (Prohibition) Act 2000*, and Victoria introduced the *Nuclear Activities (Prohibitions) Act 1983*.

Primary technologies

RD&D can support cost reductions through improved reactor efficiencies.

RD&D could enable nuclear fission to become more cost effective for electricity generation. Cost forecasts indicate that a new large-scale nuclear plant would cost around $180-293/MWh in 2024, while SMRs are forecast to cost $456-757/MWh in 2024.[91] These costs would need to be reduced to comparable levels to be cost competitive with other technologies and seen as a viable technology in Australia.

Further development and demonstration of generation IV designs can contribute to increased reactor efficiencies, with the improved fuel, coolant and moderator combinations enhancing fuel utilisation.[92]

Advanced reactor and fuel cycle designs can enhance safety and resilience.

Researchers are also focused on improving reactor safety. The different combinations of fuel, coolant and moderator provided by generation IV designs can offer inherent safety advantages like improved physical stability, high heat capacity, and negative reactivity feedback.[93] The use of SMRs can also contribute to increased safety, with their smaller size per unit allowing for better heat removal and lower core pressures that can reduce meltdown risk.

Auxiliary technologies

A secure and internationally coordinated nuclear supply chain is essential to enable safe operation of nuclear reactors.

The deployment of next-generation nuclear reactors will depend on the availability of advanced fuels and the infrastructure required to produce them. RD&D into fuel fabrication can support efforts to enhance uranium enrichment and produce novel fuels such as HALEU or TRISO for use in advanced reactors.

The handling of spent nuclear fuel requires careful orchestration to ensure safe waste disposal, encompassing interim storage, waste transportation, any reprocessing or recycling operations, and final geologic disposal. Spent fuel may be directly disposed of or reprocessed for further use, and research can assist in further exploring the stability of waste streams while being transported, their behaviour in various geological environments, and how best to dispose of new fuel types.[94]

Building future nuclear capability will require research to understand, mitigate and respond to cybersecurity threats.

As advanced reactor systems increasingly rely on automation, remote operation, and digital monitoring, RD&D must also address new cybersecurity risks. These risks increase with the integration of these systems, reduced personnel and transportable facilities.

4.6.4 Auxiliary technology: Transmission and distribution infrastructure

A variety of solutions will be needed to enable reliable generation, transmission and distribution throughout the energy network.[95]

The increased penetration of VRE generation leads to systemwide challenges regarding power quality, grid stability, and reliability. Australia's Global Power System Transformation (G-PST) Roadmap,[96] which was developed by CSIRO and AEMO with Australian and international research organisations, outlines essential research areas to support the transition to a stable, secure, and affordable power system:

1. **Inverter design:** Developing the skills, services, design methods, and standards required for Inverter-Based Resources (IBRs) to ensure the reliability of power systems.
2. **Stability tools and methods:** Creating innovative tools and methods to maintain reliability, security, and stability in power systems increasingly using IBRs, as traditional synchronous machines are phased out.
3. **New technologies for power system operator control rooms:** Innovating new technologies and approaches for better real-time visibility and analysis in power system operator control rooms to improve operational efficiency and decision-making. Developing advanced control systems can ensure improved energy management, monitoring and implementation of predictive maintenance on the VRE technology level.
    - Continuous development of artificial intelligence (AI) and machine learning (ML) applications can optimise VRE performance and maintenance by predicting energy production and

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[89] See, e.g., National Academies of Sciences, Engineering, and Medicine (NASEM) (2023) Laying the foundation for new and advanced nuclear reactors in the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/26824; Crownhart C (2024) The next generation of nuclear reactors is getting more advanced. Here's how. MIT Technology Review. <https://www.technologyreview.com/2024/01/18/1086753/advanced-nuclear-power/> (accessed 12 December 2024); U.S. Department of Energy (2023) Pathways to Commercial Liftoff: Advanced Nuclear. <https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf> (accessed 12 December 2024); Bloomberg (2021) China is home to world's first small modular nuclear reactor. <https://www.bloomberg.com/news/articles/2021-12-21/new-reactor-spotlights-china-s-push-to-lead-way-in-nuclear-power> (accessed 12 December 2024); GE Vernova (2023) GE Hitachi signs contract for the first North American small modular reactor. <https://www.gevernova.com/news/press-releases/ge-hitachi-signs-contract-for-the-first-north-american-small-modular-reactor> (accessed 12 December 2024).

[90] Environmental Protection and Biodiversity Conservation Act 1999 (Cth) s 140A <https://classic.austlii.edu.au/au/legis/cth/consol_act/epabca1999588/s140a.html> (Accessed 10 December 2024). See also, e.g., Environmental Protection and Biodiversity Conservation Act 1999 (Cth) s 22A.

[91] Graham P, Hayward J, Foster J (2025) GenCost 2024-25: Final report. CSIRO, Australia.

[92] These designs can also have improved waste management capabilities: NASEM (2023) Laying the foundation for new and advanced nuclear reactors in the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/26824; Kornecki, K., & Wise, C. F. (2024) The role of advanced nuclear reactors and fuel cycles in a future energy system. PNAS Nexus, 3(2), pgae030. https://doi.org/10.1093/pnasnexus/pgae030; U.S. Department of Energy. (2023) Liftoff: Advanced Nuclear. <https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf> (accessed 10 December 2024). Please note that these TRLs have been provided for large-scale reactors.

[93] Negative reactivity feedback is a safety feature when increasing reactor conditions (e.g. fuel temperature, coolant density) naturally decrease reactivity, slowing the fission process to stabilise the reactor and prevent excessive power output.

[94] Generation IV reactors introduce new considerations and requirements for waste management, given their fuel wastes differ in amount, chemical composition, radionuclide inventory, thermal power, and durability in a disposal environment: Kornecki, K., & Wise, C. F. (2024) The role of advanced nuclear reactors and fuel cycles in a future energy system. PNAS Nexus, 3(2), pgae030. https://doi.org/10.1093/pnasnexus/pgae030

[95] Liu, Y., Yu, Y., Gao, N., & Wu, F. (2020) A Grid as Smart as the Internet. Engineering, 6(7), 778-788. https://doi.org/10.1016/j.eng.2019.11.015; Morey, M., Gupta, N., Garg, M. M., & Kumar, A. (2023). A comprehensive review of grid-connected solar photovoltaic system: Architecture, control, and ancillary services. Renewable Energy Focus, 45, 307-330. https://doi.org/10.1016/j.ref.2023.04.009

[96] CSIRO (2021) Executive Summary Report For Australia's Global Power System Transformation (GPST) Research Roadmap. CSIRO, Australia.

enhancing grid stability,[97] and may help operators analyse vast operational data, leading to better understanding of system behaviours. It is crucial to mitigate resilience and cyber-security risks while using these tools.[98]

4. **New planning metrics, methods and tools:** Establishing new planning metrics, methods, and tools to reflect the changing characteristics and influence of the resource mix on power systems.
5. **New procedures for restoration and Black Start:** Developing new procedures for restarting and restoring power systems with high or complete penetration of inverter-based resources.
6. **Services:** Defining and quantifying the technical service requirements necessary to maintain a reliable and cost-effective supply-demand balance in power systems with a higher penetration of renewable energy sources.
7. **Architecture:** Identifying suitable future power system architectures to effectively coordinate new technological capabilities, regulatory approaches, market designs, and the interface between distribution and transmission in a highly distributed, variable renewable energy-based system.
    - The addition of smart grid systems is integral to this architectural evolution, facilitating improved demand response and increasing network reliability. Sensors and monitoring technologies, such as supervisory control and data acquisition systems, enable real-time observation of power system parameters such as voltage, current, frequency and power factor. This facilitates prompt identification of power quality issues and their correction through automatic control technologies. Smart grid systems also improve power quality and minimise interference by managing nonlinear loads.[99] The extensive data collected enables advanced planning analytics (such as stochastic optimisation) that can inform future system responses.[100]
8. **Distributed energy resources (DERs)**: Exploring the challenges and opportunities presented by high levels of DERs to enhance the control and operation of power systems.
9. **DERs and stability:** Modelling and analysing the dynamic responses of DERs to ensure power system operators can maintain security and stability in systems with very high DER penetration.

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[97] See, e.g., AEMO (2024) Executive Summary Report for the Operations Technology Roadmap. Australian Energy Market Operator, Australia. <https://aemo.com.au/-/media/files/initiatives/operations-technology-roadmap/executive-summary-report-for-the-otr.pdf> (accessed 11 December 2024).

[98] CSIRO (2024) Global Power System Transformation (G-PST) Stage 3 Research Roadmap Reports. CSIRO, Australia. <https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap/stage3-reports> (accessed 11 December 2024).

[99] Liu Y (2024) Smart grid power quality monitoring and regulation based on photoelectric sensors and optical system signal processing. *Thermal Science and Engineering Progress* 53, 102768. https://doi.org/10.1016/j.tsep.2024.102768; Swathika GOV, Karthikeyan A, Karthikeyan K, Sanjeevikumar P, Thomas SK, Babu A (2024) Critical review of SCADA and PLC in smart buildings and energy sector. Energy Reports 12, 1518–1530. https://doi.org/10.1016/j.egyr.2024.07.041

[100] CSIRO (2024) Global Power System Transformation (G-PST) Stage 3 Research Roadmap Reports. CSIRO, Australia. <https://www.csiro.au/en/research/technology-space/energy/g-pst-research-roadmap/stage3-reports> (accessed 11 December 2024).

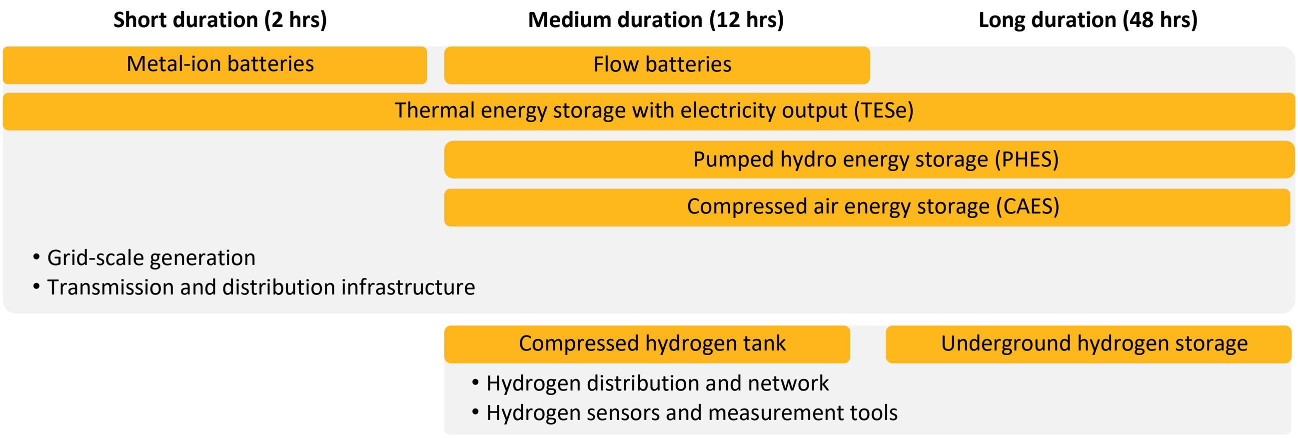
5 Electricity storage

5.1 Executive summary

RD&D can address the key hurdles that must be resolved to enable the deployment of a diverse mix of electricity storage technologies in Australia.

Technology landscape: Short, medium and long duration storage

Australia requires a diversity of short, medium and long duration storage technologies to support the increased penetration of variable renewable energy generation.



RD&D Opportunities

Metal-ion batteries, Flow batteries	• There is an opportunity to both reduce costs and supply chain risk through RD&D into developing battery chemistries with more affordable and abundant materials. • Research to enhance battery lifespan will also be important for reducing the cost of ownership of battery storage systems.
Thermal energy storage with electricity output	• RD&D opportunities for thermal energy storage are oriented around improving operating costs and making the system better suited for the storage cycles required by the use case. • Research areas include efficiency improvement by addressing heat exchange inefficiencies, heat pump efficiency and overall round-trip efficiency to minimise energy losses, and increasing the durability and lifetime of systems through RD&D into materials to achieve better thermal cycle stability and durability.
Pumped hydro energy storage	• Although PHES is a mature technology that is commercial and used widely, further RD&D can lower project costs through modular or scalable designs, and optimising reservoir configurations that leverage the local environment. • RD&D of pumping units with variable speed capabilities will allow for more flexibility and integration with VRE generation technologies.
Compressed air energy storage	• To address the high costs associated with pressurising large volumes of air for CAES, RD&D is required to incorporate more advanced materials suited for the higher pressures associated with CAES to extend asset lifetimes, as well as efforts to achieve higher efficiency rates. • Further research is required to improve site selection and current understanding of the impacts of compressed air on natural reservoirs, as well as operational requirements.
Hydrogen technologies	*See Low Carbon Fuels – Hydrogen storage*

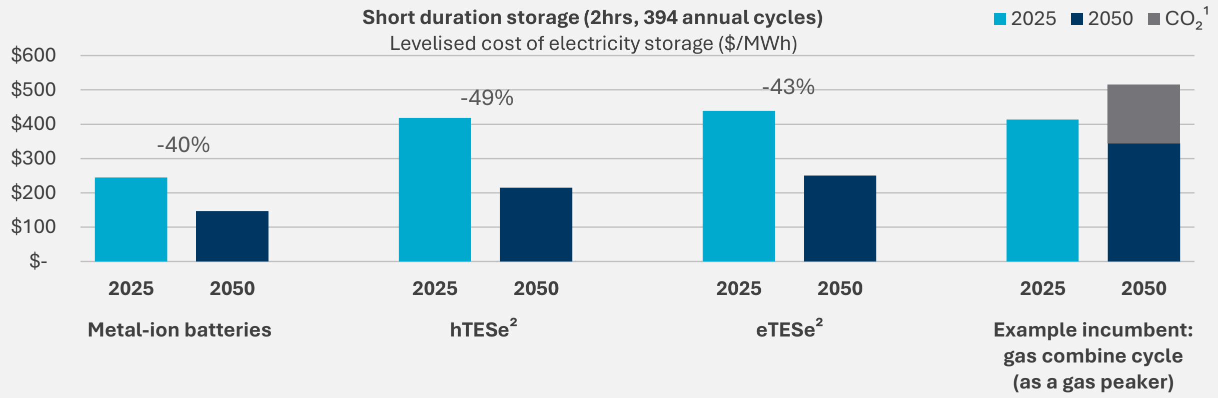
Auxiliary

See Electricity – Electricity generation and Low Carbon Fuels – Hydrogen Storage

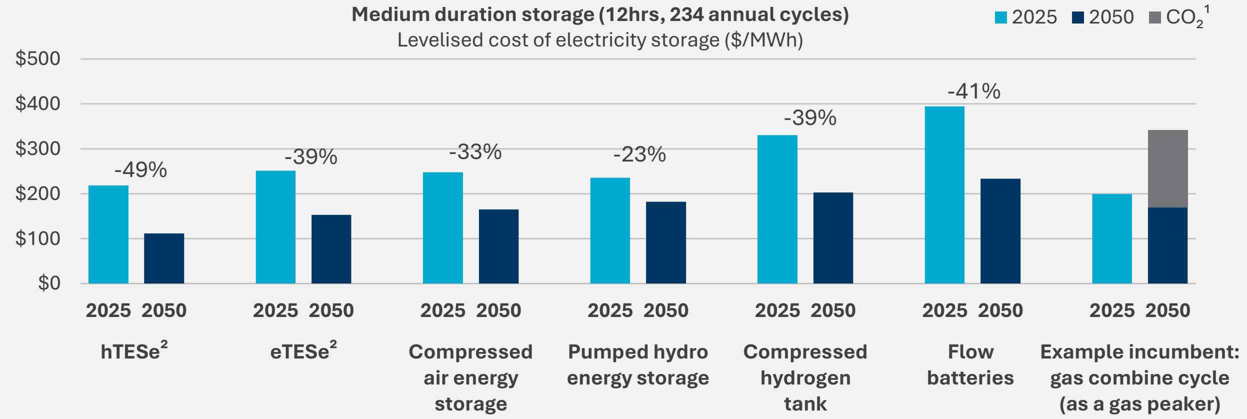
Levelised cost analysis

The competitiveness of the energy storage technologies explored varies by use case. Metal-ion batteries (for short duration) and TESe and PHES (for medium duration) are projected to be cost competitive with gas peaker plants in 2025. By 2050, all electricity storage technologies explored are projected to be competitive with gas peaker plants when accounting for a CO_2 emission cost.

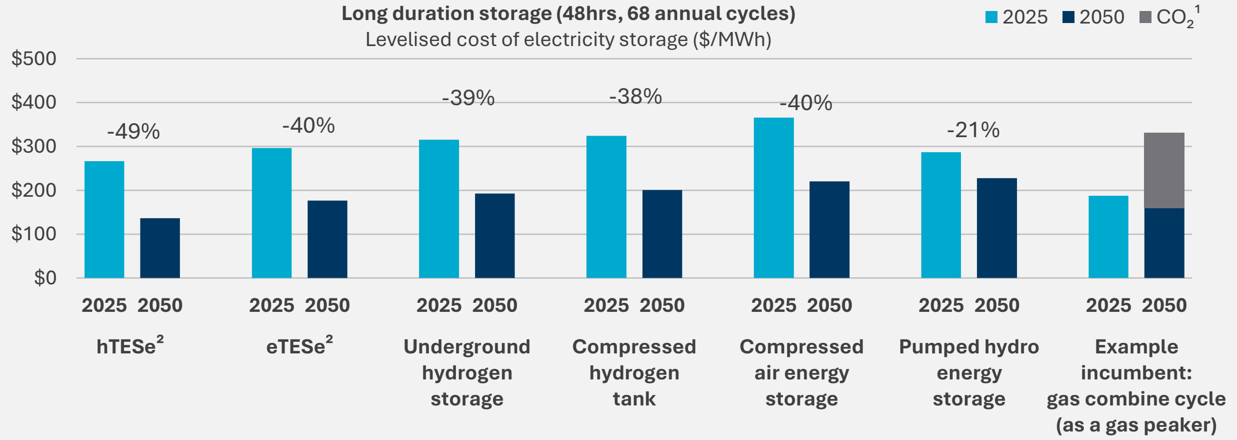
Short duration storage: 2hrs, 394 annual cycles



Medium duration storage: 12hrs, 234 annual cycles



Long duration storage: 48hrs, 68 annual cycles



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.
2. hTESe: Thermal energy storage with heat input and electricity output; eTESe: Thermal energy storage with electricity input and electricity output

5.2 Introduction

Energy storage is essential to the supply of safe, reliable, and cost-effective energy in Australia. In the electricity sector it can be used to shift energy supply to match demand, avoid or defer transmission and distribution investments, and provide essential network support services that maintains grid stability.

While often taken for granted, fossil fuels have historically provided energy storage in Australia in the form of coal stockpiles, line packed gas in pipelines, and fuel stored in tanks. However, the storage of renewable energy is becoming increasingly important as Australia decarbonises the energy system.

As of January 2025, the NEM had approximately 3GW/20GWh of renewable energy storage capacity.[101] This capacity is largely from pumped hydro and lithium-ion (Li-ion) batteries, and is expected to increase based on proposed and committed projects. However, a variety of storage systems will be needed to meet Australia's diverse storage requirements across major and remote grids, and to meet the different energy needs of industries and communities. This includes building on Australia's experience in Li-ion and pumped hydro to consider other forms of energy storage that can deliver electrical outputs. For example, electrochemical storage technologies such as flow batteries, mechanical systems such as compressed air storage, chemical storage via hydrogen, as well as the range of thermal storage systems and media that are emerging.

This chapter presents an analysis of low emissions technologies to identify technically feasible and cost competitive solutions that could support Australia's electricity storage needs. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

5.2.1 Electricity storage use case(s)

To explore low emissions technologies in the electricity storage subsector, three use cases have been defined, reflecting three discharge durations, short, medium and long (see Table 9). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with these use cases.

These use cases are representative of commercial utility-scale storage deployments (e.g. 100 MWh+ storage systems) across three discharge durations, short, medium and long. These durations represent how long a storage technology can sustain its maximum discharge rate, which allows them to service different demand sectors and markets. Although there is no universal definition for these storage durations,[102] these values are considered a useful proxy for analysing the cost competitiveness of various energy storage solutions. In addition, all use cases consider specific annual cycles which specify how the storage technology is utilised. For example, the short duration use case considered a storage technology with a 2-hour storage duration that is utilised for 394 cycles per year. The discharge durations and annual cycles described in Table 9 are based on CSIRO's Renewable Energy Storage Roadmap,[103] with the exception of the medium duration use case. While the Roadmap uses an 8-hour storage duration and 285 annual cycles, this report represents the medium duration storage use case using 12-hour storage duration and 234 annual cycles to provide clearer differentiation between the low and medium duration use cases in the technology analysis.

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[101] CSIRO internal analysis.

[102] For example, the Long Duration Energy Storage (LDES) Council defines LDES as having a duration of 8 hours or more, while NREL identifies 10 hours as the most common threshold for LDES (where they define LDES as for the application to firm VRE generation). As noted by the NREL, they have "yet to determine a single uniform definition for LDES to describe both duration and application and concludes it may not be possible to reconcile the two": NREL (2021) An Evolving Dictionary for an Evolving Grid: Defining Long-Duration Energy Storage. <https://www.nrel.gov/news/program/2021/an-evolving-dictionary-for-an-evolving-grid-defining-long-duration-energy-storage.html> (accessed 17 January 2025).

[103] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

These use cases are illustrative and present requirements that technologies must be able to meet to service Australia’s electricity storage subsector. In reality, electricity storage operations in Australia will operate over different discharge durations and annual cycles based on demand requirements.

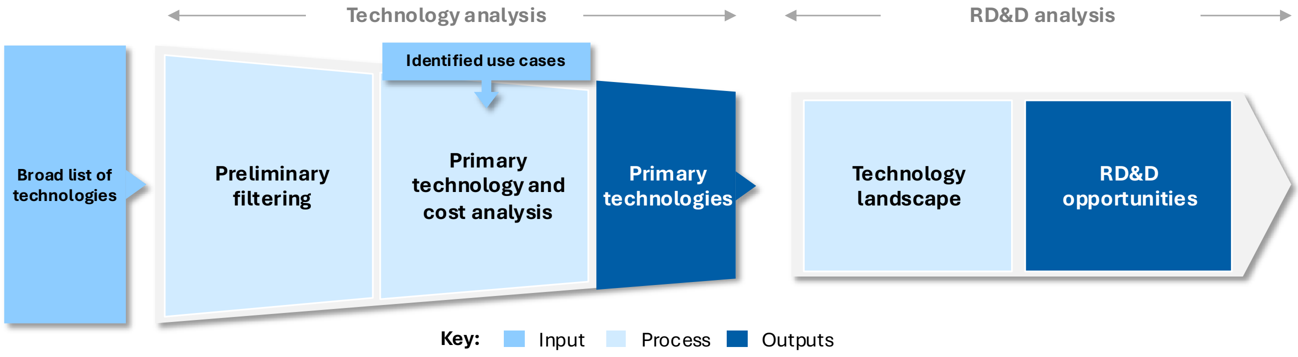
Table 9: Use case(s) – Electricity storage

Use case(s)	Short duration (2 hours, 394 annual cycles)	Medium duration (12 hours, 234 annual cycles)	Long duration (48 hours, 68 annual cycles)
Description:	**2 hours of electricity storage (394 annual cycles)** Primarily used for short-term grid stabilisation, frequency regulation and peak shaving.	**12 hours of electricity storage (234 annual cycles)** Primarily used for overnight storage, grid stability and renewable smoothing.	**48 hours of electricity storage (68 annual cycles)** Primarily used as extended backup for intermittent renewables, increased grid resilience and strategic energy reserves.

5.3 Methodology: Electricity storage inputs and criteria

The methodology is comprised of several steps (see Figure 10). Technology analysis was performed to first determine prospective technologies with the potential to contribute to decarbonisation across various storage durations. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress.

Figure 10: Technology and RD&D analysis framework for electricity storage



5.3.1 Broad technology list

A broad technology list comprised of seven technologies has been developed (see Table 10). These technologies were then passed through two preliminary filters: relevance to Australia and technological maturity. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case(s).

Table 10: Technology category definitions – Electricity storage

Technology category	Definition
Batteries	Batteries store and release electrical energy through electrochemical processes. They consist of one or more electrochemical cells with external connections for powering electrical devices.
Batteries: Metal-ion (e.g. Li-ion, Na-ion)	Rechargeable batteries that utilise the movement of ions (such as lithium or sodium) between electrodes through an electrolyte to store and release electrical energy.
Batteries: Flow batteries (e.g. VRFB, ZBFB)	Rechargeable batteries, where two chemical components are dissolved in liquids and pumped through the system on either side of a membrane. They store and release energy through reversible oxidation and reduction reactions.

Pumped hydro energy storage (PHES)	The movement of water between two linked water reservoirs at different elevations. Power is generated as water moves from the upper to the lower reservoir through a turbine, and power is consumed to pump water back to the upper reservoir.
Compressed air energy storage (CAES)	Electricity is used to compress ambient air stored under pressure. When electricity is required, the compressed air is released to drive a turbine, generating electricity. There are three types of CAES systems: diabatic, adiabatic and isothermal.
Liquid air energy storage (LAES)	The liquefaction and storage of air at very low temperatures. The stored liquid air is then evaporated and expanded to drive a turbine, generating electricity.
Gravity storage	Leverages the force of gravity to generate electricity. A mass is elevated using electric power. When electricity is needed, the mass is allowed to fall, converting potential energy back into electrical energy through generators.
Thermal energy storage with electricity output (TESe)	Storing an energy input in the form of thermal energy in a medium. The energy input can be in the form of electricity or heat for use at a later period to generate electricity using heat engines or turbines (eTESe and hTESe respectively). There are three categories of TES media: sensible, latent and thermochemical heat storage.
Hydrogen-based storage	Energy is stored by producing hydrogen, that can be stored in different forms and later converted back into electricity using fuel cells or steam turbines. Hydrogen storage methods include tanks and underground storage.
Hydrogen: Compressed hydrogen tanks	Hydrogen is compressed at high pressure (up to 800 bar) in steel or carbon fibre tanks.
Hydrogen: Underground hydrogen storage (UHS)	Hydrogen is compressed and injected into geological or engineered subsurface structures including salt caverns, depleted gas fields, aquifers or excavated caverns. Filtering and primary technology analysis is based on salt cavern storage.

5.3.2 Primary technology parameters

Technology assessment involved evaluating the technologies identified through preliminary filtering against two performance parameters for large-scale electricity storage (Table 11).

The threshold for 'Discharge duration' was defined by the use case. That is, technologies were assessed on their ability to deliver 2-, 12- and 48-hours of electricity storage for each use case, respectively. The lowest cost mitigation technologies able to meet the scale of generation required, were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in *Section 5.4.2 Primary technology analysis.*

Table 11: Use cases and technology filtering criteria – Electricity storage

Subsector	**Electricity storage**		
Use case(s)	**Short duration (2 hours, 394 annual cycles)**	**Medium duration (12 hours, 234 annual cycles)**	**Long duration (48 hours, 68 annual cycles)**
Preliminary filtering criteria[104]	**Relevance to Australia** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions. *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources*		
	Technology maturity Technology has a TRL greater than 3. The TRL index can be found in *Appendix A.2*		

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[104] Please note that abatement potential does not apply to storage technologies because they do not directly produce greenhouse gas emissions, and lifecycle emissions from their manufacture, maintenance and disposal have been excluded from the analysis.

Primary technology analysis	**Discharge duration** Ability of a given technology to meet the length of time required by each storage use case.
	Levelised Cost of Storage (LCOS) in 2050 Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOS relative to other assessed technologies (in $ per MWh).

5.4 Technology analysis

This chapter outlines the process of identifying *Primary technologies* for large-scale electricity generation across the three use cases: short duration (2 hours), medium duration (12 hours), and long duration (48 hours). Following the technology analysis framework process, **batteries, thermal energy storage with electricity output (TESe), pumped hydro energy storage (PHES), compressed air energy storage (CAES) and hydrogen-based storage** emerged as *Primary technologies* for further RD&D exploration**.** These technologies were able to service the designated use cases and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in electricity storage, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. The results of the technology analysis for the Electricity generation subsector are provided in Table 12.

Table 12: Technology analysis results – Electricity storage[105]

■ Meets criteria □ Meets with caveats ▢ Does not meet ★ Primary technology ▨ Not assessed further

1. Preliminary filtering

2. Primary technology analysis

		Short duration (2 hours)			Medium duration (12 hours)			Long duration (48 hours)		
Technologies	**Maturity**	**Discharge duration**	**2050 LCOS**		**Discharge duration**	**2050 LCOS**		**Discharge duration**	**2050 LCOS**	
	TRL > 3	*2 hours*			*12 hours*			*48 hours*		
Batteries: Metal-ion	TRL 8 - CRI 6	1-8 hrs	$147/MWh	★	1-8 hrs	▨	▨	1-8 hrs	▨	▨
Batteries: Flow	TRL 6 - CRI 2	8-14 hrs	$370/MWh	▨	8-14 hrs	$233/MWh	★	8-14 hrs	▨	▨
Pumped hydro energy storage (PHES)	TRL 7 - CRI 6	12-48+ hrs	$443/MWh	▨	12-48+ hrs	$182/MWh	★	12-48+ hrs	$228/MWh	★
Compressed air energy storage (CAES)	TRL 4 - CRI 6	6-8 hrs	▨	▨	6-8 hrs	$165/MWh	★	6-8 hrs	$220/MWh	★
Liquid air energy storage (LAES)	TRL 6	10-25 hrs	▨	▨	10-25 hrs	Inconclusive	▨	10-25 hrs	▨	▨
Gravity storage	TRL 2-8	2-4 hrs	Inconclusive	▨	2-4 hrs	Inconclusive	▨	2-4 hrs	▨	▨
Thermal energy storage with electricity output (TESe)	TRL 1-9	1-24+ hrs	$215/MWh (hTESe) $251/MWh (eTESe)	★	1-24+ hrs	$111/MWh (hTESe) $153/MWh (eTESe)	★	1-24+ hrs	$136/MWh (hTESe) $176/MWh (eTESe)	★
Hydrogen: Compressed hydrogen tanks	CRI 6	1-48+ hrs	$419/MWh	▨	1-48+ hrs	$203/MWh	★	1-48+ hrs	$201/MWh	★
Hydrogen: Underground hydrogen storage	TRL 3-9	24+ hrs	▨	▨	24+ hrs	▨	▨	24+ hrs	$193/MWh	★

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[105] Details for these figures, including sources/assumptions, are found in Table 13 (maturities) and under 'Abatement potential', 'Levelised cost analysis and *Technical Appendix: Levelised cost analysis*.

5.4.1 Preliminary filtering

Key information - Preliminary filtering

Two criteria were employed to ensure that the technologies are mature and able to be employed in the Australian context:

- **Relevance to Australia:** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- **Technology maturity*:*** Technology has a TRL greater than 3.

Relevance to Australia

All technologies were found to meet this criterion across the designated use cases, as they can be reasonably deployed in the Australian context.

Technological maturity

All evaluated technologies were found to meet this criterion, possessing technology types with a TRL above 3 (see Table 13). Certain battery types, CAES, gravity storage, TESe and hydrogen-based storage technologies have TRLs below 4 and therefore meet the criterion with these caveats.

Table 13: Technology maturities – Electricity storage

Technology category	TRL
Batteries	• Overall: TRL 1-9; CRI 1-6 ○ Metal-ion: TRL 8-9; CRI 1-6 (reflective of Li-ion, Na-ion)[106] ○ Flow: TRL 6-8; CRI 1-2 (reflective of VRFB, ZBFB)[107] ○ Metal-sulphur: TRL 9; CRI 6 (Na-S)[108] ○ Metal-air: TRL 2-4 (Fe-air), TRL 2-4 (Zn-air)[109] ○ Solid state: TRL 1-2 (Li-based solid state)[110]

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[106] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024). Hina Battery (2022) Sodium-ion battery production line delivers its first product. <https://cnevpost.com/2022/12/02/hina-gwh-sodium-ion-battery-production-line-first-product/> (accessed 12 December 2024); CATL (2024) Developing second-generation sodium-ion batteries and global licensing. <https://www.electrive.com/2024/05/06/catl-gears-up-for-next-gen-sibs-and-global-licensing/> (accessed 12 December 2024); Clean Energy Council (2024) The future of long-duration energy storage. <https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf> (accessed 12 December 2024).

[107] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024); IRENA (2020) Electricity Storage Valuation Framework. Figure 13. <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_storage_valuation_2020.pdf> (accessed 12 December 2024); Clean Energy Council (2024) The future of long-duration energy storage. <https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf> (accessed 12 December 2024). Per VRBF TRL, see also, Santos B (2022) China connects world's largest redox flow battery system to grid. PV Magazine. <https://www.pv-magazine.com/2022/09/29/china-connects-worlds-largest-redox-flow-battery-system-to-grid/> (accessed 12 December 2024); Sumitomo Electric. Redox Flow Batteries. <https://sumitomoelectric.com/products/redox/ranges> (accessed 12 December 2024).

[108] Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024). Note that room temperature Na-S battery systems are in early stages of development (TRL 4).

[109] See, e.g., Ikeuba AI, Iwuji PC, Nabuk IE, Obono OE, Charlie D, Etim AA, Nwabueze BI, Amajama J (2024) Advances on lithium, magnesium, zinc, and iron-air batteries as energy delivery devices—a critical review. *Journal of Solid State Electrochemistry* 28, 2999–3025. https://doi.org/10.1007/s10008-024-05866-x; Hosseini S, Masoudi Soltani S, Li Y-Y (2021) Current status and technical challenges of electrolytes in zinc–air batteries: An in-depth review. Chemical Engineering Journal 408, 127241. https://doi.org/10.1016/j.cej.2020.127241; Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024).

[110] Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. < https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024). Solid state batteries do not fall in the scope of this report, given their low TRL of 1-2. For reference, Solid-state batteries such as Li-based solid state (TRL 1-2) feature solid

PHES	- Overall: TRL 7 - CRI 6
	  - Conventional open-loop: CRI 6[111]
	  - Seawater: CRI 4-6[112]
	  - Closed-loop and underground PHES: TRL 7-8

CAES	- Overall: TRL 4-6; CRI 2-6
	  - Diabatic: CRI 6[113]
	  - Adiabatic: CRI 2-3 [114]
	  - Isothermal: TRL 4-6[115]

LAES	- TRL 6[116]
Gravity storage	- TRL 2-8[117]

Thermal energy storage with electricity output (TESe)	- Overall: TRL 1 - CRI 5
	  - Sensible: TRL 6- CRI 5 (Molten salts, concrete, graphite, packed beds) [118]
	  - Latent: TRL 4-6 (Latent silicon, miscibility gap alloys)[119]
	  - Thermochemical: TRL 1-3[120]

Hydrogen-based storage	- Overall: TRL 3 - CRI 6
	  - Compressed hydrogen tanks: CRI 6
	  - Underground hydrogen storage: TRL 3-9[121]

5.4.2 Primary technology analysis

Key information – Primary technology analysis

Two criteria were employed to ensure the suitability and feasibility of each technology for the use case applications determined.

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electrodes and electrolytes, eliminating the need for a separate separator, made from ceramics, glass, or solid polymers: see, e.g., Fraunhofer Institute for Systems and Innovation Research ISI (2022) Solid-State Battery Roadmap. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2022/SSB_Roadmap.pdf> (accessed 12 December 2024); Sung J, Heo J, Kim D-H, Jo S, Ha Y-C, Kim D, Ahn S, Park J-W (2024) Recent advances in all-solid-state batteries for commercialization. Materials Chemistry Frontiers 8(8), 1012–1029. https://doi.org/10.1039/D3QM01171B; Zhao Q, Stalin S, Zhao C-Z, Archer LA (2020) Designing solid-state electrolytes for safe, energy-dense batteries. Nature Reviews Materials 5(2), 229–252. https://doi.org/10.1038/s41578-019-0165-5

[111] IEA (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[112] See, e.g., ARENA (2022) Cultana Pumped Hydro Energy Storage – Phase 2. <https://arena.gov.au/projects/cultana-pumped-hydro-energy-storage-phase-2/> (accessed 12 December 2024).

[113] European Association for Storage of Energy (EASE) and European Energy Research Alliance (EERA) (2017) EASE/EERA Energy Storage Technology Development Roadmap. <https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/> (accessed 12 December 2024) ; Rabi AM, Radulovic J, Buick JM (2023) Comprehensive Review of Compressed Air Energy Storage (CAES) Technologies. Thermo, 3(1), 104-126. https://doi.org/10.3390/thermo3010008

[114] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

[115] Massachusetts Institute of Technology (MIT) (2022) The Future of Energy Storage. MIT Energy Initiative. <https://energy.mit.edu/wp-content/uploads/2022/05/The-Future-of-Energy-Storage.pdf> (accessed 12 December 2024).

[116] Internal analysis.

[117] Per commercial offerings, see, e.g., Energy Vault (2025) Innovative Energy Storage Solutions. <https://www.energyvault.com/> (accessed 17 February 2025).

[118] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

[119] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

[120] Thermochemical TES are excluded from this report due to their low maturity. See, e.g., Smith J, Weinberger P, Werner A (2024) Dehydration performance of a novel solid solution library of mixed Tutton salts as thermochemical heat storage materials. Journal of Energy Storage 78, 110003. https://doi.org/10.1016/j.est.2023.110003; Ortiz C, García-Luna S, Carro A, Carvajal E, Chacartegui R (2024) Techno-economic analysis of a modular thermochemical battery for electricity storage based on calcium-looping. Applied Energy 367, 123366. https://doi.org/10.1016/j.apenergy.2024.123366

[121] Salt cavern storage is most mature (TRL 8-9), while other forms of UHS are still emerging: Depleted gas field (TRL4), lined hard rock cavern (TRL5), and aquifers (TRL3; does not meet).

- **Discharge duration:** Technologies able to meet the length of time required by each storage use case.
- **Levelised Cost of Electricity (LCOE):** Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Discharge duration

This filter evaluates the ability of a given technology to meet the length of time required by each storage end-use case.

Discharge duration represents how long (in hours) a technology can continuously deliver its maximum power output before its stored energy is depleted.[122] It is calculated in hours by dividing a system's energy capacity (MWh) by its maximum power output (MW). Energy capacity represents the total amount of usable energy stored in the system.[123] Maximum power output represents the maximum rate at which the system can deliver power.

A technology was considered to meet this criterion if its discharge duration is equal to, or greater, than the minimum duration defined for the designated use case. If a technology cannot meet the minimum duration specified by the use case but recent research and/or commercial developments indicate reasonable potential for the technology to meet this duration by 2050, then the technology was considered to meet this criterion with caveats.

In practice, technologies may be used to meet several discharge durations. For instance, they could provide both extended duration storage and short duration cycles to reduce overall LCOS.[124] While discharge duration is critical for selecting a storage technology, other factors such as power output and the ability to meet variable demand will need to be considered to ensure a comprehensive and effective evaluation.

Batteries

Metal-ion batteries are deemed to have discharge durations that satisfy the short duration use case, but do not meet the medium or long duration use cases. Li-ion batteries were used as a representation of metal-ion batteries, as the most mature and commercially available chemistry. At grid-scale, Li-ion batteries are typically used for short discharge duration storage of up to 4 hours and are being constructed for applications of up to 8 hours.[125]

Flow batteries are deemed to have discharge durations that satisfy the medium duration use case, and the short duration use case with caveats. They do not meet the 48-hour discharge duration threshold required to satisfy the long duration use case. Vanadium redox flow batteries (VRFB), as an example of flow batteries, are

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[122] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024); National Renewable Energy Laboratory (NREL) (2022) Advanced energy storage systems research overview. <https://www.nrel.gov/docs/fy22osti/80583.pdf> (accessed 12 December 2024).

[123] For instance, physically larger storage systems (e.g. PHES, underground hydrogen) can be disproportionately large relative to their discharge capacity, allowing for longer durations. Larger amounts of thermal media (i.e. increased scale of a TESe system) will generally increase total energy capacity, with diminishing returns.

[124] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

[125] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024). See also, e.g., Contemporary Amperex Technology Co. Limited (CATL) (2024) Latest advancements in energy storage technologies. <https://www.catl.com/en/news/684.html> (accessed 12 December 2024); Clean Energy Council (2024) The future of long-duration energy storage. <https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf> (accessed 12 December 2024). For examples of 8 hour Li-ion batteries, see e.g., S&P Global Market Intelligence (2024) Lithium-ion takes early lead in California's race for longer-lasting energy storage: California Community Project. <https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/lithium-ion-takes-early-lead-in-calif-race-for-longer-lasting-energy-storage-68468842> (accessed 12 December 2024).

typically used in practice for discharge durations of 8 to 12 hours.[126] This is consistent with pilot commercial projects for zinc bromine flow batteries (ZBFB), water-based flow batteries and iron redox flow batteries.[127] Iron redox flow batteries can provide between 8 and 14 hours.[128]

Differing emerging battery chemistries may have potential across the end-use cases. Metal-sulphur battery chemistries are commonly used at scale for up to 6-hour durations (Na-S).[129] Some metal-air battery projects in development (Zn-air, Fe-air) are targeting durations of up to 100 hours.[130]

PHES

PHES systems meet the medium and long duration use cases discharge duration performance parameters, given they are typically deployed for discharge durations of 12 to 48+ hours.[131] They can be deployed for shorter durations if needed, meeting the short duration use case with caveats depending on geographical and site characteristics.

CAES

CAES are deemed to meet the medium and long duration use cases with caveats. Commercial CAES systems currently offer discharge durations of about 6 to 8 hours,[132] with potential for longer duration (48+ hours) systems to be commercially viable.[133]

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[126] Clean Energy Council (2024) The future of long-duration energy storage. <https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf> (accessed 12 December 2024). Flow batteries such as VRFBs may theoretically achieve extended discharge durations if designed with an increased amount of electrolyte.

[127] See, e.g., PV Magazine USA (2023) California Children's Hospital to build resilient clean energy microgrid. PV Magazine USA. <https://pv-magazine-usa.com/2023/09/25/california-childrens-hospital-to-build-resilient-clean-energy-microgrid/> (accessed 16 December 2024); Table B1, Zakeri B, Syri S (2015). Electrical energy storage systems: A comparative life cycle cost analysis. Renewable and Sustainable Energy Reviews. 42, 569–596. 10.1016/j.rser.2014.10.011; Origin Energy (2023) Origin has acquired a 5 per cent equity interest in Newcastle-based clean-tech company Allegro Energy and agreed to a pilot of their long-duration battery at Eraring Power Station. https://www.originenergy.com.au/about/investors-media/origin-has-acquired-a-5-per-cent-equity-interest-in-newcastle-based-clean-tech-company-allegro-energy-and-agreed-to-a-pilot-of-their-long-duration-battery-at-eraring-power-station/ (accessed 16 December 2024).

[128] See, e.g., Renew Economy (2024) Stanwell signs major deal for Australian-made long-duration iron flow batteries. <https://reneweconomy.com.au/stanwell-signs-major-deal-for-australian-made-long-duration-iron-flow-batteries/> (accessed 12 December 2024).

[129] See, e.g., Best Magazine (2024) World's largest sodium-sulphur energy storage system deployed in Japan. https://www.bestmag.co.uk/worlds-largest-sodium-sulphur-ess-deployed-japan/ (accessed 12 December 2024); Allset Energy (2024) NAS battery solutions for energy storage. https://www.allsetenergy.com.au/solutions/nas-battery/ (accessed 12 December 2024).

[130] Form Energy (2024) Form Energy and Georgia Power continue forward with 15-megawatt iron-air battery system agreement. https://formenergy.com/form-energy-georgia-power-continue-forward-with-15-megawatt-iron-air-battery-system-agreement/ (accessed 12 December 2024); Scientific American (2024) Rusty batteries could greatly improve grid energy storage. https://www.scientificamerican.com/article/rusty-batteries-could-greatly-improve-grid-energy-storage/ (accessed 12 December 2024); TechCrunch (2022) Form Energy's iron-air battery on pace for 2024 launch with $450M Series E. https://techcrunch.com/2022/10/06/form-energys-iron-air-battery-on-pace-for-2024-launch-with-450m-series-e/ (accessed 12 December 2024); Popular Mechanics (2024) How iron-air batteries are transforming energy storage. https://www.popularmechanics.com/science/energy/a42532492/iron-air-battery-energy-storage/ (accessed 12 December 2024); Energy Storage News (2024) Iron-air multi-day energy storage: Form Energy's first pilot project. https://www.energy-storage.news/iron-air-multi-day-energy-storage-form-energy-first-pilot/ (accessed 12 December 2024).

[131] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

[132] See, e.g., Hydrostor (2024) The Goderich A-CAES facility: Advancing compressed air energy storage. https://hydrostor.ca/projects/the-goderich-a-caes-facility/ (accessed 12 December 2024); PV Magazine (2022) China's first salt cavern for compressed air energy storage comes online. https://www.pv-magazine.com/2022/05/30/chinas-first-salt-cavern-for-compressed-air-energy-storage-comes-online/#:~:text=Chinese%20state-owned%20energy%20group%20Huaneng,%20Tsinghua (accessed 12 December 2024).

[133] Suggested to go beyond 24 hours: Sandia National Laboratories (2013) Compressed Air Energy Storage (CAES) technology development report. https://www.sandia.gov/app/uploads/sites/163/2021/09/SAND2013-5131.pdf (accessed 12 December 2024); National Renewable Energy Laboratory (NREL) (2021) Energy storage technology and cost characterization report. https://www.nrel.gov/docs/fy21osti/77480.pdf (accessed 12 December 2024). There are a range of companies are working on innovating CAES for up to 50 hour durations: see, e.g., regarding ApexCAES, King M, Jain A, Bhakar R, Mathur J, Wang J (2021) Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK. Renewable and Sustainable Energy Reviews 139, 110705. https://doi.org/10.1016/j.rser.2021.110705; Apex Compressed Air Energy Storage (2024) Bethel Energy Center: Advancing sustainable energy storage solutions. http://www.apexcaes.com/bethel-energy-center (accessed 12 December 2024).

LAES

LAES are deemed to meet the medium duration use case with caveats. LAES systems in commercial development are targeting discharge durations of 10 to 12,[134] and pilot scale systems of 50 to 100MW have reached durations of up to 25 hours.[135]

Gravity storage

Gravity storage technologies are deemed to meet the short duration end-use case, and the medium duration end-use case with caveats. Commercial gravity storage projects currently offer discharge durations of about 2 to 4 hours.[136] The technology has potential for future longer duration commercial systems to extend to up to 24 hours.[137]

TESe

TESe encompasses various thermal media, each with distinct characteristics and discharge durations. TESe may satisfy all discharge durations for short and medium duration use cases. Achieving longer durations is less mature, resulting in a 'meets with caveats' designation for the long duration storage use case.

Commercially TESe media have generally provided thermal storage of electricity ranging from 1 to more than 24 hours. For example, graphite and silicon systems typically target 8 hours and molten salts systems are typically designed for up to 18 hours of storage.[138] TESe have potential to meet the duration criteria of the long duration end use case with caveats, with some media, for example, pilot-scale molten salt systems shown to have discharge durations of up to 200 hours.[139]

Hydrogen-based storage

Compressed hydrogen storage meets the duration criteria of all electricity storage use cases. Compressed hydrogen tanks are typically used in applications where energy is stored for short durations (a period of hours) or long periods (up to several days). This storage type is a closed system, allowing for long-term storage with negligible losses where appropriate materials and dimensions are used.[140] However, where inadequately maintained and monitored, compressed hydrogen tanks can experience hydrogen embrittlement and leakage. This poses an immediate explosive risk and can cause other negative effects, such as reducing hydroxyl radicals that break down methane or depleting stratospheric ozone.

Storing hydrogen underground provides storage capacity magnitudes greater than surface-level gaseous storage systems, that can last for months or years depending on frequency and volume of discharge. These

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[134] See, e.g., Highview Power (2024) Projects: Developing large-scale liquid air energy storage solutions. https://highviewpower.com/projects (accessed 12 December 2024); Renew Economy (2024) Rio Tinto backs world's largest liquid air energy storage plant with eyes on Australia. https://reneweconomy.com.au/rio-tinto-backs-worlds-largest-liquid-air-energy-storage-plant-with-eyes-on-australia/ (accessed 12 December 2024).

[135] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024); LDES Council (2022) Net-zero power: Long duration energy storage for a renewable grid. McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid (accessed 12 December 2024).

[136] Energy Vault (2024) CN Rudong energy storage project. https://www.energyvault.com/projects/cn-rudong (accessed 12 December 2024); Energy Vault (2024) Zhangye energy storage project. https://www.energyvault.com/projects/zhangye (accessed 12 December 2024).

[137] Energy Vault (2024) G-Vault gravity energy storage product overview. https://www.energyvault.com/products/g-vault-gravity-energy-storage (accessed 12 December 2024).

[138] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024). Bauer T, Odenthal C, Bonk A (2021) Molten salt storage for power generation. Chemie Ingenieur Technik 93, 534–546. https://doi.org/10.1002/cite.202000137

[139] LDES Council (2022) Net-zero power: Long duration energy storage for a renewable grid. McKinsey & Company. <https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid> (accessed 12 December 2024).

[140] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671–15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

systems effectively separate power and energy components, by decoupling the rate of injection/withdrawal rate from the amount of capacity within the system.[141] However, it has limited suitability for electricity storage below 24 hours, as rapid cycling can lead to pressure and temperature fluctuations and induce geological and structural faults (discussed further in the *Hydrogen chapter* of the *Low Carbon Fuels* technical appendix).[142] Typically, these storage systems work with large (GWh/TWh) capacities at low pressures. Given these large energy capacities, replenishing times likely require several days, rendering them incompatible with the cyclical daily operating profile observed in this end use case. [143]

Refer to the *Hydrogen chapter* of the *Low Carbon Fuels* technical appendix for additional commentary on the scalability of compressed hydrogen tanks and underground hydrogen storage.

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Storage (LCOS) was estimated to determine the viability of each technology considered. LCOS is defined as the average net present cost per unit of electricity storage (in $/MWh) over the lifetime of the system.[144]

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in the *Technical Appendix: Levelised cost analysis.*

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs of new deployments are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from the levelised cost analysis are outlined in Figure 11 (short duration), Figure 12 (medium duration), and Figure 13 (long duration). The following technologies were projected to be the most cost competitive, distinguished by a cost differential in LCOS relative to other assessed technologies; suggesting areas of promise for further RD&D activity:

- **Short duration:** Li-ion batteries and TESe;
- **Medium duration:** Flow batteries, PHES, CAES, TESe and compressed hydrogen tanks;
- **Long duration:** PHES, CAES, TESe, compressed hydrogen tanks and underground hydrogen storage.

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[141] National Renewable Energy Laboratory (NREL) (2021) Energy storage technology and cost characterization report. <https://www.nrel.gov/docs/fy21osti/77480.pdf> (accessed 12 December 2024).

[142] International Energy Agency (IEA) (2019) The Future of Hydrogen: Seizing today's opportunities. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf (accessed 12 December 2024).

[143] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671–15690. https://doi.org/10.1016/j.ijhydene.2021.02.080; Burke A, Ogden J, Fulton L, Cerniauskas S (2024) Hydrogen storage and transport: Technologies and costs. Institute of Transportation Studies, UC Davis. <https://escholarship.org/content/qt83p5k54m/qt83p5k54m_noSplash_8bb1326c13cfb9aa3d0d376ec26d3e06.pdf?t=s9oa2u> (accessed 12 December 2024).

[144] This represents lifetime storage cost throughput, distinct from the purchase cost of a storage asset (which may also be expressed in $/MWh).

Results for LAES and gravity storage technologies remain inconclusive due to have an absence of assumptions available to conduct levelised cost analysis.

This economic assessment is based on the use case characteristics established in Table 11. This assessment does not capture the cost of generating the electricity needed to be stored and instead considers the power capital cost required for use of each storage technology. The total CAPEX cost has been broken down into energy capital cost (dependent on the amount of energy stored) and power capital cost (dependent on the rate of energy discharge). Fixed OPEX costs reflect the costs of maintaining system and is assumed to be a proportion of the energy capital cost.

The charging cost is based on the electricity and thermal energy prices outlined in the *Technical Appendix: Levelised cost analysis*. Electricity prices are assumed to be lower than the average wholesale price to reflect the likelihood that electricity will only be stored when generation exceeds demand (resulting in lower electricity prices than average). The round-trip efficiency assumptions incorporated in the charging cost account for the cost of converting the energy input into the required storage medium and then into the electricity output. The assumptions adopted in the model, including round-trip efficiency assumptions, are outlined in the *Technical Appendix: Levelised cost analysis*.

Note that the modelled technology type for metal-ion batteries is a Li-ion battery, for flow batteries is a vanadium redox flow battery, and for compressed air energy storage systems (CAES) is an adiabatic system.[145]

Additional technologies have been included for each use case. These technologies did not meet the earlier filtering criteria with cost analysis conducted for reference only. Notably, a gas peaker plant has been modelled with a CO_2 emission cost included in 2050.[146]

Electricity storage: Short duration use case (2 hours)

The LCOS for the short-duration use case is modelled based on a 2-hour storage duration and 394 charging cycles per year.[147] The levelised costs of technologies that are considered practical for the two-hour use case are shown in Figure 11. While CAES and underground hydrogen storage do not meet the discharge duration filter for short duration electricity storage, these are included for completeness.

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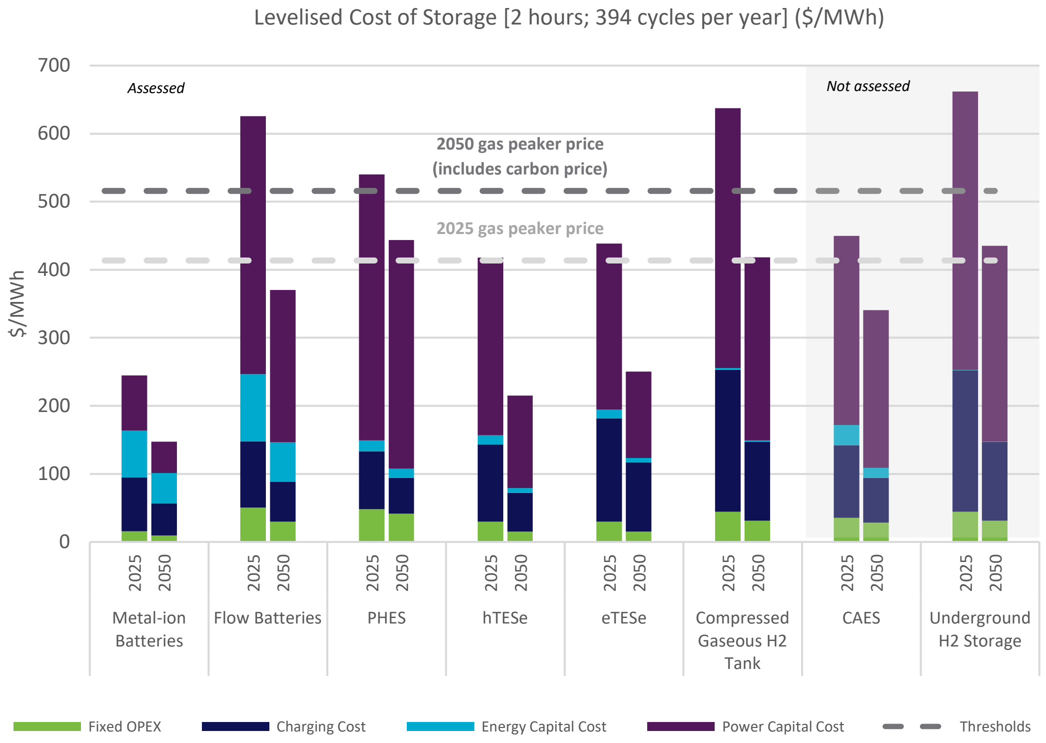
[145] Refer to *Section 5.6.4 Compressed air energy storage (CAES),* 5.6.4 for a definition and additional detail on adiabatic CAES systems.

[146] A gas peaker plant is a power plant that is typically used to generate electricity during periods of high demand, known as peak demand periods. These plants are usually powered by natural gas and can be quickly ramped up or down to balance the supply and demand of electricity in the grid. The gas peaker plant forecast in 2050 is assumed to operate for the same number of hours per year as the storage technologies in each use case. This results in different levelised costs of gas peaker electricity across the different use cases. The CO_2 emission cost is applied to each tonne of emissions produced by a particular technology and contributes to the levelised cost of that technology in the long-term. As it serves as a proxy for government intervention, no CO_2 emission cost has been assumed for the short-term. The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

[147] Charging cycles represent the number of times the storage system is fully charged or discharged each year. The charging cycles assumption for the short duration electricity storage use case is derived from the CSIRO Energy Storage Roadmap and is mapped to the short duration application example for major grids: CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

Figure 11: Levelised cost of electricity storage – Short duration use case



All technologies modelled for the two-hour use case are modelled to experience a reduction in costs between 2025 and 2050 due to improvements in round-trip efficiency and reduced scaling costs. All assessed short duration energy storage technologies have a lower levelised cost of electricity than a gas peaker plant in 2050, once accounting for a CO_2 emission cost.[148]

Batteries

Metal-ion batteries are estimated to have the lowest levelised cost in 2050. Despite having higher energy capital costs than most other storage options, the metal-ion battery's high round trip efficiency and low fixed OPEX drive down its overall costs.

The higher energy and power capital costs for flow batteries render this technology to be a less cost competitive option in both 2025 and 2050.

PHES

The higher power capital cost for PHES renders this technology the most costly option in both 2025 and 2050 relative to other assessed technologies. PHES estimates do not decrease significantly from 2025 to 2050 due to limited expected improvements in the technology.

TESe

Both TESe options were estimated to present marginally higher costs compared to the most competitive technology (Li-ion) in 2050, with hTESe are relatively more cost competitive than eTESe due to lower charging costs. The cost of converting electricity to the required thermal energy medium for eTESe is captured in the charging cost.

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[148] The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

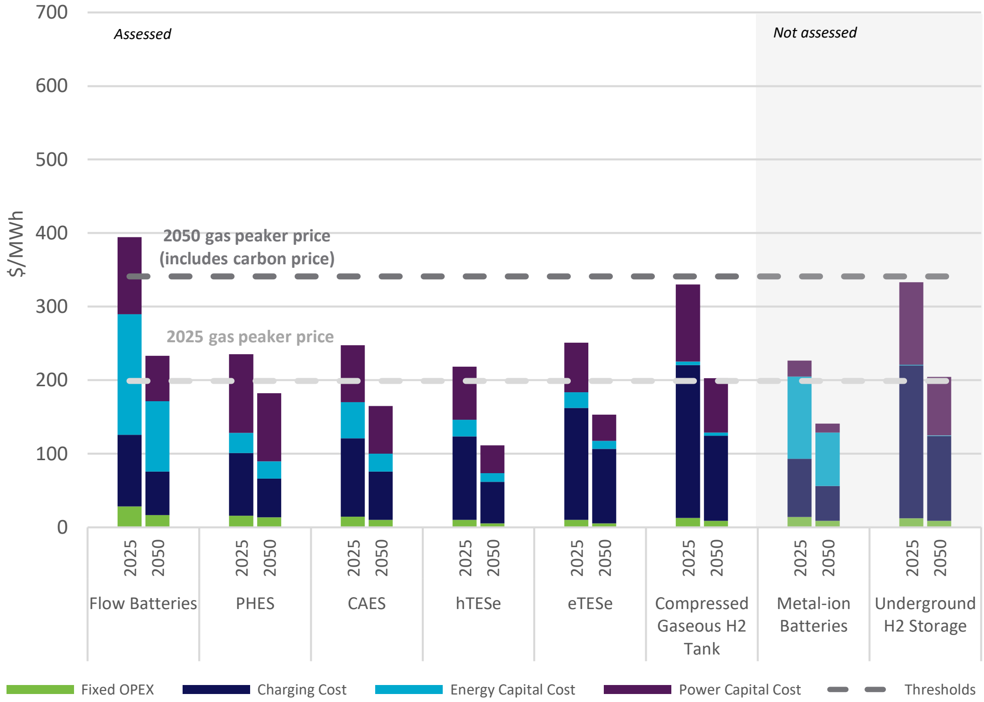
Compressed hydrogen tanks

The high charging (energy input) cost associated with compressed hydrogen tanks render this technology to be a less cost competitive option in 2050. The high charging (energy unit) costs estimated for compressed hydrogen tanks are driven by the additional electricity required to produce the green hydrogen input.

Electricity storage: Medium duration use case (12 hours)

The LCOS for the short-duration use case is modelled based on a 12-hour storage duration and 234 charging cycles per year.[149] The levelised costs of technologies that are considered practical for the 12-hour use case are shown in Figure 12. While metal-ion batteries and underground hydrogen storage do not meet the discharge duration criteria for medium duration electricity storage, they have been included for completeness.

Figure 12: Levelised cost of electricity storage – Medium duration use case



All assessed medium duration energy storage technologies have a lower levelised cost of electricity than a gas peaker plant in 2050, once accounting for a CO_2 emission cost.[150]

Batteries

Unlike metal-ion batteries, flow batteries meet the longer scale requirements imposed by the medium duration use case. However, based on the Renewable Energy Storage Roadmap cost assumptions, the energy capital costs of flow batteries increase in proportion with duration requirements, rendering it to be the least cost competitive assessed technology in 2050.

PHES

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[149] Charging cycles represent the number of times the storage system is fully charged or discharged each year. The charging cycles assumption for the medium duration electricity storage use case is derived from the CSIRO Energy Storage Roadmap, and is mapped to the medium duration application example for major grids: CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

[150] The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

While PHES is estimated to be the second lowest cost option in 2025, PHES estimates in 2050 are not significantly cheaper due to limited expected improvements in the technology.

CAES

Due to capital cost reductions, the cost of CAES fall towards the level of PHES in 2050, and is marginally lower than PHES in 2050 due to lowered energy capital costs and charging costs.

TESe

hTESe is projected to be the most cost competitive option out of all practical 12-hour use case storage options and, for this use case, has a lower LCOS compared to a gas peaker in 2025.

As in the short duration case, eTESe are relatively less cost competitive than hTESe, due to the costs incurred by converting electricity into the required thermal energy medium.

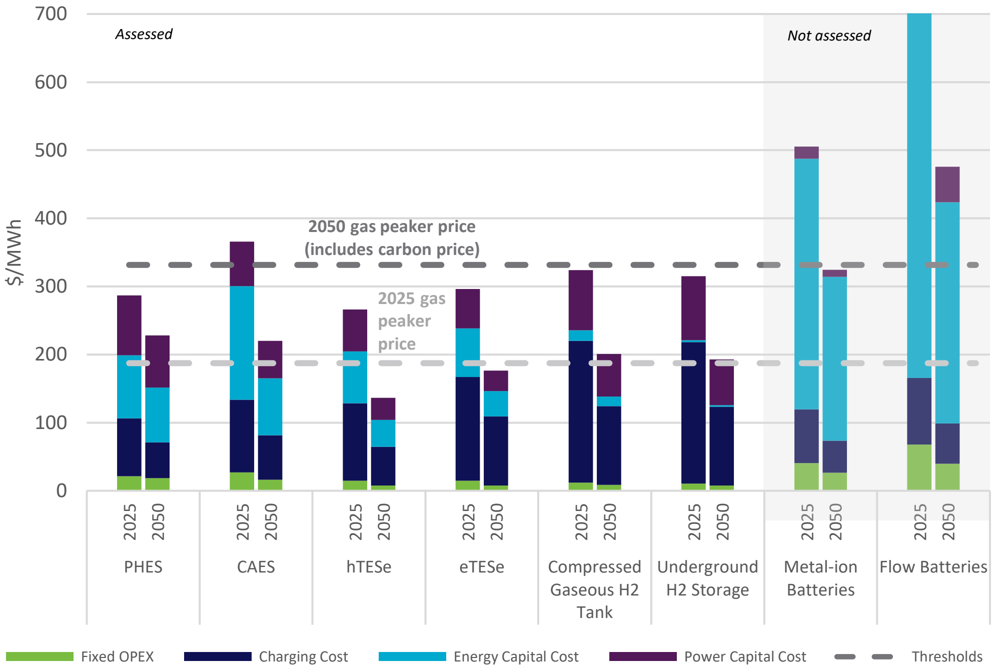
*Compressed hydrogen tank*s

Compressed hydrogen tanks are estimated to have the highest charging (energy input) cost component due to it having the lowest round-trip efficiency out of all technology options, but becomes cost competitive with gas peakers in 2050.

Electricity storage: Long duration use case (48 hours)

The LCOS for the short-duration use case is modelled based on a 48-hour storage duration and 68 charging cycles per year.[151] The levelised costs of technologies that are considered practical for the 48-hour use case are shown in Figure 13. While metal-ion and flow batteries do not meet the discharge duration criteria for long duration electricity storage, they have been included for completeness.

Figure 13: Levelised cost of electricity storage – Long duration use case



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[151] Charging cycles represent the number of times the storage system is fully charged or discharged each year. The charging cycles assumption for the long duration electricity storage use case is derived from the CSIRO Energy Storage Roadmap, and is mapped to the long multiday duration application example for major grids: CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

All assessed long duration electricity storage technologies have a lower levelised cost of electricity than a gas peaker plant in 2050, once accounting for a CO_2 emission cost.[152] Across technologies, energy capital costs for long duration storage are estimated to be higher than in the 12-hour use case, driving up the overall levelised cost.

PHES, CAES

As with medium duration storage, PHES and CAES are estimated to have similar levelised costs of electricity storage in 2050. Like the shorter duration end-use cases, PHES estimates in 2050 are not much lower than in 2025 due to limited expected improvements in the technology.

TESe

hTESe and eTESe are projected to be the most cost competitive storage options in 2050. As in the shorter duration use cases, eTESe is estimated to be more expensive than hTESe.

Hydrogen-based storage

The hydrogen-based storage solutions' levelised costs are primarily influenced by their lower round-trip efficiency, resulting from having to convert electricity into the required hydrogen input. However, compared with the medium duration case, these solutions are more competitive than PHES and CAES, due to their lower cost of scaling up to longer duration requirements. Underground hydrogen storage is more cost competitive than compressed hydrogen tanks due to the more expansive storage capacity and very low energy capital cost of underground hydrogen storage.

5.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

The technology analysis framework identified batteries, TESe, PHES, CAES and hydrogen-based storage as *Primary technologies* for the short, medium and long duration use cases (Figure 14).

Although not explored further, the other low emissions technologies evaluated in this report could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the electricity storage subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

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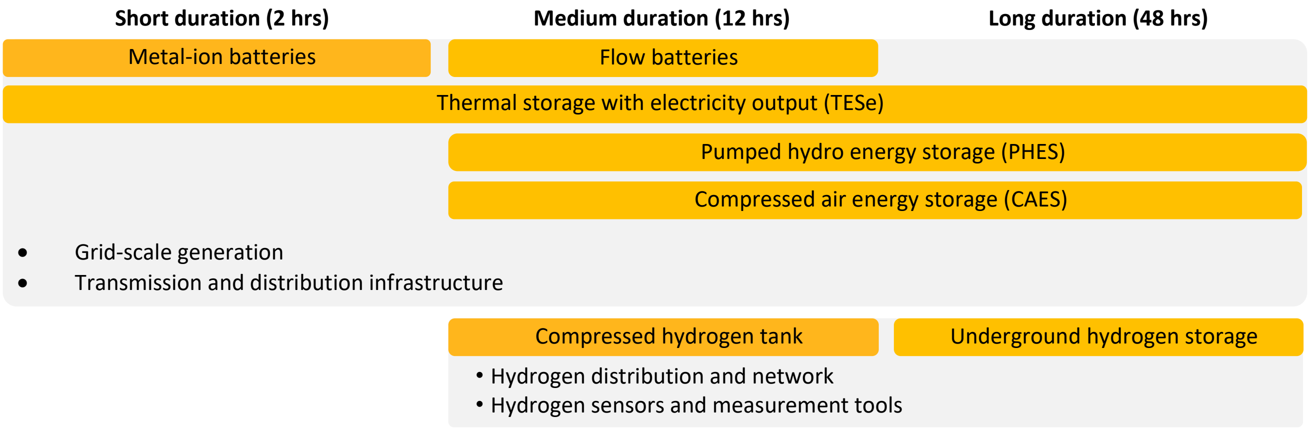
[152] The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

Figure 14: Technology landscape identification – Electricity storage



The associated *Auxiliary technologies* and E*nergy efficiency solutions* identified for analysis are outlined in Table 14 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

Batteries, TESe, PHES, CAES and hydrogen-based storage cannot exist in isolation and their successful use and deployment is dependent on a range of *Auxiliary technologies*, summarised in Table 14. *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure* notes RD&D opportunities for transmission and distribution infrastructure, as *Auxiliary technologies* for all primary electricity storage technologies.

Table 14: Auxiliary technologies – Electricity storage

Primary Technology	Auxiliary Technology	Description
Batteries	**Grid-scale generation**	Large-scale energy generation that is essential for a reliable, sustainable, and efficient supply of electricity that meets the power demands of Australia.
	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.
TESe	**Grid-scale generation**	Large-scale energy generation that is essential for a reliable, sustainable, and efficient supply of electricity that meets the power demands of Australia.
	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.
PHES	**Grid-scale generation**	Large-scale energy generation that is essential for a reliable, sustainable, and efficient supply of electricity that meets the power demands of Australia.
	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.
CAES	**Grid-scale generation**	Large-scale energy generation that is essential for a reliable, sustainable, and efficient supply of electricity that meets the power demands of Australia.
	Transmission and distribution infrastructure	Infrastructure required to transport electricity generated by solar PVs to end-users, including transmissions lines (high voltages), distribution lines (lower voltages) and transformer systems.
Hydrogen-based storage	**Distribution**	Hydrogen gas is compressed and distributed by pipeline (gaseous) or by tube trailer (gaseous). Given the large volumes of hydrogen required for UHS, more volumetrically dense means of distribution may be adopted.

	Sensing and monitoring tools	Systems required for the reliable, efficient and safe operation of compressed hydrogen tanks and UHS, including: • Prospecting technologies for geological exploration and site assessments. • Monitoring tools for safe and optimised operation.
	Modelling tools	Modelling tools and methodologies to assess subsurface conditions and optimise injections/withdrawal cycles.

Energy efficiency solutions

No explicit *Energy efficiency solutions* were identified for electricity storage; rather, a range of storage, transmission and distribution *Auxiliary technologies* will be a core focus of RD&D efforts across all *Primary technologies.*

5.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the identified technology landscape, spanning *Primary and Auxiliary technologies*.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include non-technical RD&D opportunities. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 15. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Please note, levelised cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system.

Table 15: Summary of RD&D opportunities – Electricity storage[153]

		Batteries				**Thermal storage with electricity output (TESe)**	
		Metal-ion	**Flow**	**Metal-S**	**Metal-air**	**Sensible heat storage**	**Latent heat storage**
Primary technologies	**Commercial**	Li-ion	VRFB	Na-S	-	Molten salts	-
	Mature	Na-ion	ZBFB	-	-	Concrete, packed bed systems, graphite	-
	Emerging	Zn-ion	Fe-redox, water-based	-	Zn-air, Fe-air	Particle systems, aluminium	Silicon (high heat), miscibility gap alloys (MGAs)
Primary RD&D		• Reduce storage costs (see '*Levelised cost analysis*') through: - E.g. Developing battery chemistries with more affordable and abundant materials - E.g. Enhancing battery cycle life and round-trip efficiency (RTE) **(Target for high-temperature Na-S: 7,000 cycles with 80%+ RTE, cf. 4,500 cycles at 70-80% RTE)**[154]				• Reduce storage costs (see '*Levelised cost analysis*') through: - E.g. Developing advanced thermal media with improved performance attributes (cycle stability, thermodynamic efficiency, energy density etc). - E.g. Reducing costs and advancing system components (heat exchangers, heat pumps, mechanical components) to improve system conversion efficiency - E.g. Optimising deployment, including by integrating advanced control systems and developing compact, modular designs.	
Auxiliary RD&D		• Establish sufficient low emissions grid-scale generation infrastructure (refer to *Section 4 Electricity generation*) • Establish sufficient reliable generation, transmission and distribution infrastructure to support the energy network through: - E.g. enhancing inverter-based resources, new stability tools, better real-time visibility, innovative planning methods, black start procedures, system restoration, technical service quantification, future power system architectures, and managing high levels of distributed energy resources (refer to *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure*)					

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cf. – Compare.

[153] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6.

[154] Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. < https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024).

		Pumped hydro energy storage (PHES)[155]	**Compressed air energy storage (CAES)**	**Hydrogen-based storage**	
		PHES designs	**CAES systems**	**Compressed hydrogen tank**	**Underground hydrogen tank**
Primary technologies	**Commercial**	Conventional open-loop, seawater	Diabatic, adiabatic	Metal & metal-composite pressurised vessels	Salt cavern
	Mature	Closed-loop, underground	-	-	-
	Emerging	-	Isothermal	-	Fast cycling salt cavern, lined hard rock cavern, depleted gas field storage
Primary RD&D		• Reduce storage costs (see '*Levelised cost analysis*') through: - E.g. Optimising PHES systems for different geographies and scales, including via modular and scalable designs - E.g. Implementing variable speed capabilities to enhance compatibility with VRE	• Reduce storage costs (see '*Levelised cost analysis*') through: - E.g. Identifying advanced materials and designs that can endure higher pressures - E.g. Improving efficiency **(A-CAES target: >70% cf ~60%)**[156] enabled by enhanced thermal management • Optimise deployment and reduce environmental impacts through: - E.g. Alternative designs like aboveground storage	• Reduce storage costs (see '*Levelised cost analysis*') through: *For specific RD&D opportunities and technical targets, refer to the Low Carbon Fuels technical appendix. In addition to the containment structure, processing and purification systems are also regarded as identified technologies required for adoption of UHS systems.*	
Auxiliary RD&D		• Establish sufficient low emissions grid-scale generation infrastructure (refer to *Section 4 Electricity generation)* • Establish sufficient reliable generation, transmission and distribution infrastructure to support the energy network (refer to *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure)*		• Establish sufficient production and distribution infrastructure • Ensure safe operation of hydrogen storage systems *Refer to Low Carbon Fuels technical appendix for detailed production, storage and distribution discussion. See also: Transport technical appendix for fuel cells and the Industry technical appendix for hydrogen steam turbines.*	

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[155] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6.

[156] He W, Wang J (2018) Optimal selection of air expansion machine in compressed air energy storage: A review. Renewable and Sustainable Energy Reviews 87, 77–95. https://doi.org/10.1016/j.rser.2018.01.013; Cheung B, Cao N, Carriveau R, Ting DS-K (2012) Distensible air accumulators as a means of adiabatic underwater compressed air energy storage. International Journal of Environmental Studies 69(4), 566–577. https://doi.org/10.1080/00207233.2012.699360; He Y, Chen H, Xu Y, Deng J (2018) Compression performance optimization considering variable charge pressure in an adiabatic compressed air energy storage system. Energy 165(Part B), 349–359. https://doi.org/10.1016/j.energy.2018.09.168

5.6.1 Batteries

Batteries store and release electrical energy through electrochemical processes, consisting of one or more cells with external connection for electrical output. Batteries are comprised of a positive and negative electrode (cathode and anode respectively) and an electrolyte. The electrodes are connected to an external circuit which allows the electrons to flow. Ions move through the electrolyte to maintain the charge balance between the electrodes. This transfer of electrons is referred to as a 'oxidation-reduction' or 'redox' reaction and is the principal reaction allowing for battery operation.[157]

Core categories of battery chemistries relevant to grid-scale storage include:

- **Metal-ion batteries**, which use metal ions in the cathode to facilitate redox reactions, such as Li-ion (CRI 6) and Na-ion batteries (TRL 8 – CRI 2).[158]
- **Flow batteries**, that utilise liquid electrolytes pumped through a cell stack, stored in separate tanks, such as vanadium redox and zinc bromine batteries (TRL 6 – CRI 4).[159]
- **Metal-sulphur batteries**, which employ sulphur as the cathode and a metal like lithium or sodium as the anode, such as Na-S batteries (TRL 9; CRI 6 for high temperature).[160]
- **Metal-air batteries**, which generate electricity by oxidising metal at the anode and using atmospheric oxygen as a reactant at the cathode, such as Fe-air batteries (TRL 2 – 4).[161]

Battery systems are well suited to short duration storage for grid-scale applications, with a high degree of modularity and flexibility to quickly response to grid demands resulting from fast electrochemical reactivity.

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[157] In reference to grid scale storage, the acronym 'BESS' (Battery Energy Storage System) is commonly applied.

[158] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024); CNEV Post (2022) Hina GWh sodium-ion battery production line delivers first product. <https://cnevpost.com/2022/12/02/hina-gwh-sodium-ion-battery-production-line-first-product/> (accessed 12 December 2024). See also, e.g., Electrive (2024) CATL gears up for next-gen sodium-ion batteries and global licensing. <https://www.electrive.com/2024/05/06/catl-gears-up-for-next-gen-sibs-and-global-licensing/> (accessed 12 December 2024); Clean Energy Council (2024) The future of long-duration energy storage. <https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf> (accessed 12 December 2024).

[159] CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024); IRENA (2020) Electricity Storage Valuation Framework. Figure 13. <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_storage_valuation_2020.pdf> (accessed 12 December 2024); Clean Energy Council (2024) The future of long-duration energy storage. <https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf> (accessed 12 December 2024). Per VRBF TRL, see also, Santos B (2022) China connects world's largest redox flow battery system to grid. PV Magazine. <https://www.pv-magazine.com/2022/09/29/china-connects-worlds-largest-redox-flow-battery-system-to-grid/> (accessed 12 December 2024); Sumitomo Electric. Redox Flow Batteries. <https://sumitomoelectric.com/products/redox/ranges> (accessed 12 December 2024).

[160] Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. < https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024). Note that room temperature Na-S battery systems are in early stages of development (TRL 4).

[161] See, e.g., Ikeuba AI, Iwuji PC, Nabuk IE, Obono OE, Charlie D, Etim AA, Nwabueze BI, Amajama J (2024) Advances on lithium, magnesium, zinc, and iron-air batteries as energy delivery devices—a critical review. Journal of Solid State Electrochemistry 28, 2999–3025. https://doi.org/10.1007/s10008-024-05866-x (accessed 12 December 2024); Hosseini S, Masoudi Soltani S, Li Y-Y (2021) Current status and technical challenges of electrolytes in zinc–air batteries: An in-depth review. Chemical Engineering Journal 408, 127241. https://doi.org/10.1016/j.cej.2020.127241; Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. < https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024). Note that solid state batteries do not fall in the scope of this report, given their low TRLs of 1-2. For reference, Solid-state batteries such as Li-based solid state (TRL 1-2) feature solid electrodes and electrolytes, eliminating the need for a separate separator, made from ceramics, glass, or solid polymers: see, e.g., Fraunhofer Institute for Systems and Innovation Research ISI (2022) Solid-State Battery Roadmap. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2022/SSB_Roadmap.pdf> (accessed 12 December 2024); Sung J, Heo J, Kim D-H, Jo S, Ha Y-C, Kim D, Ahn S, Park J-W (2024) Recent advances in all-solid-state batteries for commercialization. Materials Chemistry Frontiers 8(8), 1012–1029. https://doi.org/10.1039/D3QM01171B; Zhao Q, Stalin S, Zhao C-Z, Archer LA (2020) Designing solid-state electrolytes for safe, energy-dense batteries. Nature Reviews Materials 5(2), 229–252. https://doi.org/10.1038/s41578-019-0165-5

Li-ion chemistries are the current standard for grid-scale storage, representing over 90% of global stationary storage employed in recent years.[162] This is due to their maturity, relatively high round trip efficiency (i.e., about 85%)[163] and high energy density (i.e. above 300Wh/kg).[164]

Primary technologies

Reducing system costs is central for advancing stationary battery storage, including through alternative materials and chemistries.

Given the high costs of lithium metal, there are significant opportunities to continue leveraging RD&D to reduce costs for stationary electricity storage. Despite lithium comprising only 7% of total battery weight on average,[165] it significantly impacts overall cost, manufacturing complexity and environmental footprint.[166] Li-ion battery costs are forecasted to decrease with further material and cell design optimisation, with cost forecasts falling to about $147/MWh by 2050 for short duration storage (cf. about $245 in 2025). These costs serve as benchmarks for advanced battery chemistries, which aim to achieve improved costs through more cost-effective materials and increased battery lifetime.

In response to supply and price risks associated with materials used in current battery chemistries, battery chemistries which use more affordable and abundant materials are under development, to reduce the cost of Li-ion battery systems and simplify manufacturing processes. Flow battery chemistries can utilise inexpensive materials stored in scalable tanks, and do not experience the same degradation as Li-ion batteries.[167] Zn-ion batteries also show potential, given abundant zinc deposits globally and the capability to operate using inexpensive aqueous electrolytes.[168] These electrolytes are also non-flammable, addressing safety concerns commonly associated with Li-ion battery systems.[169] While some of these alternatives may exhibit lower gravimetric or energy density relative to Li-ion, these limitations are less critical for stationary applications where size and weight are not primary constraints.[170]

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[162] International Energy Agency (IEA) (2024) Grid-scale storage: Enabling the clean energy transition. <https://www.iea.org/energy-system/electricity/grid-scale-storage> (accessed 12 December 2024).

[163] Cole W, Frazier AW (2020) Cost projections for utility-scale battery storage: 2020 update. National Renewable Energy Laboratory (NREL). <https://www.nrel.gov/docs/fy20osti/75385.pdf> (accessed 12 December 2024). Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024).https://www.nrel.gov/docs/fy20osti/75385.pdf

[164] Li J, Du Z, Ruther RE, An SJ, David LA, Hays K, Wood M, Phillip ND, Sheng Y, Mao C, Kalnaus S, Daniel C, Wood DL III (2017) Toward low-cost, high-energy density, and high-power density lithium-ion batteries. JOM 69, 1484–1496. https://doi.org/10.1007/s11837-017-2404-9; International Renewable Energy Agency (IRENA) (2019) Utility-scale batteries: Innovation landscape brief. https://elk.adalidda.com/2019/09/IRENA_Utility-scale-batteries_2019.pdf (accessed 12 December 2024); Zubi G, Dufo-López R, Carvalho M, Pasaoglu G (2018) The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews 89, 292–308. https://doi.org/10.1016/j.rser.2018.03.002.

[165] As Lithium carbonate equivalent. See: World Intellectual Property Organization (WIPO) (2018) Patent WO2018218358A1: Energy storage systems and methods. https://patentimages.storage.googleapis.com/c0/71/73/3b77700a8a5e93/WO2018218358A1.pdf (accessed 12 December 2024); Pagliaro M, Meneguzzo F (2019) Lithium battery reusing and recycling: A circular economy insight. Heliyon 5(6), e01866. https://doi.org/10.1016/j.heliyon.2019.e01866.

[166] Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024).

[167] See, e.g., Berling S, Walsh FC, Ponce de León C (2025) Batteries – Battery types – Zinc batteries: Zinc–bromine flow batteries. In Encyclopedia of Electrochemical Power Sources (Second Edition), Volume 3, 840–850. https://doi.org/10.1016/B978-0-323-96022-9.00015-3; Denholm P, Cole W, Blair N (2023) Moving beyond 4-hour Li-ion batteries: Challenges and opportunities for long(er)-duration energy storage. Technical Report NREL/TP-6A40-85878. National Renewable Energy Laboratory (NREL). <https://www.nrel.gov/docs/fy23osti/85878.pdf> (accessed 12 December 2024).

[168] Blanc LE, Kundu D, Nazar LF (2020) Scientific challenges for the implementation of Zn-ion batteries. Joule 4(4), 771–799. https://doi.org/10.1016/j.joule.2020.03.002

[169] Harris SJ, Timmons A, Pitz WJ (2009) A combustion chemistry analysis of carbonate solvents used in Li-ion batteries. Journal of Power Sources 193(2), 855–858. https://doi.org/10.1016/j.jpowsour.2009.04.030

[170] Denholm P, Cole W, Blair N (2023) Moving beyond 4-hour Li-ion batteries: Challenges and opportunities for long(er)-duration energy storage. Technical Report NREL/TP-6A40-85878. National Renewable Energy Laboratory (NREL). <https://www.nrel.gov/docs/fy23osti/85878.pdf> (accessed 12 December 2024). See also, Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024).

Improving battery performance and longevity can enhance the economic viability and reliability of battery storage systems.

Research efforts can also unlock performance gains across a range of battery chemistries, particularly through innovations that extend cycle life and round-trip efficiency (RTE). These parameters directly affect system lifetime and operating costs.

Cycle life refers to the number of charge and discharge cycles a battery can endure before substantial capacity loss. Maximising cycle life reduces the need for early replacement. RTE, defined as the percentage of input electricity that can later be retrieved, improves system efficiency, minimises heat and stress on components, further reducing wear.[171] Specific battery chemistries, such as high temperature Na-S, are targeting cycle life of above 7,000 cycles with over 80% RTE, compared to 4,500 cycles at 70-80% RTE today.[172] Irrespective of battery chemistry, optimising electrode materials, electrolytes, and battery design can help reduce operational degradation by improving cycle life and limiting self-discharge. These approaches may also mitigate capacity fade, degradation of active materials, and the formation of unwanted byproducts such as lithium polysulfides, that can impact performance and durability.

Auxiliary technologies

The distribution of generated electricity will be reliant on the availability of transmission networks and infrastructure.

Transmission systems and smart grid technologies are essential to facilitate, regulate and optimise energy distribution within the grid; for more detail, see the discussion in *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure*. In particular, incorporation of AI and ML may allow algorithms to improve expectations for battery state-of-charge and state-of-health estimations.

For additional detail on electricity generation technologies, refer to *Section 4: Electricity generation*.

5.6.2 Thermal energy storage with electricity output (TESe)

Thermal energy storage (TES) systems are capable of both receiving and supplying heat and electricity. TESe technologies specifically utilise electricity (eTESe) or direct heat (hTESe) to store thermal energy, which is later converted back into electricity.

TES storage media are the primary heat absorbents in a TES system, and are classified into categories including:

- **Sensible heat storage**, which involves capturing and releasing energy through heating or cooling a solid or liquid storage medium. Most technologies are capable of covering a wide range of temperatures and durations (with the latter ranging from hours to weeks). Examples of sensible media include molten salts, graphite and packed bed systems.
- **Latent heat storage**, which involves storing and releasing energy with a change in physical state, with specific technologies suited to particular temperature ranges and intraday to multiday durations. This

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[171] U.S. Energy Information Administration (2021) Utility-scale batteries and pumped storage return about 80% of the electricity they store https://www.eia.gov/todayinenergy/detail.php?id=46756 (accessed 7 January 2025).

[172] Fraunhofer Institute for Systems and Innovation Research (2023) Roadmap for Energy Transition in Industry. <https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/abt-roadmap.pdf> (accessed 12 December 2024). For reference, Li-ion batteries currently have cycle life of about 1,000 cycles and 85% RTE: Choi C, Harrop L, Huang Y, Rinaldi V, Yang Y (2021) Beyond Li-ion batteries for grid-scale energy storage. Cambridge University Press. https://www.cambridge.org/core/elements/beyond-liion-batteries-for-gridscale-energy-storage/39C988EEA9FDD5C9828F420EE8C1AB6F (accessed 12 December 2024); Cole W, Frazier AW (2020) Cost projections for utility-scale battery storage: 2020 update. National Renewable Energy Laboratory (NREL). <https://www.nrel.gov/docs/fy20osti/75385.pdf> (accessed 12 December 2024).

is also known as phase change storage.[173] Latent media examples include high temperature silicon (used for ranges around its liquefaction point of 1,414°C) and miscibility gap alloys (typically used for temperature ranges of about 20-650°C).[174]

Each category includes various media with distinct properties, resulting in varying operating temperatures, durations and scales.

Box 4: Thermochemical TES

A third category, thermochemical heat storage operates through a reversible chemical reaction that releases and stores energy. These emerging technologies include media such as zeolites and silica gel and are currently at a low maturity level (i.e., below TRL 4). As a result, these media fall out of the scope of this report, but may potentially support intraday durations extending to months. While they provide efficient heat storage at high densities, their complexity results in higher LCOE compared to sensible and latent technologies for similar conditions. They are likely to be used commercially only in applications requiring frequent cycles, compact design, and beneficial integration of secondary heat sources.[175]

Primary technologies

Developing advanced thermal media can underpin efficiency, system durability and cost performance improvements.

RD&D into new thermal media or optimised existing materials can serve to reduce costs and help achieve forecasted values; falling from $219-251/MWh in 2025 to $111-153/MWh by 2050 for medium duration storage (please refer to the Levelised cost analysis in *Section 5.4.2 Primary technology analysis,* for cost forecasts across the defined profiles).[176] One key research area is the use of alternate thermal media with higher specific heat capacities (ability to retain higher temperatures which can increase the thermodynamic efficiency and energy density of TESe systems. For example, in solid packed beds that exceed 700°C, gaseous working fluids such as air are commonly used to transfer heat, but they limit energy storage density and increase system costs due to their lower heat capacity and high-temperature material requirements.[177] Optimising the specific porosity (space between solid particles) to improve fluid flow and heat exchange, or developing alternative high-performance thermal media better suited to space-constrained applications, could improve performance prospects.

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[173] Sarbu I, Sebarchievici C (2018) A comprehensive review of thermal energy storage. Sustainability 10(1), 191. https://doi.org/10.3390/su10010191; CSIRO (2023) Renewable Energy Storage Roadmap: CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024); McKinsey & Company (2024) Net-zero heat: Long-duration energy storage to accelerate energy system decarbonization. https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/net%20zero%20heat%20long%20duration%20energy%20storage%20to%20accelerate%20energy%20system%20decarbonization/net-zero-heat-long-duration-energy-storage-to-accelerate-energy-system-decarbonization.pdf (accessed 12 December 2024).

[174] Regarding silicon, see e.g. 1414 Degrees (2021) Partnership with Woodside to progress the development of SiBox. <https://1414degrees.com.au/1414-degrees-woodside-partnership/> (accessed 13 December 2024). Regarding MGAs, see ARENA (2023) Market context report: MGA thermal energy storage application in Australia. <https://arena.gov.au/assets/2023/02/market-context-report-mga-thermal-energy-storage-application-in-australia.pdf> (accessed 12 December 2024).

[175] Fraunhofer Institute for Energy Economics and Energy System Technology (2024) Thermal energy storage: Technologies and applications. < https://www.energie.fraunhofer.de/en/business-areas/energy-storage/thermal-energy-storage.html> (accessed 12 December 2024); Gamisch S, Kick M, Klünder F, Weiss J, Laurenz E, Haussmann T (2023) Thermal storage: From low-to-high-temperature systems. Energy Technology, 2300544. https://doi.org/10.1002/ente.202300544. Regarding a TRL for thermochemical, see, e.g., Smith J, Weinberger P, Werner A (2024) Dehydration performance of a novel solid solution library of mixed Tutton salts as thermochemical heat storage materials. Journal of Energy Storage 78, 110003. https://doi.org/10.1016/j.est.2023.110003; Ortiz C, García-Luna S, Carro A, Carvajal E, Chacartegui R (2024) Techno-economic analysis of a modular thermochemical battery for electricity storage based on calcium-looping. Applied Energy 367, 123366. https://doi.org/10.1016/j.apenergy.2024.123366.

[176] Range of figures represents TESe used from heat (i.e. hTESe) or electricity (eTESe) respectively.

[177] Gamisch S, Kick M, Klünder F, Weiss J, Laurenz E, Haussmann T (2023) Thermal storage: From low-to-high-temperature systems. Energy Technology, 2300544. https://doi.org/10.1002/ente.202300544

The thermal cycle stability of TESe media is also central to system longevity. Repeated heating and cooling without significant degradation is essential to ensure the long-term reliability and efficiency of TESe systems. RD&D aimed at improving the durability and conductivity of thermal materials, or developing protective coatings, can prevent degradation and extend operational life. For example, high temperatures can cause graphite to oxidise, leading to reduced thermal conductivity and capacity.[178] Protective coatings could help mitigate oxidation and degradation of graphite in such conditions.

Improving the round-trip efficiency of a TESe system can enhance energy recovery, reduce lifecycle costs and complexity, thereby strengthening viability for grid-scale deployment.

A technical barrier to the cost effectiveness of TESe systems is the low trip round efficiency (RTE) of current heat-to-electricity conversion processes (i.e., the ratio of usable energy retrieved from TESe storage to the ratio of energy initially put into the system). Current conversion thermodynamic processes such as conventional and organic Rankine cycles, Brayton cycles or thermophotovoltaics (TPV) often fall below 40%.[179] RD&D could enable significant performance improvements by advancing novel conversion processes and mechanical designs.

Emerging technologies, such as Stirling engine systems paired with insulated sand-based thermal storage, have demonstrated lab-scale efficiencies of up to 85%.[180] Alternatively, supercritical CO_2 Brayton cycles (advanced thermodynamic conversions that use supercritical CO_2 as a working fluid), are being explored for their high thermal efficiencies and good operational flexibility; though challenges remain in material compatibility and system integration.[181] For discussion of conventional thermodynamic conversion, excluding integration with TES media, please see *Section 5.6.4 Compressed air energy storage (CAES).*[182]

Cost reductions of the mechanical components (e.g., pumps, turbines, generators) and improvements in heat exchangers also present RD&D opportunities. To retrieve stored electricity using conventional Rankine or Brayton cycles, heat is transferred to a working fluid, which then powers a turbine connected to an electric generator. Optimising traditional heat exchangers, for example combining nanofluids with typical heat exchanger geometries could boost thermal conductivity and heat transfer rates.[183] Further gains may come from using low-friction materials, advanced turbine cooling techniques, seal designs, and heat tracing to prevent energy loss and solidification in high-temperature liquid systems.

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[178] Gamisch S, Kick M, Klünder F, Weiss J, Laurenz E, Haussmann T (2023) Thermal storage: From low-to-high-temperature systems. Energy Technology, 2300544. https://doi.org/10.1002/ente.202300544

[179] Reaching best efficiencies of 37-42%. See, e.g., Dunham MT, Iverson BD (2014) High-efficiency thermodynamic power cycles for concentrated solar power systems. Renewable and Sustainable Energy Reviews 30, 758–770. https://doi.org/10.1016/j.rser.2013.11.010.; Gamisch S, Kick M, Klünder F, Weiss J, Laurenz E, Haussmann T (2023) Thermal storage: From low-to-high-temperature systems. Energy Technology 11(6), 2300544. https://doi.org/10.1002/ente.202300544; LaPotin A, Schulte KL, Steiner MA, Buznitsky K, Kelsall CC, Friedman DJ, Tervo EJ, France RM, Young MR, Rohskopf A, Verma S, Wang EN, Henry A (2022) Thermophotovoltaic efficiency of 40%. Nature 604, 287–291. https://doi.org/10.1038/s41586-022-04473-y; Helman U, Kaun B, Stekli J (2020) Development of long-duration energy storage projects in electric power systems in the United States: A survey of factors shaping the market. Frontiers in Energy Research 8. https://doi.org/10.3389/fenrg.2020.00008; O'Connor P et al. (2020) Hydropower Vision: A new chapter for America's first renewable electricity source. https://doi.org/10.2172/1502612; Augustine C, Blair N (2020) Storage technology modeling input data report; Albertus P, Manser J, Litzelman S (2020) Long-duration electricity storage: Applications, economics, and technologies. Joule 4, 21–32. https://doi.org/10.1016/j.joule.2019.11.009; Denholm P, Cole W, Blair N (2023) Moving beyond 4-hour Li-ion batteries: Challenges and opportunities for long(er)-duration energy storage. NREL. https://www.nrel.gov/docs/fy23osti/85878.pdf (accessed 13 December 2024).

[180] Tetteh S, Yazdani M, Santasalo-Aarnio A (2021) Cost-effective Electro-Thermal Energy Storage to balance small scale renewable energy systems. Journal of Energy Storage, 41, 102829. <https://doi.org/10.1016/j.est.2021.102829>

[181] White M, Bianchi G, Chai L, Tassou S, Sayma A (2020) Review of supercritical CO2 technologies and systems for power generation < https://doi.org/10.1016/j.applthermaleng.2020.116447>

[182] Thermodynamic conversion refers to the process of converting stored thermal energy into electricity including heat exchange, conversion of thermal energy to mechanical work and the conversion of mechanical work into electricity.

[183] Roy U, Roy P (2020) Advances in heat intensification techniques in shell and tube heat exchanger. Advanced Analytic and Control Techniques for Thermal Systems with heat Exchangers <https://doi.org/10.1016/B978-0-12-819422-5.00007-4>

Deployment optimisation, including controls, footprint and integration, could help to accelerate the deployment and uptake of TESe.

Beyond material and conversion efficiency improvements, the successful deployment of TESe technologies can benefit from system-wide RD&D to improve design integration, automation, and spatial efficiency. Systems that can be easily installed, operated, and maintained are more likely to gain traction in a broad range of applications, especially where space constraints or most sensitivity are limiting factors.

Efforts to reduce the physical footprint of TESe systems may encourage their broader use. Compact and/or modular designs could also present cost efficiencies.

RD&D into the integration of advanced control systems could enable predictive maintenance and increased automation. Minimising system management complications and realising cost savings, will require RD&D across all system components. [184]

Auxiliary technologies

The distribution of generated electricity will be reliant on the availability of transmission networks and infrastructure.

Transmission systems and smart grid technologies are essential to facilitate, regulate and optimise energy distribution within the grid; for more detail, see the discussion in *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure*.

For additional detail on electricity generation technologies, refer to *Section 4 Electricity generation.*

5.6.3 Pumped hydro energy storage (PHES)

A PHES system consists of two water reservoirs linked at different elevations. The system is ‘charged’ when power is consumed to pump water from the lower to the upper reservoir, and ‘discharged’ when power is generated as water moves back down to the lower reservoir through a turbine.

PHES is a mature technology that is commercial and used widely.[185] A range of different PHES system designs exist, including conventional open-loop (CRI 6),[186] seawater (CRI 4-6),[187] closed-loop and underground PHES (TRL 7-8).

Historically, PHES was introduced as a profitable ‘time shift of energy’ mechanism by allowing energy generated during off-peak pricing periods to be used during peak-demand pricing. More recently, PHES plants have been used to provide frequency control and load regulation as the increasing penetration of VRE generation can cause power grid instability.[188]

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[184] Gamisch S, Kick M, Klünder F, Weiss J, Laurenz E, Haussmann T (2023) Thermal storage: From low-to-high-temperature systems. Energy Technology 11(6), 2300544. https://doi.org/10.1002/ente.202300544. See also Baigorri J, Zaversky F, Astrain D (2023) Massive grid-scale energy storage for next-generation concentrated solar power: A review of the potential emerging concepts. Renewable and Sustainable Energy Reviews 185, 113633. https://doi.org/10.1016/j.rser.2023.113633.

[185] Morabito A (2022) Underground cavities in pumped hydro energy storage and other alternate solutions. Encyclopedia of Energy Storage 3, 193–204. https://doi.org/10.1016/B978-0-12-819723-3.00145-1.

[186] IEA (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[187] See, e.g., ARENA (2024) Cultana pumped hydro energy storage phase 2 project. https://arena.gov.au/projects/cultana-pumped-hydro-energy-storage-phase-2/ (accessed 13 December 2024).

[188] Baldin M (2022) The pumped hydro storage plants and their civil engineering structures. Encyclopedia of Energy Storage 3, 136–156. https://doi.org/10.1016/B978-0-12-819723-3.00141-4; U.S. Department of Energy (2018) Hydropower Vision: A new chapter for America’s first renewable electricity source. https://www.energy.gov/sites/default/files/2018/02/f49/Hydropower-Vision-021518.pdf (accessed 13 December 2024).

Primary technologies

Optimising PHES system configurations to suit local environments can reduce cost of electricity production and expand viable project sites.

The levelised cost of PHES was forecasted to decrease from $236/MWh in 2025 to $182/MWh in 2050 for the medium duration use case (please refer to the Levelised cost analysis in *Section 5.4.2 Primary technology analysis,* for cost forecasts across the defined profiles). This could be achieved, in part, through research that supports the optimisation of site-specific reservoir configurations that leverage local environments. The design and mechanical elements of PHES differ from site to site (i.e., local topography, geology, and hydrology), and innovations that align infrastructure design with natural or pre-existing features can substantially reduce capital expenditure.[189]

Research is advancing alternative PHES models such as seawater PHES and underground PHES, which avoid the need for traditional dual-reservoir construction. For example, seawater systems reduce construction needs by directly pumping water from the ocean, albeit requiring corrosion-resistant materials and saltwater containment strategies to protect soil from salt water.[190] Underground PHES can repurpose existing mine shafts or natural cavities, providing the surrounding geology, particularly rock compressive strength, is suitable.[191] There has been Australian interest to build underground PHES, with a pre-feasibility study conducted in 2018 in Bendigo finding that it would be technically and economically feasible to build a plant using existing mining infrastructure.[192] The added potential of scalable and modular designs may also broaden potential site locations.[193]

Integrating variable-speed pumping units and hybrid configurations can enhance and VRE compatibility.

To support grid-scale renewable integration, PHES systems must offer greater operational flexibility. RD&D efforts are supporting this by developing variable speed pumping units, which can be adjusted in real time to accommodate intermittent renewable energy inputs. These allow for improved grid balancing, enabling PHES plants to store surplus energy for use at times of supply deficiencies, and provide precise power output control when needed.[194]

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[189] Argonne National Laboratory (2014) Energy storage for the electricity grid: Benefits and emerging technologies. https://publications.anl.gov/anlpubs/2014/12/106380.pdf (accessed 13 December 2024); Ioakimidis CS, Genikomsakis KN (2018) Integration of seawater pumped-storage in the energy system of the island of São Miguel (Azores). Sustainability 10(10), 3438. https://doi.org/10.3390/su10103438

[190] Katsaprakakis DA, Christakis DG, Stefanakis I, Spanos P, Stefanakis N (2013) Technical details regarding the design, the construction and the operation of seawater pumped storage systems. Energy 55, 619–630. https://doi.org/10.1016/j.energy.2013.01.031.

[191] Morabito A (2022) Underground cavities in pumped hydro energy storage and other alternate solutions. Encyclopedia of Energy Storage 3, 193–204. https://doi.org/10.1016/B978-0-12-819723-3.00145-1https://www.sciencedirect.com/science/article/pii/B9780128197233001451.

[192] Arup (2024) Bendigo underground pumped storage project. https://www.arup.com/projects/bendigo-underground-pumped-storage/ (accessed 13 December 2024).

[193] See, e.g., Morabito A (2022) Underground cavities in pumped hydro energy storage and other alternate solutions. Encyclopedia of Energy Storage 3, 193–204. https://doi.org/10.1016/B978-0-12-819723-3.00145-1. These designs may also allow for potential smaller PHES systems (below 10MW) for remote and rural communities: see, e.g., Government of Western Australia (2024) Walpole mini pumped hydro project. https://www.climateaction.wa.gov.au/initiatives/walpole-mini-pumped-hydro (accessed 13 December 2024).

[194] Baldin M (2022) The pumped hydro storage plants and their civil engineering structures. Encyclopedia of Energy Storage 3, 136–156. https://doi.org/10.1016/B978-0-12-819723-3.00141-4. Modern PHES systems can also integrate inertial response to dynamically reacting to power fluctuations and energy demand to swiftly bring the power system to equilibrium: See also, Table 5 in Argonne National Laboratory (2014) Energy storage for the electricity grid: Benefits and emerging technologies. https://publications.anl.gov/anlpubs/2014/12/106380.pdf (accessed 13 December 2024).

Importantly, these variable-speed technologies can be retrofitted into existing PHES and hydroelectric plants, enhancing performance without plant reconstruction (see also *Box 2: Hydroelectricity RD&D case study*).[195] Hybridisation with complementary storage technologies, such as batteries, is also being explored to increase plant flexibility, provide fast response times, and improve system efficiency during periods of rapid load variation.[196]

Auxiliary technologies

The distribution of generated electricity will be reliant on the availability of transmission networks and infrastructure.

Transmission systems and smart grid technologies are essential to facilitate, regulate and optimise energy distribution within the grid; for more detail, see the discussion in *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure*. In particular, advanced control systems may allow for improved flexibility when storing energy from VRE sources, and for predictive maintenance of PHES systems.

For additional detail on electricity generation technologies, refer to *Section 4 Electricity generation.*

5.6.4 Compressed air energy storage (CAES)

CAES systems involve compressing ambient air and storing it, most generally, in underground caverns. When electricity is required, the pressurised air is released, expanding to drive a power-generating turbine.

There are three main types of CAES systems:[197]

- **Diabatic CAES systems** (D-CAES) is the most mature CAES system (TRL 9; CRI 6).[198] It compresses and stores air while releasing the heat generated during compression into the atmosphere. When the air is expanded to generate power, external fuel is burned to reheat the air, resulting in relatively low process efficiency of about 40-55%.[199] D-CAES is primarily used to boost performance of gas plants and is not considered in this analysis.
- **Adiabatic CAES systems** (A-CAES) (TRL 9; CRI 2-3) resemble D-CAES systems, but also captures the heat generated during compression, often using TES systems.[200] Given the challenge associated with

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[195] See, e.g., Vasudevan KR, Ramachandaramurthy VK, Venugopal G, Ekanayake JB, Tiong SK (2021) Variable speed pumped hydro storage: A review of converters, controls and energy management strategies. Renewable and Sustainable Energy Reviews 135, 110156. https://doi.org/10.1016/j.rser.2020.110156; National Hydropower Association (2017) Pumped storage and wind integration: Final report. https://www.hydro.org/wp-content/uploads/2017/08/PS-Wind-Integration-Final-Report-without-Exhibits-MWH-3.pdf (accessed 13 December 2024).

[196] See, e.g., ANDRITZ (2024) XFlex Hydro: Advanced solutions for flexible hydropower generation. https://www.andritz.com/resource/blob/439184/2bc91977238ad53a602564a35f5d491b/18-xflex-hydro-data.pdf (accessed 13 December 2024).

[197] With TRL>3. Other CAES systems are being developed, e.g. supercritical CAES at earlier stages of development (TRL<4): Massachusetts Institute of Technology (MIT) (2022) The Future of Energy Storage: An Interdisciplinary MIT Study. <https://energy.mit.edu/wp-content/uploads/2022/05/The-Future-of-Energy-Storage.pdf> (accessed 13 December 2024).

[198] EASE-EERA (2017) Energy Storage Technology Development Roadmap. <https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/> (accessed 13 December 2024)https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/; Rabi AM, Radulovic J, Buick JM (2023) Comprehensive review of compressed air energy storage (CAES) technologies. Thermo 3(1), 104–126. https://doi.org/10.3390/thermo3010008.

[199] For instance, the CAES system in Huntdorf, Germany has achieved a process efficiency of 42%, while the system in McIntosh, USA has achieved a process efficiency of 54%. See Wang J, Lu K, Ma L, Wang J, Dooner M, Miao S, Li J, Wang D (2017) Overview of compressed air energy storage and technology development. Energies 10(7), 991. https://doi.org/10.3390/en10070991; Budt M, Wolf D, Span R, Yan J (2016) A review on compressed air energy storage: Basic principles, past milestones and recent developments. Applied Energy 170, 250–268. https://doi.org/10.1016/j.apenergy.2016.02.108

[200] CSIRO (2023) Renewable Energy Storage Roadmap: CSIRO (2023) Renewable Energy Storage Roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy/Renewable-Energy-Storage-Roadmap> (accessed 12 December 2024).

capturing 100% of the generated heat, many A-CAES designs are 'partially adiabatic'[201] and achieve process efficiencies of above 60%.[202] Australia's first adiabatic CAES facility is planned for Broken Hill, NSW with a capacity of 200MW and 1,600MWh.[203]

- **Isothermal CAES systems** (I-CAES) (TRL 4-6) aim to maintain a constant temperature throughout compression and expansion processes by the continual capture and supply of heat.[204] In small-scale studies, this has reached efficiencies of about 80% using a hydraulic pump/turbine and spray cooling.[205] However, common technical devices cannot realise compression and expansion processes at a constant temperature,[206] and the system's technical complexity is anticipated to make them unsuitable for grid-scale applications.[207]

A-CAES systems are suitable for grid-scale applications and can be adapted for small to large-scale applications, given appropriate storage capacities and pressures.[208]

Primary technologies

Cost reductions are a core focus area to improve commercial viability of CAES and could be enabled through high-performance materials and process optimisation.

Cost reductions, driven by RD&D, could facilitate the commercial adoption of CAES technologies and their ability to compete with other energy storage technologies.[209] These costs largely stem from the high pressures often used, which can raise production and maintenance costs.[210] Advanced materials and designs are being

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[201] Heidari M (2015) Contribution to the technique of compressed air energy storage. Ph.D. Dissertation, The École Polytechnique Fédérale de Lausanne (EPFL); Kim S, Dusseault MB, Babarinde O, Wickens J (2023) Compressed air energy storage (CAES): Current status, geomechanical aspects, and future opportunities. Geological Society London Special Publications 528(1). https://doi.org/10.1144/SP528-2022-54. Similarly, a 'perfect' isothermal CAES system is challenging to create: Rabi AM, Radulovic J, Buick JM (2023) Comprehensive review of compressed air energy storage (CAES) technologies. Thermo 3(1), 104–126. https://doi.org/10.3390/thermo3010008.

[202] Wang J, Lu K, Ma L, Wang J, Dooner M, Miao S, Li J, Wang D (2017) Overview of compressed air energy storage and technology development. Energies 10(7), 991. https://doi.org/10.3390/en10070991; Zhang X, Li Y, Gao Z, Chen S, Xu Y, Chen H (2023) Overview of dynamic operation strategies for advanced compressed air energy storage. Journal of Energy Storage 66, 107408. https://doi.org/10.1016/j.est.2023.107408. See also, the case study of Jintan: PV Magazine (2022) China's first salt cavern for compressed air energy storage comes online. <https://www.pv-magazine.com/2022/05/30/chinas-first-salt-cavern-for-compressed-air-energy-storage-comes-online/> (accessed 13 December 2024); Tsinghua University (2024) Advanced energy storage research at the Department of Electrical Engineering. <https://www.eea.tsinghua.edu.cn/en/info/1038/2062> (accessed 13 December 2024). The company Storelectric states efficiencies of about 67% for a 500 MW system: Storelectric (2024) Adiabatic vs. isothermal CAES: Efficiency comparison for large-scale energy storage. https://storelectric.com/adiabatic-v-isothermal-caes/ (accessed 13 December 2024).

[203] With an expected duration of 8 hours. Hydrostor (2024) Hydrostor's compressed air energy storage selected as preferred option by TransGrid to provide backup electricity for Broken Hill, New South Wales. https://www.hydrostor.ca/hydrostors-compressed-air-energy-storage-selected-as-preferred-option-by-transgrid-to-provide-back-up-electricity-for-broken-hill-new-south-wales/ (accessed 13 December 2024).

[204] Massachusetts Institute of Technology (MIT) (2022) The Future of Energy Storage: An Interdisciplinary MIT Study. https://energy.mit.edu/wp-content/uploads/2022/05/The-Future-of-Energy-Storage.pdf (accessed 13 December 2024).

[205] Chen H, Peng Y-H, Wang Y-L, Zhang J (2020) Thermodynamic analysis of an open-type isothermal compressed air energy storage system based on hydraulic pump/turbine and spray cooling. Energy Conversion and Management 204, 112293. https://doi.org/10.1016/j.enconman.2019.112293; Hunt JD, Zakeri B, Nascimento A, Pacheco DAJ, Patro ER, Đurin B, Pereira MG, Leal Filho W, Wada Y (2023) Isothermal deep ocean compressed air energy storage: An affordable solution for seasonal energy storage. Energies 16(7), 3118. https://doi.org/10.3390/en16073118.

[206] Budt M, Wolf D, Span R, Yan J (2016) A review on compressed air energy storage: Basic principles, past milestones and recent developments. Applied Energy 170, 250–268. https://doi.org/10.1016/j.apenergy.2016.02.108.

[207] Kim S, Dusseault MB, Babarinde O, Wickens J (2023) Compressed air energy storage (CAES): Current status, geomechanical aspects, and future opportunities. Geological Society London Special Publications 528(1). https://doi.org/10.1144/SP528-2022-54.

[208] Kim S, Dusseault MB, Babarinde O, Wickens J (2023) Compressed air energy storage (CAES): Current status, geomechanical aspects, and future opportunities. Geological Society London Special Publications 528(1). https://doi.org/10.1144/SP528-2022-54.

[209] Energy storage is not the only expensive use of compressed air systems; they also serve as one of the most expensive utilities in industrial facilities: Dindorf R (2012) Estimating potential energy savings in compressed air systems. Procedia Engineering 39, 204–211. https://doi.org/10.1016/j.proeng.2012.07.026; Olabi AG, Wilberforce T, Ramadan M, Abdelkareem MA, Alami AH (2021) Compressed air energy storage systems: Components and operating parameters – A review. Journal of Energy Storage 34, 102000. https://doi.org/10.1016/j.est.2020.102000.

[210] Dindorf R (2012) Estimating potential energy savings in compressed air systems. Procedia Engineering 39, 204–211. https://doi.org/10.1016/j.proeng.2012.07.026.

incorporated, such as high-speed turbomachinery for compression and expansion with high power densities and storage tanks that can endure higher pressures.[211] These measures, along with optimising system operations such as storage pressure, can help reduce costs in line with cost forecasts (please refer to the Levelised cost analysis in *Section 5.4.2 Primary technology analysis,* for cost forecasts across the defined profiles). Improved efficiencies are also expected to reduce costs, particularly for larger scale systems.

Efficiency improvements in A-CAES systems can reduce lifecycle costs and enhance grid functionality.

Achieving higher efficiency rates, with some sources suggesting efficiencies above 70% are possible for large-scale A-CAES systems (compared to about 60% today), can contribute to improved cost effectiveness and enable broader grid integration.[212] A-CAES systems store and recover heat during compression and expansion cycles, making thermal regulation a key driver of efficiency and reliability.[213]

Research is investigating improved thermal management systems, including insulation for compression, expansion, and heat storage components, advanced heat exchangers, and the incorporate of TES media (see *Section 5.6.2 Thermal energy storage with electricity output (TESe)*).[214] Innovations such as external heat integration (e.g., from solar thermal or waste heat) and improved heat recuperation can increase energy conversion efficiency across a wide range of operating conditions.[215]

These performance gains also support CAES in delivering ancillary benefits to the grid, such as voltage control and frequency support.

Site optimisation and alternative reservoir designs can reduce environmental impacts, while enabling greater deployment flexibility.

The viability of CAES systems is strongly influenced by site-specific geological factors. Traditional underground storage methods require careful assessment to avoid adverse effects, including altered air dispersion patterns, natural gas mixing, secondary mineralisation, bacterial growth, and porosity and permeability degradation (see also the *Hydrogen chapter* of the *Low Carbon Fuels* technical appendix).[216]

Further research into site selection could be used to optimise CAES systems while reducing environment impacts and understand long-term management of wellfields. Investigation may include furthering understandings of how CAES wellfields can be developed and maintained, including whether new drilling and

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[211] See, e.g., Augwind Energy (2024) AirBattery: Advanced compressed air energy storage technology. https://www.aug-wind.com/airbattery (accessed 13 December 2024).

[212] He W, Wang J (2018) Optimal selection of air expansion machine in compressed air energy storage: A review. Renewable and Sustainable Energy Reviews 87, 77–95. https://doi.org/10.1016/j.rser.2018.01.013; Cheung B, Cao N, Carriveau R, Ting DS-K (2012) Distensible air accumulators as a means of adiabatic underwater compressed air energy storage. International Journal of Environmental Studies 69(4), 566–577. https://doi.org/10.1080/00207233.2012.699360; He Y, Chen H, Xu Y, Deng J (2018) Compression performance optimization considering variable charge pressure in an adiabatic compressed air energy storage system. Energy 165(Part B), 349–359. https://doi.org/10.1016/j.energy.2018.09.168

[213] Rabi AM, Radulovic J, Buick JM (2023) Comprehensive review of compressed air energy storage (CAES) technologies. Thermo 3(1), 104–126. https://doi.org/10.3390/thermo3010008.

[214] Regarding the use of packed bed TESe in CAES systems, see, e.g., Sciacovelli A, Li Y, Chen H, Wu Y, Wang J, Garvey S, Ding Y (2017) Dynamic simulation of adiabatic compressed air energy storage (A-CAES) plant with integrated thermal storage – Link between components performance and plant performance. Applied Energy 185(Part 1), 16–28. https://doi.org/10.1016/j.apenergy.2016.10.058. Research is also investigating the coupling of aquifer TES and CAES to store heat of compression in the subsurface, which would eliminate the requirement for surface TES.

[215] Rabi AM, Radulovic J, Buick JM (2023) Comprehensive review of compressed air energy storage (CAES) technologies. Thermo 3(1), 104–126. https://doi.org/10.3390/thermo3010008. See, e.g., the examples of the 'ADELE / ADELE-ING' projects operating between 2010-2017 in Germany, aiming to achieve efficiencies of 70% using a large-scale advanced A-CAES (AA-CAES) system. The projects were unable to achieve a final system in the timeframe, given the challenges associated with developing a high-temperature TES that handles thermal and mechanical stress, and creating an electrically driven compressor that can operate at the high-outlet temperatures required for AA-CAES: Budt M, Wolf D, Span R, Yan J (2016) A review on compressed air energy storage: Basic principles, past milestones and recent developments. Applied Energy 170, 250–268. https://doi.org/10.1016/j.apenergy.2016.02.108.

[216] Kim S, Dusseault MB, Babarinde O, Wickens J (2023) Compressed air energy storage (CAES): Current status, geomechanical aspects, and future opportunities. Geological Society London Special Publications 528(1). https://doi.org/10.1144/SP528-2022-54.

completion techniques and tools are needed.[217] To expand deployment opportunities and reduce environmental concerns, researchers are also exploring above ground approaches or manufactured reservoirs, which offer increased flexibility in site selection.[218]

Auxiliary technologies

Transmission systems and smart grid technologies are essential to facilitate, regulate and optimise energy distribution within the grid; for more detail, see the discussion in *Section 4.6.4 Auxiliary technology: Transmission and distribution infrastructure*.

For additional detail on electricity generation technologies, refer to *Section 4 Electricity generation*.

5.6.5 Hydrogen-based electricity storage

The deployment of hydrogen-based storage could be accelerated by reductions in system costs and energy losses.

Closed-loop hydrogen storage, where hydrogen is stored as a compressed gas in tanks or underground caverns, could play a role in electricity storage. These systems do not experience chemical degradation over time, and if chemical losses due to leakage or evaporation are sufficiently managed, can enable energy storage over diverse durations with minimal loss.[219] For medium durations, compressed hydrogen tanks present potential, optimised for rapid cycling. Hydrogen can service longer duration needs through increased storage capacity (in the case of underground hydrogen storage). Cost forecasts suggest system costs for storing electricity could reach about $193-201/MWh for long duration storage in 2050, compared to $315-324/MWh in 2025 for caverns and compression tanks respectively (*please refer to the Levelised cost analysis in Section 5.4.2 Primary technology analysis, for cost forecasts across the defined profiles*).

Refer to the *Hydrogen (and derivative) storage* chapter of the *Low Carbon Fuels* technical appendix for discussion of RD&D opportunities related to hydrogen storage solutions.

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[217] Internal stakeholder consultation.

[218] Burian O, Dančová P (2023) Compressed air energy storage (CAES) and liquid air energy storage (LAES) technologies—A comparison review of technology possibilities. Processes 11(11), 3061. https://doi.org/10.3390/pr11113061; Green-Y Energy (2024) Energy storage system: Sustainable and efficient energy storage solutions. <https://www.green-y.ch/en/energy-storage-system/> (accessed 13 December 2024). See also, e.g., EASE-EERA (2017) Energy storage technology development roadmap. <https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/> (accessed 13 December 2024); Kim S, Dusseault MB, Babarinde O, Wickens J (2023) Compressed air energy storage (CAES): Current status, geomechanical aspects, and future opportunities. Geological Society London Special Publications 528(1). https://doi.org/10.1144/SP528-2022-54; US Department of Energy (2020) Grid Energy Technology Cost and Performance Assessment. <https://www.pnnl.gov/sites/default/files/media/file/CAES_Methodology.pdf> (accessed 13 December 2024); EERA (2017) European Energy Storage Technology Development Roadmap. <https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/> (accessed 13 December 2024).

[219] Clean Energy Council (2024) The future of long-duration energy storage. https://cleanenergycouncil.org.au/getmedia/e456a7e4-28f7-4241-b7ac-511037d932bb/the-future-of-long-duration-energy-storage.pdf (accessed 13 December 2024).

6 Appendix

A.1 Glossary

Table 16: Terms and definitions

TERM	DEFINITION
Adiabatic compressed air energy storage (A-CAES)	Commonly referred to by its acronym A-CAES, adiabatic compressed air energy storage is a method of storing energy by compressing air and capturing the heat generated during this process.
Annual cycles	The amount of time an energy storage system can discharge its stored energy at its rated power capacity before depleting its energy reserves.
Artificial intelligence / Machine learning (AI/ML)	Commonly referred to by its acronym AI/ML, artificial intelligence refers to the stimulation of human intelligence in machines that programmed to think and learn like humans and machine learning is a subset of AI that involves the development of algorithms and statistical models that enable computers to learn from and make predictions or decisions based on data.
Batteries: Flow	Rechargeable batteries, where two chemical components are dissolved in liquids and pumped through the system on either side of a membrane. They store and release energy through reversible oxidation and reduction reactions.
Batteries: Metal-ion	Rechargeable batteries that utilise the movement of ions (such as lithium or sodium) between electrodes through an electrolyte to store and release electrical energy. Examples include Li-ion and Na-ion.
Bioenergy with carbon capture and storage (BECCS)	Commonly referred to by its acronym BECCS, bioenergy with carbon capture and storage is an electricity generation technology that combines energy production via biomass (organic materials such as wood, agricultural residues or dedicated energy crops) with the capture and storage of CO_2.
Biomass	Biomass refers to organic material that comes from plants and animals, and it is a renewable source of energy. Biomass can be used directly for heating or power generation, or it can be converted into biofuels.
Carbon capture and storage (CCS)	Commonly referred to by its acronym CCS, carbon capture and storage is the practice of capturing atmospheric carbon dioxide emissions (typically produced from the use of fossil fuels and industrial processes) for long term secure storage.
Charging cycle	The number of times the storage system is fully charged or discharged each year.
Compressed air energy storage (CAES)	Commonly referred to by its acronym CAES, a compressed air energy storage system is where electricity is used to compress ambient air stored under pressure. When electricity is required, the compressed air is released to drive a turbine, generating electricity. There are three types of CAES systems: diabatic, adiabatic and isothermal.
Compressed hydrogen tank	Hydrogen is compressed at high pressure (up to 800 bar) in steel or carbon fibre tanks.
Concentrated solar power (CSP)	Commonly referred to by its acronym CSP, concentrated solar power is a technology that uses mirrors or lenses to gather direct solar irradiation and create high temperature heat stored within heat transfer fluids. Electrical energy by the heat transfer fluid driving a thermodynamic cycle with a generator.
Concentrated solar thermal (CST)	Commonly referred to by its acronym CST, concentrated solar thermal specifically refers to the initial generation and storage of thermal energy in concentrated solar power technology.
Diabetic compressed air energy storage (D-CAES)	Commonly referred to by its acronym D-CAES, diabetic compressed air energy storage is a type of energy storage system where air is compressed using electricity and the heat generated is dissipated into the environment. The compressed air is then stored in underground caverns or high pressure tanks.
Discharge duration	The measurement for how long a technology can sustain its maximum discharge rate by dividing the system's energy capacity by its maximum power output.

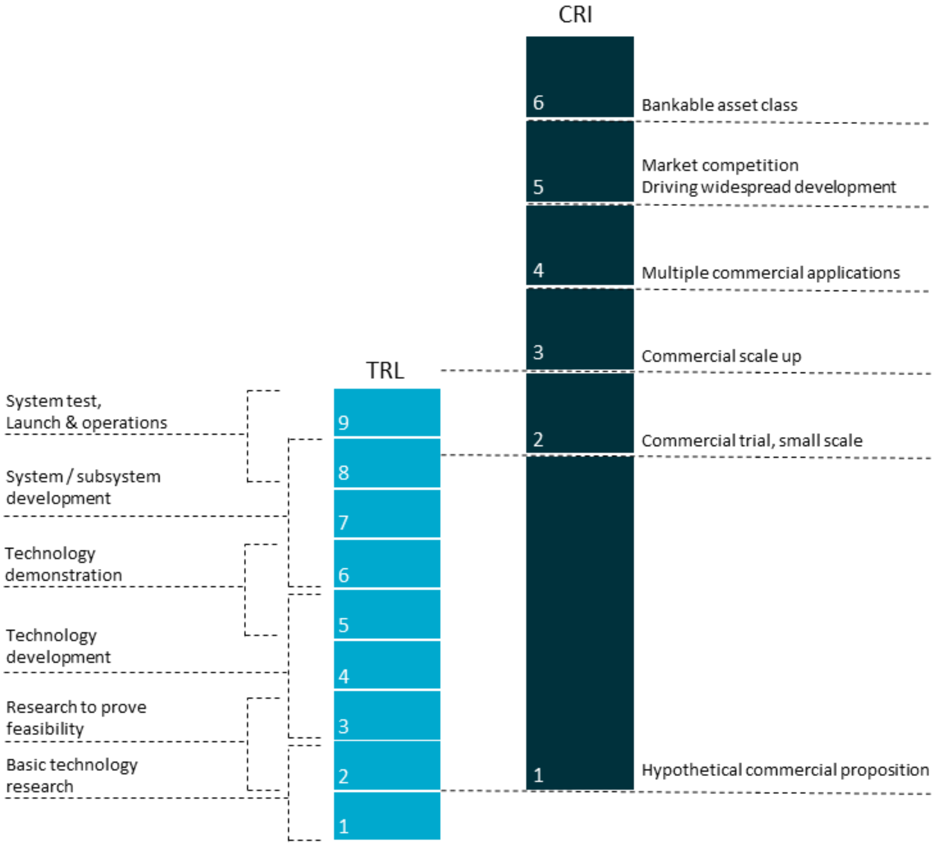
Distributed energy resources	Commonly referred to by its acronym DER, distributed energy resources are small scale units of local generation connected to the grid at the distribution level. These resources can include solar panels, wind turbines, energy storage systems etc.
First generation feedstock	First-generation feedstocks are types of biomasses that are often used for food, such as corn, soy, and sugarcane. Biofuels are made through fermentation or chemical processes that convert the oils, sugars, and starches in the biomass into liquid fuels.
Flexible AC transmission systems (FACTS)	Commonly referred to by its acronym FACTS, flexible AC transmission systems are advanced power electronic systems designed to enhance the control and efficiency of alternating current (AC) transmission networks.
Frequency regulation	The practice of responding to electric frequency changes in the power grid to ensure the balance of electricity supply and demand.
Geothermal energy	Harnesses heat from the Earth's interior to generate steam, which drives turbines to produce electricity.
Gravity storage	Energy is stored by elevating a mass using electric power. When electricity is needed, the mass is allowed to fall, converting potential energy back into electrical energy through generators.
Grid stabilisation	The practice and technologies used to maintain a stable and reliable electrical power grid. This ensures that the supply of electricity consistently matches demand.
Grid-scale storage	Large-scale energy storage systems that are essential for balancing supply and demand, improving grid stability, and integrating renewable energy sources into the electricity network.
Heat transfer fluids (HTF)	Commonly referred to by its acronym HTF, heat transfer fluids are substances used to transfer heat from one part of a system to another. Within energy generation and storage, HTFs will hold thermal energy that can be converted into electrical energy.
High assay, low enriched uranium (HALEU)	Commonly referred to by its acronym HALEU, high assay low enriched uranium is uranium that has been enriched to 5% and 20% U-235 for the purposes of use within nuclear energy generators. This is enrichment level is higher than typical low-enriched uranium.
Hydrogen reciprocating	Uses hydrogen in internal combustion engines to generate electricity with water vapor as the primary by-product.
Hydrogen storage	Energy is stored by producing hydrogen, that can then be stored in different forms and later converted back into electricity using fuel cells or steam turbines. Hydrogen can be stored using a variety of mechanisms, including tanks and underground storage.
Isothermal compressed air energy storage (I-CAES)	Commonly referred to by its acronym I-CAES, isothermal compressed air energy storage is a type of energy storage system where air is compressed and stored at a constant temperature. This is achieved by managing the heat generated during the compression process, often through heat exchangers or other cooling methods
Latent heat storage	Involves storing and releasing energy with a change in physical state, with specific technologies suited to particular temperature ranges and intraday to multiday durations. This is also known as phase change storage. Latent media examples include high temperature silicon (used for ranges around its liquefaction point of 1,414°C) and miscibility gap alloys (typically used for temperature ranges of about 20-650°C).
Liquefaction	The process of turning a solid or a gas into liquid.
Liquid air energy storage (LAES)	Commonly referred to by its acronym LAES, liquid air energy storage is an energy storage technology that liquifies and stores air at very low temperatures. The stored liquid air is then evaporated and expanded to drive a turbine, generating electricity.
Liquid natural gas (LNG) vehicles	Commonly referred to by its acronym LNG, liquid natural gas vehicles are vehicles that employ an internal combustion engine fuelled by liquefied natural gas (LNG).
Lithium-ion batteries (Li-ion)	Commonly referred to by its acronym Li-ion, lithium-ion batteries are a type of rechargeable battery that relies on lithium ions moving between the anode and cathode to store and release energy.
Municipal solid waste (MSW)	Commonly referred to by its acronym MSW, municipal solid waste includes a wide range of materials such as product packaging, food scraps, yard waste, furniture, clothing, bottles, and appliances.
Nuclear	Produces electricity using nuclear fission or fusion reactions in reactors. This category considers both large-scale reactors and small modular reactors (SMRs).

Ocean electricity generation	This category includes ocean, wave and tidal technologies. Uses the movements of the ocean, including surface waves (wave energy) and the effect of the gravitational pull of the sun and moon (tidal energy) to generate electricity.
Peak shaving	The practice of reducing energy consumption during high demand periods (peak demand periods).
Photovoltaics (PV)	Commonly referred to by its acronym PV, photovoltaics are technologies that convert sunlight directly into electricity using semiconductor materials.
Plant capacity	Plant configurations in iron and steel making that can technologically meet current production capacities, in terms of plant size and process inputs.
Pumped hydro energy storage (PHES)	Commonly referred to by its acronym PHES, pumped hydro energy storage is a technology that stores energy using two water reservoirs are linked at different elevations. Power is generated as water moves from the upper to the lower reservoir through a turbine, and power is consumed to pump water back to the upper reservoir.
Rankine cycles	The thermodynamic cycle used in steam-based power boilers to generate electricity. Pressurized water is superheated to create steam that powers a turbine to generate electricity, and the steam is cooled returning it to water to restart the cycle.
Reactive power	The portion of electricity that does not perform any useful work but is necessary to maintain voltage levels in the power system. It is measured in volt-amperes reactive (VAR) and is essential for the proper functioning of alternating current (AC) systems.
Reciprocating engine	A type of heat -based engine that utilises pistons that convert pressure into rotation motion. Commonly known as the piston engine.
Renewable smoothing	The process of ensuring stable supply of power from renewable energy sources by using energy storage systems to even out fluctuations in supply.
Round trip efficiency	The ratio of the energy retrieved from a storage system to the energy initially supplied to it, expressed as a percentage. It measures the efficiency of energy storage systems, indicating how much energy is lost during the storage and retrieval process.
Second generation feedstock	Second-generation feedstocks are produced from non-food biomass, such as perennial grass and fast-growing trees. The processes to make biofuels are more complex and less developed than for first-generation feedstocks, often involve converting fibrous non-edible material (cellulose) into fuel.
Sensible heat storage	Involves capturing and releasing energy through heating or cooling a solid or liquid storage medium. Most technologies are capable of covering a wide range of temperatures and durations (with the latter ranging from hours to weeks). Examples of sensible media include molten salts, graphite and packed bed systems.
Sodium ion	Commonly referred to by its acronym Na-ion, a sodium ion is a positively charged ion formed when a sodium atom loses one electron.
Tank-to-wheel (TtW)	Commonly referred to by its acronym TtW, tank-to-wheel refers to the analysis of emissions and energy consumption that occur during the operation of a vehicle, from the point when fuel is added to the tank until it is used to power the vehicle.
Thermal cycle (as a part of TES systems)	A thermal cycle refers to the process of charging and discharging thermal energy in a thermal storage system.
Thermal energy storage (TESe)	Commonly referred to by its acronym TESe, thermal energy storage is an energy input stored in the form of thermal energy in a medium. The energy input can be in the form of electricity or heat for use at a later period to generate electricity using heat engines or turbines (eTESe and hTESe respectively). There are three categories of TES media: sensible, latent and thermochemical heat storage.
Thermal energy storage (electricity input, electricity output) (eTESe)	Commonly referred to by its acronym eTESe, thermal energy storage is an energy input stored in the form of thermal energy in a medium. The energy input is in the form of electricity and is used at a later period to generate electricity using turbines.
Thermal energy storage (electricity input, heat output) (eTESh)	Commonly referred to by its acronym eTESh, thermal energy storage is an energy input stored in the form of thermal energy in a medium. Electricity is converted to heat and used to heat up the thermal medium. A heat output is used with a resistance mechanism to create steam.

Thermophotovoltaics	Technology that uses photovoltaic cells to capture infrared radiation (heat energy) and converts it into electricity. Also known as thermovoltaics.
Tri-structural isotropic particle (TRISO)	Commonly referred to by its acronym TRISO, tri-structural isotropic particles are a type of nuclear fuel particle designed for high-temperature gas cooled reactors. Each particle consists of a uranium, carbon and oxygen fuel kernel, which is encapsulated by three layers of carbon- and ceramic-based materials to precent radioactive fission product release.
Underground hydrogen storage (UHS)	Commonly referred to by its acronym UHS, underground hydrogen storage is where hydrogen is compressed and injected into geological or engineered subsurface structures including salt caverns, depleted gas fields, aquifers or excavated caverns.
Vanadium redox flow batteries (VRFB)	Commonly referred to by its acronym VRFB, vanadium redox flow batteries are a type of rechargeable flow battery that utilize vanadium ions in liquid electrolyte to store energy.
Variable renewable energy (VRE)	Commonly referred to by its acronym VRE, variable renewable energy refers to renewable energy sources that produce electricity intermittently, depending on environmental conditions. This includes sources like wind power and solar power, which are not continuously available due to their dependence on weather and time of day.
Volt-ampere reactive (VAR)	Commonly referred to by its acronym VAR, volt-ampere reactive is a unit of measurement of reactive power that exists in an electrical circuit. VARS occur when the voltage and AC electric currents are out-of-phase.
Well-to-tank (WtT)	Commonly referred to by its acronym WtT, well-to-tank is the lifecycle emissions and energy consumption associated with the production, processing, and transportation of fuels before they are used in vehicles or other applications.
Wind energy	The process of converting the kinetic energy from wind into electrical power using wind turbines.
Zinc bromine flow batteries (ZBFB)	Commonly referred to by its acronym ZBFB, zinc bromine flow batteries are a type of rechargeable flow battery that utilize zinc and bromine ions in liquid electrolyte to store energy.

A.2 Technology maturity rating index

Figure 15: Technology Readiness Levels and Commercial Readiness Index[220]



A.3 Technology analysis framework supplementary information

A.3.1 Broad list of technologies

Over 500 technologies were identified from most recent literature and existing global databases, such as the IEA Clean Energy Technology Guide,[221] publications from domestic[222] and international[223] government bodies,

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[220] Adapted from ARENA (2014) Commercial Readiness Index. <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf> (accessed 6 January 2025).

[221] IEA (2023) ETP Clean Energy Technology Guide, <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide>

[222] Australian Government (2021) Low Emissions Technology Statement 2021. Department of Industry, Science, Energy and Resources. <dcceew.gov.au/sites/default/files/documents/low-emissions-technology-statement-2021.pdf; Australian Government (2020) Technology Investment Roadmap. Department of Industry, Science, Energy and Resources. <Technology Investment Roadmap Discussion Paper (storage.googleapis.com)>

[223] U.S. Department of Energy (2022) ARPA-E Strategic Vision Roadmap, August 2022. Report to Congress. <arpa-e.energy.gov/sites/default/files/2022 ARPA-E Strategic Vision Roadmap.pdf> (accessed 15 November 2023).

and prominent literature from Australian research centres (e.g., ClimateWorks Australia,[224] Net Zero Australia,[225] and the CSIRO[226]).

These technologies were assigned to key (sub)sectors. As the level of detail varied across sources only technologies that directly contribute to emissions reduction efforts were considered as inputs to the prioritisation framework. This ensured a structured and objective filtering process to prioritise technologies.

A.3.2 Primary technology analysis criteria, by subsector

To technically evaluate technologies, criteria were identified for each (sub)sector to assess each technology's ability to meet the functional requirements of its use case. For example, for Transport, use cases require a minimum travel distance between refuelling/recharging, therefore a 'range' performance parameter was included. For energy applications in which a scale of production or storage is required by the use case, a performance parameter that assessed the capacity of a technology was used.

The threshold for each criterion was established based on the performance of conventional technologies used for the same application, using values sourced from literature.

Table 17: Technology analysis framework criteria used, by (sub)sector

		Subsector	**Criteria**
Energy supply	**Electricity**	Electricity generation	Levelised cost
		Electricity storage	Discharge duration Levelised cost
	Low carbon fuels	Hydrogen production	Scalability Levelised cost
		Hydrogen storage	Storage capacity Discharge frequency Levelised cost
Energy	**Transport**	Road	Refuelling duration
		Aviation	Minimum range requirement
		Rail	Levelised cost

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[224] Climateworks (2020), Decarbonisation Futures: Solutions, actions and benchmarks for a net zero emissions Australia <https://www.climateworkscentre.org/wp-content/uploads/2020/04/Decarbonisation-Futures-March-2020-full-report-.pdf> (accessed 6 September 2023); Jointly with Climate-KIC Australia, Australian Industry Energy Transition Initiative (2023) Pathways to industrial decarbonisation. <https://energytransitionsinitiative.org/wp-content/uploads/2023/08/Pathways-to-Industrial-Decarbonisation-report-Updated-August-2023-Australian-Industry-ETI.pdf> (accessed 14 July 2023).

[225] Net Zero Australia (2023) Modelling Summary Report. <https://www.netzeroaustralia.net.au/wp-content/uploads/2023/04/Net-Zero-Australia-Modelling-Summary-Report.pdf> (accessed 14 July 2023); Net Zero Australia (2023) Downscaling reports (series). <https://www.netzeroaustralia.net.au/final-modelling-results/> (accessed 19 February 2024).

[226] CSIRO (2023) Renewable energy storage roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy-and-Resources/Renewable-Energy-Storage-Roadmap>; CSIRO (2021) CO2 Utilisation Roadmap - CSIRO. <https://www.csiro.au/-/media/Services/Futures/21-00285_SER-FUT_REPORT_CO2UtilisationRoadmap_WEB_210810.pdf>; CSIRO (2023) Sustainable Aviation Roadmap <https://www.csiro.au/en/research/technology-space/energy/sustainable-aviation-fuel>; CSIRO (2023) Hydrogen vehicle refuelling infrastructure <https://www.csiro.au/en/about/challenges-missions/hydrogen/hydrogen-vehicle-refuelling-infrastructure>; CSIRO (2023) Pathways to Net Zero Emissions – An Australian Perspective on Rapid Decarbonisation. <https://www.csiro.au/en/research/environmental-impacts/decarbonisation/pathways-for-australia-report>

	Shipping	Safety Minimum range requirement Levelised cost
Industry	Iron and steelmaking	Plant capacity Levelised cost
	Medium temperature steam	Resource scalability Levelised cost
	Mining heavy haulage	Truck utilisation Levelised cost

A.4 Abatement potential data repository

Subsector	**Abatement threshold**		**Emissions data**		**Source**
	Threshold	**Explanation**	**Direct emissions**	**Indirect emissions**	
Electricity generation	100%	Technology options were compared against a *‘zero-emissions’ benchmark*, based on the availability of technology solutions with significant abatement potential by 2050 and the impact that non-zero emissions energy supply sources can have on the overall life cycle emissions of an energy sector seeking to achieve their individual emissions targets.	Full fuel cycle (incl. fugitives)	No	ACIL Allen (2016)[227]
Electricity storage	*Not applicable*				

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[227] See tables 3.2 and 3.3, ACIL Allen Consulting (2016) AEMO Emissions Factors. Australian Energy Market Operator (AEMO). <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/ntndp/2016/data_sources/acil-allen---aemo-emissions-factors-20160511-pdf-document.pdf?la=en&hash=AB233ACCECC78768D7C236E307433C10>. See also, Oh K-Y, Nam W, Ryu M-S, Kim J-Y, Epureanu BI (2018) A review of foundations of offshore wind energy converters: Current status and future perspectives. Renewable and Sustainable Energy Reviews 88, 16–36. https://doi.org/10.1016/j.rser.2018.02.005

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