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6 May 2021

Our Ref: CSIRO submission 20/751

Mr Ted O'Brian MP
Committee Chair
House Standing Committee on Environment and Energy
PO Box 6021
Parliament House
Canberra ACT 2600

Dear Mr O'Brian and Committee members

**Re: Inquiry into the current circumstances, and the future need and potential for dispatchable energy generation and storage capability in Australia.**

CSIRO welcomes the opportunity to provide a submission to the above Inquiry and acknowledges the critical role of dispatchable energy generation and storage in securing the desired transition to a low-carbon energy system.

CSIRO considers science and innovation will be critical in supporting this transition and in contributing to securing a resilient and prosperous future across the Australian energy sector, industry and society.

CSIRO is addressing the challenges associated with the transition of energy, industrial, manufacturing, agricultural and transport sectors through assessment, development, and demonstration of priority low emission technologies.

Please find attached CSIRO's submission which summarises recently completed CSIRO research that relates to the Inquiry's Terms of Reference, and also an indication of ongoing research.

[redacted] CSIRO Government Relations) would be pleased to assist should you require any further information or wish to discuss any aspect of this submission with CSIRO and can be contacted at [redacted]

Yours sincerely

[redacted]

Dr Peter Mayfield
Executive Director – Environment, Energy and Resources
CSIRO

Australia's National Science Agency

# Inquiry into the current circumstances, and the future need and potential for dispatchable energy generation and storage capability in Australia

## House Standing Committee on the Environment and Energy

CSIRO Submission 20/751

May 2021

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# Contents

# Key Points

- CSIRO welcomes the opportunity to provide a submission to the Inquiry into the current circumstance, and the future need and potential for dispatchable energy generation and storage capability in Australia and acknowledges the critical role these technologies have to secure the desired transition to a low-carbon energy system.
- CSIRO considers science and innovation will be critical in supporting this transition and in contributing to securing a resilient and prosperous future across the Australian energy sector, industry and society.
- As Australia's national science agency, CSIRO is well positioned to deliver the science and technology that will enable Australia's transition to a lower emissions energy future.
- CSIRO is addressing the challenges associated with the transition of energy, industrial, manufacturing, agricultural and transport sectors through assessment, development, and demonstration of priority low emission technologies.
- In this submission, CSIRO provides an overview of Australia's energy system and technology options that are part of Australia's energy mix together with examples of relevant CSIRO research.

# Introduction

The generation mix in Australia's energy markets is changing as older coal-fired generators are approaching the end of their asset lives and energy systems drive towards cleaner energy sources[1]. The concomitant change in the generation mix and increasing decentralisation presents a challenge to the stability of the electricity system and calls for action to resolve capacity constraints as well as voltage and frequency stabilisation.

Electricity grids in Australia were mainly built to transfer electricity from large, centralised coal-fired power stations, natural gas and hydropower to end-users essentially in one direction. This system excelled in providing dispatchable electricity at any given time. The problem of integrating renewable energy sources into the centralised system involves a) an increased number of large-scale renewable sources, and b) large numbers of end-users (e.g. rooftop solar) supplying energy back into the grid. These changes increase the intermittency of supply and infrastructure costs when creating additional capacity. Any changes in energy supply reliability and affordability also need to be acceptable to the general public.

In addition to the changing energy mix, the spatial distribution of power generation is also changing. According to the Australian Energy Market Operator (AEMO), starting around 2023, Australia could have one of the highest decentralisation ratios of non-grid generation in the world.[2] CSIRO and Energy Networks Australia estimate that by 2050, between 30 to 45 per cent of our annual electricity consumption could be supplied from consumer-owned generators.[3]

As Australia's national science agency, CSIRO is well positioned to support Australian governments and industry in facilitating Australia's energy transition. CSIRO is addressing the challenges associated with the transition of the energy, industrial, manufacturing, agricultural and transport sectors to meet Australia's lower emissions ambitions. CSIRO's research includes the assessment, development and demonstration of priority low emission technologies.

CSIRO welcomes the opportunity to contribute to the inquiry by the House Standing Committee on the Environment and Energy into the current circumstances, and the future need and potential for dispatchable energy generation and storage capability in Australia. CSIRO would be happy to provide further information should that be of interest to the Committee.

[1] AEMO 2020 Integrated System Plan (ISP)

[2] AEMO and Energy Networks Australia 2018, Open Energy Networks, consultation Paper. Retrieved from: https://www.aemo.com.au/-/media/Files/Electricity/NEM/DER/2018/OEN-Final.pdf

[3] CSIRO and Energy Networks Australia 2017, Electricity Network Transformation Roadmap: Energy Networks Australia, Retrieved from: https://www.energynetworks.com.au/resources/reports/electricity-network-transformation-roadmap-final-report/

# Australia's Energy System

The transition towards a lower emission economy will require a combination of existing and emerging energy supply options that will require a great change over time, as science, market demand and policy models conflate towards lower emission options. Currently, however, the new decentralised generation in geographically dispersed locations is posing challenges on the existing grid. With the right decisions, Australia can achieve this transition and provide a reliable, cost efficient energy supply with lower emissions by building a combination of grid and storage systems that can manage dispatchable energy inputs from several Variable Renewable Energy (VRE) sources.

Grid reliability and capacity are barriers to achieving the benefits of the anticipated growth in renewables but could potentially be overcome through the integration of smaller but more numerous renewable generators and dispatchable sources to move power around the system locally and interstate. Ongoing changes to cost and available capacity in energy supply technologies affect development timeframes, investment options and associated outcomes.

Gas peaking plants and the addition of technologies such as synchronous condensers for inertia will become increasingly important since they provide stability to voltage levels and frequency due to their natural inertia.  Digital innovation can also play a role, for example, through Artificial Intelligence and Machine Learning. 'The smarts' could tell the grid what energy sources to use, when and for how long to use them, and thereby provide a leveling effect of generation and load. Also, artificial inertia can be added to the system through digital technologies to provide a stabilising effect to voltage and frequency, similar to conventional synchronous generators.

Coal and gas remain important in our energy mix over the near future and will phase out as other options such as utility-scale solar, wind and hydrogen develop. Hence, it will take time for wind and solar generation capacity to grow to produce enough electricity to reach what coal fired generation provides today. This replacement will depend on a range of factors such as technology readiness, market demand, policies and incentives as well as on the development of carbon capture, usage and storage (CCUS), for example. Furthermore, as the percentage of VRE in the grid increases with time, there will be a need for greater interconnection, more cost-effective technology options for energy storage for both short (stabilising) and medium duration (time shifting) applications, as well as the adoption of other associated 'firming' options.

Beyond the electricity grid, a range of alternative fuels and technologies for industrial and residential heating and transport will be crucial. Gas will play a strong underpinning transitional role as technologies for the safe and economical production and use of hydrogen evolve. A high-level summary of these specific technologies is provided below. More information and data produced by CSIRO is provided in the Appendix to support clean energy investment and development decisions.

# Specific Technologies

**Solar and Wind**
Utility-scale solar and wind are cost effective and can leverage the stability of existing coal and gas generation. It is possible to reach as high as 50 per cent instantaneous penetration of renewables using a highly interconnected grid to shift power around and balance the load, by leveraging fossil sources[4]. A further increase in renewables will require strengthening of the network in combination with energy storage.

Concentrated Solar-thermal Power (CSP) provides an alternative way of generating electricity from solar energy and typically includes several hours of thermal energy storage. CSP plants operate similar to fossil power generation plants and provide dispatchable synchronous generation.

**Gas**
Gas-fired electricity generation has lower emissions than coal and there is existing infrastructure in place around Australia. Gas has a high utility for peak and shoulder periods of the day, competes cost-wise with coal and offers a 31 per cent and 50 per cent reduction of greenhouse gas emissions depending on the generation technology used.[5] Gas can play a significant role in stabilising and supporting the deployment of variable renewable energy in Australia where its niche in the electricity system is to provide a secure and affordable fuel as coal-fired power leaves the market and renewable sources proportionally increase.

**Hydrogen**
As a zero emissions energy carrier, clean hydrogen could make a significant impact on emissions in the next ten years. Hydrogen provides an option for diversified and distributed energy production and storage, for example through use in Remote Area Power systems (RAPS). It also has the potential for long term energy storage using linepack[6] in gas networks, large scale underground hydrogen storage or in chemical form such as ammonia. It can also be used in combination with electrolysers and stationary fuel cells as flexible loads and generators for grid support in high VRE scenarios.

A key element is to foster innovation and create hydrogen hubs – industrial zones which aggregate large-scale supply and demand to realize economies of scale which will help decrease production costs and encourage infrastructure investment. Through sector coupling, hydrogen can realize synergies which contribute to the decarbonisation of some of the world's most carbon-intensive sectors – transport, electricity, steelmaking, petrochemicals, agriculture, maritime industries. CSIRO's research expertise and networks mean it is well placed to address opportunities and challenges across the whole hydrogen energy value chain.[7]

**Energy storage**
By 2030 it is expected that four of Australia's states will be achieving at least 50 per cent electricity generation from renewables[8]. This means energy storage will be critical to continue Australia's emissions reduction journey. A range of different and complementary energy storage solutions with capacity that can meet the timescales of energy demands and maintain grid stability will be needed.

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[4] AEMO released a renewables integration study in 2020, which states that without any changes the current system can handle up to 50 per cent instantaneous VRE penetration: https://aemo.com.au/-/media/files/major-publications/ris/2020/renewable-integration-study-stage-1.pdf

[5] Please see https://gisera.csiro.au/research/greenhouse-gas-and-air-quality/

[6] 'Linepack' describes the total of volume of gas contained within the system. It relates to the average pressure across the network and critical to the physical operation of the network.

[7] Please see, for example, hydrogen CSIRO mission research and roadmap, https://www.csiro.au/en/about/challenges-missions/hydrogen

[8] https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2020.pdf

1. ***Batteries***
   As the penetration of solar and wind to the grid continues to increase, the ability to use batteries to deal with the intermittency of these resources is critical if we wish to reduce our reliance on greenhouse gas emitting technologies such as coal and gas. In general, batteries work well for short duration (less than eight hours) and lower loads. Batteries can be deployed quickly and will continue to work their way down the cost curve, but there are significant challenges. For example, in many circumstances batteries need to be cooled to operate in Australia's summers.

   Australia is currently wholly reliant on the importation of batteries albeit Australia is a world leader in the production of lithium, nickel, manganese, copper, and alumina. Opportunities prevail to value-add to these minerals, specifically to the grade required to be used as part of the manufacture of battery active materials. The ability to manufacture cells and batteries, especially those based on lithium (up to 1-5 MW), would help to support the increasing penetration of renewables on the grid, especially within the remote, commercial, and residential markets. As an example, CSIRO deployed the Australia's first off-grid solar storage system by injecting cutting edge science into two innovative Aussie SMEs, two years before South Australia bought the Tesla battery. For examples of other relevant CSIRO projects refer to the Appendix below.

2. ***Pumped hydro***
   Pumped hydro energy storage is designed for much longer timeframes. Snowy 2.0 is designed for 175h and a wellspring to power Australia's transition to renewables. New plants can take 3-5 years to build and rely heavily on geography. Several studies consider the potential for future energy generation and storage from the building of irrigation dams in Australia.[9]

3. ***Thermal energy storage***
   Thermal energy storage is at an earlier stage of development and typically used in combination with concentrated solar power generation (CSP). For the decarbonisation of energy intensive industries that need heat as the dominant form of energy, thermal energy storage could become a commercially attractive solution to augment a variable renewable energy supply.

4. ***Hydrogen/chemical storage***
   For the establishment of a large hydrogen industry, the ability to store hydrogen at large scale will be essential, similar to the way natural gas is stored today. CSIRO is exploring a number of technologies including chemical storage of hydrogen, such as ammonia and others.

**Flexible Solar Cells for Off-Grid Dispatchable Power**

To date, the need for off-grid dispatchable power has typically been met by diesel generators. The domestic market for rental diesel generators is up to $600 million and spans a range of sectors including mining, agriculture, and defence. Despite the maturity of the technology, there are inherent limitations; not only is there the capital cost associated with the generators but also an ongoing cost associated with fuel and maintenance, and in remote areas the supply of fuel may be uncertain.

A renewable energy solution for small-scale off-grid dispatchable power is to couple large volumes of printable solar films (PSFs) with batteries in easily transported containment vessels (e.g. shipping containers). The PSFs can be deployed using a similar roller mechanism to generate electricity during daylight hours, with additional supply provided during low-light conditions by the batteries. While similar

[9] https://publications.csiro.au/rpr/download?pid=csiro:EP147168&dsid=DS5 and https://www.csiro.au/-/media/Major-initiatives/Northern-Australia/NAWRA-technical-reports/NAWRA-Technical-Report---Hydropower_LO-RES.pdf

systems are used for space applications where weight/stowage volumes are critical, their significant cost preclude their use for terrestrial deployment.

CSIRO Manufacturing is currently researching the production of PSFs. Unlike conventional silicon-based solar cells, these PSFs can be produced by roll-to-roll production methods akin to traditional printing methods, thereby reducing their production cost and allowing for potential domestic manufacture. Furthermore, being printed on plastic substrates, these PSFs are highly flexible and can be tightly rolled, allowing for effective storage during transport to deployment for off-grid deployment.

**Offshore renewable energy systems**
The Blue Economy Co-operative Research Centre (BECRC) [10] recognises the value of Australia's immense ocean estate. The BECRC has the objective of supporting growth of Australia's blue economy, through five research programs. One of the five research programs – the Offshore Renewable Energy Systems Research Program, led by CSIRO – aims to advance the technological and commercial readiness of emerging offshore renewable energy system technologies, so they can fulfil their potential to contribute to Australia's energy needs. For further details refer to the Appendix below.

# Forward Focus

Recently, CSIRO has updated its Energy strategy based on its role as 'Australia's energy transition catalyst' as the nation moves from fossil fuel-dominated energy dependence towards a more diverse energy mix that enables a low emissions future.

Our shifting priorities involve a strong focus on hydrogen, grid integration and simulation, energy and $CO_2$ storage, natural gas for baseload transition and rationalisation of upstream carbon-energy activities and analytical services.

To this end, we have identified three key Impact Areas in line with the Australian National Outlook (ANO2), Low Emission Technology Statement, and international assessments of the energy transition, notably:

- Electricity transition: to resolve the national challenges of electricity generation, transmission, distribution, and consumption using simulation and analysis tools, facilities, and knowhow to inform investments in stable electricity grid systems. Our focus includes managing the grid including storage, gas as transition fuel, simulation and analysis, and continuing focus on energy productivity.
- Industry transition: to create value chains across sectors and develop sustainable solutions for domestic and export industries through demonstrating viable technologies for creation, storage, transport and uses of hydrogen as well as for other low carbon industry processes. Our focus includes hydrogen, energy storage, distributed energy systems, primary industry decarbonisation and transport.

  Emissions and environment: to understand and manage the social and environmental impacts of the key energy technologies, offer solutions for emission reduction, and thereby enable generators and industry to shift from high emission fossil energy towards reduced emissions and sustainable solutions. Our focus includes supporting the closure of fossil fuel production fields and aging generation facilities, fugitive emissions and managing emissions including carbon storage and fugitive emission controls.

[10] https://blueeconomycrc.com.au/

# Appendix – summary of CSIRO papers and project reports

## Electricity networks and systems

### Reliable electricity networks

CSIRO is enabling affordable, reliable, secure and sustainable electricity networks by improving utilisation of existing infrastructure through the adoption of CSIRO's energy system modelling, simulations, and data tools. Some of our key targets in this area include:

- Collaboration with the system operator (AEMO) and distribution network operators
- International research collaboration for power systems modelling, with support of AEMO
- Development of the Australian energy system modelling platform
- Initial granular model of the Australian energy system developed that shows energy generation, use and interactions
- Demonstrated technology that reduces cost and improves reliability of low emissions power transmission, distribution, storage and utilisation

### Flexible generation, use and storage

CSIRO is enabling flexible generation, electricity use and storage, energy efficiency of build environment and emission reduction through the adoption of CSIRO's innovative systems and supply networks, and new storage solutions. Some of our key targets include:

- Data Clearing House platform for flexible energy generation, use and storage well established and in use by key partners
- Facilitation of initial deployments of Microgrids, Virtual power plants, and Community energy systems
- Demonstrated technology that reduces cost and improves reliability of low emission and renewable power generation and energy storage

See http://www.ihub.org.au/ihub-initiatives/smart-building-data-clearing-house/

The following describes three specific energy network or systems research projects, including links, that are well targeted to the Inquiry Terms of Reference:

- The Gencost report is a collaboration between CSIRO and AEMO to deliver an annual process of updating electricity generation and storage costs with a strong emphasis on stakeholder engagement. The 2020-21 report focuses on system integration costs – moving beyond LCOE to consider how the mix of energy technologies integrate and the need and cost of balancing technologies such as energy storage. This is the third update following the inaugural report in 2018 and a second report in 2019-20. See https://www.csiro.au/en/news/news-releases/2020/renewables-still-the-cheapest-new-build-power-in-australia

- Network Dynamic Constraints (VPP) – in collaboration with SAPN & Tesla – setting dynamic limits for distributed generation power levels to better utilise network infrastructure and allow more distributed renewable energy. Won ENA innovation award. 2020 Energy Networks Awards | Energy Networks Australia
- Air-conditioning Demand Response – part of the Data Clearing House (DCH) project, using flexibility in building energy usage to better manage electricity systems. This has been a major collaboration with the air-conditioning industry (through AIRAH) http://www.ihub.org.au/dch1-csiro-senaps-data-platform-demonstration-and-development-of-the-data-clearing-house/

## Battery and chemicals storage

CSIRO has completed a range of range of battery storage and chemical projects and papers relevant to the Terms of Reference. These are described below including weblinks where available.

### Battery Storage / Battery Recycling Reports and Publications

- **Status of Play: Australia's Battery Industries, 2020**

The CSIRO report "State of Play: Australia's Battery Industries" was commissioned by the Future Battery Industry Cooperative Research Centre and released in October 2020. The report indicates Australia has the potential to capitalise on the value add from moving further along the battery value chain. The report provides a snapshot of the industry in Australia circa 2019. The intent is not to shine the best possible light on what the industry might be, but to show a baseline from where the industry can grow, and possibly to identify future opportunities. It indicates this move along the value chain will bring significant social, environmental, and economic benefits, placing Australia as a trusted supplier and an exporter of value-added products, rather than just raw materials. It also indicates that in moving further along the value chain there are opportunities for Australia to meet its own energy storage requirements.

*Link to report*:

https://fbicrc.com.au/wp-content/uploads/2020/10/20-00191_MR_REPORT_FBICRC-StateOfPlayBattery_WEB_201002.pdf

- **Australian Battery Performance Standard, 2020**

Currently, it is difficult to fairly compare the performance of commercially available battery storage equipment (BSE) on the market, as there is no common standard for how performance characteristics are to be measured and reported. The Battery Storage System Performance Standard project addressed this need by developing a proposed Australian Battery Performance Standard (ABPS). The ABPS includes standardised performance testing protocols and reporting methods for battery manufacturers and system integrators. The ABPS is designed for Australian households and consumers and takes into account performance issues faced by different environments within Australia, such as Tas vs. NT. The proposed ABPS has been submitted to Standards Australia for its consideration and assessment. An industry Best Practice Guide (BPG) was also developed for use by industry stakeholders in the interim until Standards Australia considers the release of the ABPS as an Australian Standard.

*Link to report:*

https://arena.gov.au/knowledge-bank/?keywords=Battery+Storage+System+Performance+Standard

- **Australian landscape for lithium-ion battery recycling and reuse in 2020 - Current status, gap analysis and industry perspectives, February 2021**

This report discusses the battery growth drivers and markets and the status of the Australian recycling industry. A comprehensive gap analysis and literature review was undertaken to identify key issues and challenges the incumbent battery recycling industry faces. Crucially, a stakeholder survey across all sectors of the battery value chain was undertaken with key stakeholders to identify key barriers and challenges the industry faces. Through in-depth analysis recommendations are made to strengthen and grow Australia's domestic recycling capability and generate new industries and employment opportunities.

*Link to report:*
https://publications.csiro.au/publications/publication/PIcsiro:EP208519/SQbattery%20lithium/RP1/RS25/RORECENT/STsearch-by-keyword/LISEA/RI2/RT72

- **Lithium battery recycling in Australia Current status and opportunities for developing a new Industry, 2018**

This report defines the 2018 landscape of lithium battery recycling in Australia, and identifies the challenges and opportunities related to potential onshore processing of these wastes. The majority of existing recycling schemes rely on scrap metal recyclers to break down the waste for export as there is no dedicated infrastructure or technology to recover the value from the waste. This constitutes a missed opportunity for Australia to benefit economically, environmentally and socially. This report will help to shape the developing landscape of recycling and resource recovery in Australia, as well as identify strategic resources and potential economic gain from further development of the industry.

*Link to report:*

https://publications.csiro.au/publications/publication/PIcsiro:EP181926

- **Major relevant publications and patents on battery recycling recently produced:**

**Publication:**

A Review on Battery Market Trends, Second-Life Reuse and Recycling, Zhao, Y; Pohl, O; Bhatt, AI; Collis, G; Mahon, P; Ruether, T; Hollenkamp, T; Sustainable Chemistry, Volume 2, pp 167-205

**Patent:**

Bhatt A. I., Ruther T., Zhao, Y., Electrolyte Recovery, Australian Provisional Patent Application 2020902099, June 2020

## Chemical Storage Reports and Publications

- **Hydrogen to Ammonia Research and Development**

This report presents the interim project summary of the R&D activities to develop an alternative technology that can produce ammonia at much lower pressures (~30 bar) by sourcing hydrogen directly from a PEM electrolyser operated by a renewable source of electricity; and scale-up the technology to build a prototype capable of producing green ammonia with the only inputs being water, air and solar PV.

*Link to report:*

https://arena.gov.au/knowledge-bank/?keywords=Hydrogen+to+Ammonia+Research+and+Development

- **Liquid Fuel Carrier Research and Development**

This report presents the interim project summary of the R&D activities related to the development and integration of key components of a solid oxide electrolysis (SOE) technology suite which once fully developed caters for both generation of renewable hydrogen as well as its conversion to liquid fuels

*Link to report:*

https://arena.gov.au/knowledge-bank/?keywords=Liquid+Fuel+Carrier+Research+and+Development

- **Solar Thermochemical Hydrogen Research and Development**

This report presents the interim project summary of the R&D activities related to the development of cost-effective hydrogen production using a solar thermochemical process, a solar thermal beam-down collector and new catalyst materials. It also reports on a parallel stream of the project that is investigating options for converting this hydrogen to methanol, using captured $CO_2$.

*Link to report:*

https://arena.gov.au/projects/solar-thermochemical-hydrogen-research-and-development/

- **Methane Fuel Carrier Research and Development**

This report presents the interim project summary of the R&D activities related to assessing the production of methane as a readily exportable, renewable fuel derived from atmospheric carbon dioxide and hydrogen produced from renewable sources.

*Link to report:*

https://arena.gov.au/knowledge-bank/?keywords=Methane+Fuel+Carrier+Research+and+Development

- **Major relevant publications, book chapters and patents on chemical storage recently produced:**

**Publications:**

- Techno-economic analysis of a sustainable process for converting CO2 and H2O to feedstock for fuels and chemicals, A Kulkarni, T Hos, M Landau, D Fini, S Giddey, M Herskowitz, Sustainable Energy & Fuels (2021) 2, 486-500
- A review on synthesis of methane as a pathway for renewable energy storage with a focus on solid oxide electrolytic cell-based processes, S Biswas, A Kulkarni, S Giddey, S Bhattacharya, Frontiers in Energy Research (2020) 8, 570112
- A comprehensive review of carbon and hydrocarbon assisted water electrolysis for hydrogen production, H. Ju, SPS Badwal, S Giddey, Applied Energy (2018) 231, 502-533. Invited
- Emerging technologies, markets, and commercialisation of solid electrolytic hydrogen production, S.P.S. Badwal, S. Giddey, C Munnings, Wiley Interdisciplinary Reviews: Energy and Environment (2018) 7, e286. Invited

- Ammonia as a renewable energy transport media, S. Giddey, S.P.S. Badwal, C. Munnings, M. Dolan, ACS Sustainable Chemistry & Engineering (2017) 5, 10231-10239. Invited

**Book Chapters:**

- Polymer electrolyte membrane technologies integrated with renewable energy for hydrogen production, S. Giddey, S.P.S. Badwal, H. Ju; In Current Trends and Future Developments on (Bio-) Membranes - Renewable Energy Integrated with Membrane Operations; Elsevier Inc. 2019, Pages 235-259.
- Solar Fuels, S.P.S. Badwal, A. Kulkarni, H. Ju, and S. Giddey, Electrochemical Science for a Sustainable Society: A Tribute to J.O'M Bockris, Springer International Publishing AG 2017, Pages 223-259.

**Patents:**

- US patent # 9895652: Processes Utilising Selectively Permeable Membranes, SPS Badwal, S. Giddey, F. Ciacchi, Kulkarni, A.E. Hughes, and D. Kennedy, Granted in 2018 in several jurisdictions
- PCT filed in 2020: Catalysts for membrane-based ammonia synthesis at low pressures, D. Kennedy, S. Giddey, D. Alexander, K. Pham, A. Kulkarni, G. Paul, application ready for submission.

## Battery Manufacturing

- **Reports and publications**
    - Is the electrolyte the solution or is the solution in the electrolyte?, M. Barghamadi, R. Rees, A. I. Bhatt, M. Musameh, A. S. Best**,** A. F. Hollenkamp, *Energy & Environmental Science,* 7 (12) 2014 3902-3920**.**
    - Lithium-ion Battery Separators for Ionic-Liquid Electrolytes: A Review, C. Francis, I. L. Kyratzis, A. S. Best, Advanced Materials, 2020, 1904205.
    - Energy Storage Structural Composites with integrated lithium-ion batteries: A Review, Galos, K. Pattarakunnan, A. S. Best, I. L. Kyratzis, A. P. Mouritz, Advanced Materials Technologies **2021** 2001059
- **Current manufacturing projects**

CSIRO has a number of projects underway which aim to increase the capability and capacity of Australian companies to build and deploy batteries:

- CSIRO is working with VSPC Ltd., a subsidiary of Lithium Australia NL, as part of a CRC-P to develop their $LiFePO_4$ cathode material for use in fast charge applications, specifically catenary-free trams. The development of this material will also assist the company to access other markets, both locally and globally, specifically the fast-growing EV and energy storage sectors.

- CSIRO is the primary research collaborator for Energy Renaissance, Australia's first lithium-ion battery manufacturer, where we are applying our knowledge and know-how in the development of both components and products to support the company to manufacturing cells and batteries which are particularly suited to the Australian climate.

- CSIRO is a research partner within the Future Battery Industries Cooperative Research Centre (CRC) and is involved in a number of key projects to assist Australian companies, specifically miners, to move downstream in the battery value chain. The "Super Anode" project focusses on the advanced manufacturing required to transform natural flake graphite into spheronised, purified graphite required for use in the lithium-ion batteries. Success in this project could open global markets for Australian companies.

## Hydrogen

CSIRO's Hydrogen Industry Mission is supporting Australia's National Hydrogen Strategy (2019), by focussing research development and demonstration on de-risking and fast-tracking emerging hydrogen technologies and catalysing industrial demonstrations, particularly when associated with emerging hydrogen industry hubs. This will be achieved through establishing a portfolio of RD&D projects under 4 pillars of activity which have been developed in close consultation with industry and governments:

- A **Hydrogen Knowledge Centre**, supporting 'best practice' adoption across the emerging industry, delivering hydrogen and technology cost reductions through accelerated industry learning rates. The Mission will partner with the Future Fuels CRC, NERA, Australian Hydrogen Council and ARENA.
- Employing **Feasibility and Strategy studies** including technoeconomic analysis to help achieve "H2 under $2" by providing a solid evidence base for government and industry investments. This will help build demand and lead to hydrogen and technology cost reductions through economies of scale.
- Delivery of **Demonstration Projects** to provide real world hydrogen cost and technical data such as through the Victorian Hydrogen Hub, a partnership with Swinburne and the Victorian Government.
- Creating **Enabling Science and Technology** to improve technology cost and efficiencies and removing socio-economic barriers to industry development, e.g. through safety, regulation, or social licence.

The following describes a list of reports that CSIRO has recently produced on the development of a Hydrogen industry in Australia:

- *National Hydrogen Roadmap* has modelling comparing costs for e.g. different storage technologies such as battery, pumped hydro, gas turbine, H2 fuel cell. It has a qualitative cost competitiveness curve for the potential of hydrogen for the next ten years and beyond. It mentions hydrogen's potential as an alternative to thermal energy storage qualitatively i.e. metal hydrides. Accessible through https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-roadmap

- *Hydrogen RD&D* report and tech repository has details on known hydrogen production, storage and utilisation technologies and technology readiness (and which institutions are active in the different areas) which qualitatively represents hydrogen potential in the next ten years compared to incumbent technologies. This was originally published as a main report (88 pages) and a technical repository (108 pages). The main report is accessible through https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research-and-development

- *Boeing Opportunities for commercial aviation* is largely directed towards fuels and diesel/hydrogen cost trajectory for various transport applications that were specific to aviation e.g. ground support equipment. While not directly towards electricity generation, indirectly the comparison between hydrogen and alternatives in e.g. storage or technology readiness of direct air capture technologies and sensitivity analyses may be useful for developments and potential. Accessible through https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-commercial-aviation

## Printed Solar Films

**Relevant papers:**

- Humidity-tolerant roll-to-roll fabrication of perovskite solar cells via polymer-additive-assisted hot slot die deposition, J.-E Kim, S.-S. Kim, C. Zuo, M. Gao, D. Vak, D.-Y. Kim, Advanced Functional Materials (2019) 29, 1809194.
- High Performance Roll-to-Roll Produced Fullerene-Free Organic Photovoltaic Devices via Temperature-Controlled Slot Die Coating, S.-I. Na, et al., Advanced Functional Materials (2019) 29 1805825.
- One-step roll-to-roll air processed high efficiency perovskite solar cells, C. Zuo, D. Vak, D. Angmo, L. Ding, M. Gao, Nano Energy (2018) 46, 185.
- Hot slot die coating for additive-free fabrication of high-performance roll-to-roll processed polymer solar cells, S. Song, et al., Energy & Environmental Science (2018) 11, 3248.
- Manufacturing cost and market potential analysis of demonstrated roll-to-roll perovskite photovoltaic cell processes, N. L. Chang, A. W. Y. Ho-Baillie, D. Vak, M. Gao, M. A. Green, R. J. Egan, Solar Energy Materials and Solar Cells (2018) 174, 314.

**Patents:**

- US patent # 16630834: Photovoltaic apparatus and method, D. Vak, K. Weber, A. Faulks, R. Chantler.
- US patent # 10141117: Process of forming a photoactive layer of a perovskite photoactive device, D Vak.

## Concentrated Solar Thermal and ASTRI

CSIRO is the leading partner of the Australian Solar Thermal Research Institute (ASTRI), and we note ASTRI will be providing a separate submission to this Inquiry. Following is an overview of ASTRI's role in developing and facilitating uptake of those technologies where CST and the activities undertaken by ASTRI that are relevant to Australia's future dispatchable energy generation and storage needs. Below this overview is a comprehensive list of over one hundred papers that have been published in the past 10 years.

**The Australian Solar Thermal Research Institute (ASTRI)**

https://www.astri.org.au/

The Australian Solar Thermal Research Institute (ASTRI) is a consortium of leading Australian research institutions collaborating to help manage Australia's transition to a clean energy future. ASTRI is working with industry to establish a coherent value proposition for Concentrated Solar Power (CSP) and Concentrated Solar Thermal (CST) systems in the Australian market. ASTRI's seeks to improve the commercial viability and uptake of CSP and CST (CSP/T) technologies through the following key objectives:

- facilitate domestic development and commercial uptake of current CSP/T systems through the provision of technical support to local technology developers and system end users;

- develop next generation CSP technologies for incorporation within more cost effective, higher performance CSP/T systems;
- leverage industry investment in CSP/T technology development, integration and deployment pathways; and
- work collaboratively with international research entities on activities to support global solar thermal uptake.

There are a range of technology solutions that can meet the need for firm dispatchable generation. These include PV + batteries, pumped hydro energy storage (PHES), clean hydrogen and CSP/T. Each of these solutions can play a role in Australia's future energy system. This view is supported by AEMO, who have highlighted the need for an integrated mix of complementary energy storage and generation technologies to meet Australia's future needs.

At present, thermal energy, through the combustion of fossil fuels, is the primary means for generating power and process heat. However, the use of fossil fuels is unsustainable and there has been increased commercial interest in thermal energy produced from renewable technologies, including CST, PV, wind, geothermal and bioenergy. The storage of renewable based thermal energy provides greater flexibility for how it can subsequently be used, day or night, to achieve fully renewable 24/7 energy solutions.

CSP/T technologies can provide for the capture and storage of multiple hours of thermal energy at temperatures exceeding 1000°C. For power generation, temperatures of around 550°C are required, and there are now over 30 operational CSP plants around the world providing for multi-hour electricity generation. Through the use of storage, these systems allow for electricity to be generated and dispatched, as required, any time of day or night. CSP/T technologies can also be used at temperatures between 200°C to 1500°C for industrial process heat.

From an Australian perspective, ASTRI is actively exploring options for the use of CSP/T technologies, with thermal energy storage, in the following four key application areas:

- Utility scale power generation
- Remote area power systems
- Industrial process heat and
- High temperature hydrogen production.

Each of these application areas includes the use of CSP/T technologies to capture and store thermal energy, for daily use at a later time when required by the user. In essence, all of these applications deliver a dispatchable renewable energy solution enable through the use of thermal energy storage.

**Utility Scale Power Generation**

CSP is a technology option that can help to address system reliability issues due to intermittency problems associated with increasing levels of variable renewable energy generation (PV and wind).

When utilised with energy storage, CSP systems allow for dispatchable generation which provides firm capacity and improves the availability, resilience and utilisation of renewable energy resources. Used on a daily cycle, utility scale CSP, with multi-hour storage (8+ hours), is one of the most flexible and cost-effective forms of dispatchable renewable energy.

**Remote Area Power Systems (mining / fringe of grid)**

Australia has a large demand for energy for remote mining operations. Australia also has some unique challenges in regional area in providing and servicing electricity users in fringe of grid locations. Both of these remote area power requirements could be serviced by micro-grids incorporating CSP technologies.

**Industrial Process Heat**

CST as a direct heat input, or for the production of solar fuels, is a cost-effective renewable energy solution for process heat applications. There are a range of CST technologies that can be used to generate process heat at different temperature ranges. All of these technologies have been successful deployed overseas. ASTRI is working closely with Australian manufacturers on end-use applications for the use of different CST technologies.

**High-Temperature Hydrogen Production**

Clean hydrogen can be produced through technologies that utilise renewable sources of electricity (electrolysis), heat (thermolysis), light (photolysis) and/or bioenergy. The choice of production technology will depend on a range of economic, technical, locational and demand driven factors. It is unlikely that one single technology can meet all of Australia's hydrogen ambitions out to 2050, with different technologies delivering different cost and capability outcomes in different locations and end use applications, over different time periods.

There are a number of emerging clean hydrogen production technologies that use heat to improve the production process. These include solid oxide electrolysis, thermochemical water splitting, photocatalysis, and biomass. While the commercial readiness of these emerging technologies is still relatively low, they have the potential to deliver major cost reductions and increased hydrogen yields.

**Research documents**

## 1 Utility Scale Power Generation and Industrial Process Heat: Particle Receivers

This technology pathway involves the use of fine particles which are drop through a receiver, where they are heated and then fall into a storage compartment. The technology has the potential to provide for high temperature capture and storage. The technology is able to provide power or be used for high temperature industrial process heat applications. The technology allows for the storage of large amounts of thermal energy which can then be dispatched, on demand, as power or heat.

| | |
|---|---|
| 2021 | Development of a staged particle heat exchanger for particle thermal energy storage systems. |
| 2021 | Multi-stage falling particle receivers, US patent 10,914,493 B2, Feb.9, 2021. |
| 2020 | A new numerical method for determining heat transfer and packing distribution in particle heat exchangers for concentrated solar power, J. Heat and Fluid Flow |
| 2020 | Design of a multi-stage falling particle receiver with truncated -cone geometry, AIP Conf. |
| 2020 | Moving-bed particle heat exchanger, PCT patent application filed, |
| 2019 | Development of a Particle Heat Exchanger with a Vertical Pipe Array for Particle Thermal Energy Storage Systems, Conference: SolarPACES. |
| 2019 | Development of a Particle Heat Exchanger with a Vertical Pipe Array for Particle Thermal Energy Storage Systems, Conference: SolarPACES. |
| 2019 | Numerical and experimental investigation of a novel multi-stage falling particle receiver, AIP Conference Proc. 2126, 030030. |

| | |
|---|---|
| 2019 | Techno-economics of a high-temperature particle solar receiver and storage system for reforming process, CSIRO Report. |
| 2017 | Design boundaries of large-scale falling particle receivers, AIP Conference Proc. 1850, 030029, 210011. |
| 2011 | CFD analysis of heat loss from 200kW cavity reactor, Conference: SolarPACES 2011: Concentrating Solar Power and Chemical Energy Systems. |

## 2 Utility Scale Power Generation and Remote Area Power Systems: sCO2 Power Cycles

This technology pathway involves the development of advances high temperature power cycles. These power cycles use high temperature, supercritical carbon dioxide as the working fluid. These advanced power cycles are more efficient than existing steam turbines for power generation. They are also able to be applied to smaller power applications, which make them ideal for behind the meter mining and industrial power applications. CST is the technology which provides the heat for the sCO2 power cycle. Using storage, these advanced power cycles have the potential to a dispatchable power solution to replace diesel power generation in mining operations.

| | |
|---|---|
| 2021 | Optimized operation of recompression sCO2 Brayton cycle based on adjustable recompression fraction under variable conditions. |
| 2018 | Impact of ambient temperature on supercritical CO2 recompression Brayton cycle in arid locations: Finding the optimal design conditions, Journal: Energy. |
| 2018 | Multi-Objective Thermodynamic Optimisation of Supercritical CO2 Brayton cycles integrated with solar central receivers, Journal: International Journal of Sustainable Energy. |
| 2017 | Techno-economic Analysis of Supercritical Carbon Dioxide Power Blocks, Conference: SolarPACES. |
| 2017 | Evaluation of Power Block Arrangements for 100MW Scale Concentrated Solar Thermal Power Generation Using Top-Down Design, Conference: SolarPACES 2016. |
| 2017 | Thermal Performance of Solarized Supercritical CO2 Brayton Cycles Using High-Temperature Molten Salts as Heat Transfer Fluids and Thermal Energy Storage Media, Conference: SolarPACES. |
| 2017 | Thermal Performance of Solarized Supercritical CO2 Brayton Cycles Using High-Temperature Molten Salts as Heat Transfer Fluids and Thermal Energy Storage Media, Conference: SolarPACES. |
| 2017 | Thermal Performance and Operation of a Solar Tubular Receiver with CO2 as Heat Transfer Fluid, Journal: Journal of Solar Energy Engineering. |
| 2017 | Dynamic model of supercritical CO2 Brayton cycles driven by concentrated solar power, Conference: ASME 2017 11th International Conference on Energy Sustainability. |
| 2017 | Assessment of high-temperature molten salts as heat transfer fluids and thermal energy storage media for solarised supercritical CO2 Brayton cycles, CSIRO Report. |
| 2016 | Thermodynamic Feasibility of Alternative Supercritical CO2 Brayton Cycles Integrated With an Ejector, Journal: Applied energy. |

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|---|---|
| 2016 | Mechanical Stress Optimisation in a Directly Illuminated Supercritical Carbon Dioxide Solar Receiver, Conference: ASME Power & Energy Conference & Exhibition. |
| 2015 | Impact of Power Block Efficiency on the Prospects of Achieving Significantly Reduced LCOE, Conference: 2015 Asia-Pacific Solar Research Conference. |
| 2015 | Effect of Pressure Drop and Reheating on Thermal and Exergetic Performance of Supercritical CO2 Brayton Cycles Integrated with a Solar Central Receiver, Journal: Journal of Solar Energy Engineering. |
| 2015 | Effect of Pressure Drop and Reheating on Thermal and Exergetic Performance of Supercritical CO2 Brayton Cycles Integrated with a Solar Central Receiver, Journal of Solar Energy Engineering. |
| 2015 | Exergetic analysis of supercritical CO2 Brayton cycles integrated with solar central receivers, Journal: Applied Energy. |
| 2015 | Robust Design and Optimisation of a Radial Turbine Within a Supercritical CO2 Solar Brayton Cycle, Conference: 11th World Congress on Structural and Multidisciplinary Optimisation. |
| 2013 | Design and Test of a 600 kWt Receiver for Solar Air Turbine Systems, Conference: SolarPACES 2013. |
| 2013 | Solar Air Turbine Systems, Australian Renewable Energy Agency, ML6 Progress Report, CSIRO Report. |
| 2013 | Solar Air Turbine Systems, Australian Renewable Energy Agency, ML7 Progress Report, CSIRO Report. |
| 2012 | Solar Air Turbine Systems, Australian Solar institute, Progress Report C (ML4 report), Progress Report (ML5 report), CSIRO Report. |

## 3 Industrial Process Heat Applications

This technology pathway involves the use of CST technologies for industrial process heat. CST would be used to generate and store heat, which could be used for steam generation or for other heat based industrial processes. Through the use of CST technologies, industry could replace gas as the primary means for process heat. The inclusion of storage would allow a company to capture heat during the day and then use that heat for night-time production activities. In essence, this would be a dispatchable process heat solution for industry.

| | |
|---|---|
| 2021 | Techno-economic evaluation of opportunities for hybridisation of concentrated solar thermal and photovoltaic systems, CSIRO Report. |
| 2020 | Economic Viability of Concentrating Solar Thermal Systems for Process Heat Applications: Quantifying Australian Opportunities, CSIRO Report. |
| 2018 | A Study on the Economic Viability of Hybrid Solar-Biomass Systems, Conference: 2018 Asia-Pacific Solar Research Conference. |
| 2018 | Sustainable Steam on Demand for the Bayer Process, Conference: Alumina 2018 - 11th AQW International Conference. |

| | |
|---|---|
| 2018 | Opportunities for Concentrated Solar Thermal Heat Input into the Australian Minerals Industry, Conference: Australia Pacific Solar Research Conference. |
| 2017 | Assessment of CST Systems for Applications in Industrial Process Heating, Conference: Asia-Pacific Solar Research Conference. |
| 2013 | Potential Applications of Concentrated Solar Thermal Technologies in the Australian Minerals Process and Metallurgy Industry, Journal: JOM. |
| 2012 | Industrial energy usage in Australia and the potential for implementation of solar thermal heat and power, Journal: Energy. |
| 2012 | Integrating solar thermal technology into the Australian minerals processing industry, Conference: 4th Annual High Temperature Processing Symposium. |

## 4 High Temperature Hydrogen Production

This technology pathway involves the use of CST technologies for the production of Hydrogen and other solar fuels. High temperature hydrogen production has the potential to produce higher yields of hydrogen at lower cost. CST would be used to provide heat and power for the high temperature electrolysis process. The heat would also be stored to increase the capacity factor for renewable hydrogen production (i.e. allow for night-time production).

| | |
|---|---|
| 2020 | Potential Value and Technical Gaps of CSP/T-Assisted High Temperature Electrolysis, Journal: AIP Conference Proceedings. |
| 2019 | Potential Value and Technical Gaps of CSP/T-Assisted High Temperature Electrolysis, Conference: SolarPACES. |
| 2019 | Application of Particle Technology to Solar Reforming for Fuel Production, Conference: Asia-Pacific Solar Research Conference. |
| 2018 | A Concentrated Solar Process for the Production of Renewable Hydrogen from Waste Water Streams, Conference: Asia-Pacific Solar Research Conference. |
| 2016 | An experimental and techno-economic assessment of solar reforming for H2 production, Journal: International Journal of Hydrogen Energy. |
| 2016 | An experimental and techno-economic assessment of solar reforming for H2 production, Conference: 14th International Conference on Inorganic Membranes (2016). |
| 2015 | 3-A018 Solar Hybrid Fuels (Stream 2), CSIRO Report. |
| 2011 | Thermodynamic analysis of mixed and dry reforming of methane for solar thermal applications, Journal: Journal of Natural Gas Chemistry. |

## 5 Utility Scale Power Generation: Receivers

This technology pathway involves work on optimising the collection and concentrated sunlight into an accessible form of thermal energy. Receiver design are critical in that they can reduce the cost of sunlight collection and concentration. The aim of this work is to lower system cost to improve system performance and operability.

| | |
|---|---|
| 2020 | Aiming clusters of heliostats over solar receivers for distributing heat flux using one variable per group, Journal: Renewable Energy. |
| 2020 | Simulation of a demonstration high temperature liquid sodium receiver with Heliosim, Conference: Asia Pacific Solar Research Conference. |
| 2019 | A transient optical-thermal model with dynamic matrix controller for solar central receivers, Journal: Applied Thermal Engineering. |
| 2018 | Multivariate closed control loop methodology for heliostat aiming manipulation in solar central receiver systems, Journal: Journal of Solar Energy Engineering. |
| 2018 | Dynamic performance of an aiming control methodology for solar central receivers due to cloud disturbances, Journal: Renewable Energy. |
| 2018 | Sensitivity study on the off-ideal design and off-design operation of tubular solar receivers, Journal: AIP Conference Proceedings. |
| 2018 | Heliosim: An Integrated Model for the Optimisation and Simulation of Central Receiver CSP Facilities, Conference: SolarPACES. |
| 2018 | Transient numerical model for the thermal performance of the solar receiver, Journal: Applied Thermal Engineering. |
| 2018 | Storage system assessment for liquid HTF receiver pathway: ASTRI Quick Start Project, CSIRO Report. |
| 2018 | Sensitivity study on the off-ideal design and off-design operation of tubular solar receivers, Journal: AIP Conference Proceedings. |
| 2018 | Transient numerical model for the thermal performance of the solar receiver, Journal: Applied Thermal Engineering. |
| 2016 | Optimised Design of a 1 MWt Liquid Sodium Central Receiver System, Conference: Asia Pacific Solar Research Conference. |
| 2015 | Performance evaluation of a solar tubular receiver with CO2 as heat transfer fluid, CSIRO Report. |
| 2013 | Solar Receiver - Horizon 3 White Paper, CSIRO Report. |
| 2010 | Enhancing Heat Transfer in Solar Tubular Air Receivers, CSIRO Report |

## 6 Utility Scale Power Generation and Remote Area Power Systems

This body of research look at CSP impact and uptake within the National Electricity Market. The body of research seeks to define the business case and circumstances where CSP might create a value proposition for utility scale and remote area power generation. These systems assume the use of energy storage as an enabler for dispatchable power generation solutions.

| | |
|---|---|
| 2019 | Evaluation of CSP Opportunities in Australian Electricity Networks, Conference: Australia-Pacific Solar Research Conference. |

| | |
|---|---|
| 2018 | Electricity generation using Concentrated Solar Thermal (CST) and Hybrid Technologies, CSIRO Report. |
| 2018 | Evaluation and analysis of opportunities for CST implementation in Australia, CSIRO Report. |
| 2017 | Introduction to concentrating solar thermal (CST) technologies, Book: Advances in Concentrating Solar Thermal Research and Technology. |
| 2017 | Dynamic Model of a Molten Salt - Gas Heat Recovery System for a Hybrid Renewable Solar Thermal Power Plant., Journal: Revista Iberoamericana de Automática e Informática Industrial RIAI. |
| 2016 | Current and Future Status of Concentrating Solar Power in Australia, Journal: Journal of the Japan Institute of Energy. |
| 2016 | Impact of cost uncertainties and solar data variations on the economics of central receiver solar power plants: An Australian case study, Journal: Renewable Energy. |
| 2015 | Central receiver reference plant cost breakdown, CSIRO Report. |
| 2015 | Economic evaluation of shell-and-tube latent heat thermal energy storage for concentrating solar power applications, Journal: Energy Procedia. |
| 2015 | Parabolic trough reference plant cost breakdown, CSIRO Report. |
| 2015 | An integrated model for optical and thermal analysis of central receiver systems, Conference: SolarPACES 2015. |
| 2015 | Simplified Heat Loss Model for Central Tower Solar Receiver, Journal: Solar Energy. |
| 2014 | Variability in the estimated LCOE for CSP technologies arising from uncertainty in cost and solar data inputs, Conference: 2014 Asia Pacific Solar Research Conference. |
| 2014 | Improving the financial performance of concentrating solar thermal power, Conference: ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference. |
| 2011 | Cost and performance modelling of the integration of solar thermal energy into an existing Australian coal fired power generator, Conference: 8th Asia Pacific Conference on Sustainable Energy & Environmental Technologies (APSCEET 2011). |
| 2011 | Concentrating solar thermal energy in Australia: facilities and activities, Journal: Journal of the Japan Institute of Energy. |

## 7 Utility Scale Power Generation: Phase Change Energy Storage

This technology pathway looks at the use of latent energy storage technologies to increase the efficiency and cost effectiveness of thermal energy storage. The technology pathway recognises the important role of thermal energy storage in enabling a dispatched energy solution (power or heat).

| | |
|---|---|
| 2019 | A review of high temperature phase change material composites for high efficient thermal energy storage, Journal: Solar Energy & Solar Cells. |
| 2019 | Characterisation of Promising Phase Change Materials for High Temperature Thermal Energy Storage, Journal: Journal of Energy Storge. |
| 2019 | Novel Solid–Solid Phase-Change Cascade Systems for High-Temperature Thermal Energy Storage, Journal: Solar Energy. |
| 2018 | Novel Na2SO4-NaCl-ceramic composites as high temperature phase change materials for solar thermal power plants (Part I). |
| 2018 | Novel Na2SO4-NaCl-ceramic composites as high temperature phase change materials for solar thermal power plants (Part II). |
| 2017 | Thermal Stability of Na2CO3-Li2CO3 as a High Temperature Phase Change Material for Thermal Energy Storage, Journal: Thermochimica Acta. |
| 2016 | A new phase change material for high temperature thermal energy storage, Conference: ASME 2016 Power & Energy Conference. |
| 2016 | Eutectic Na2CO3-NaCl salt: a new phase change material for high temperature thermal storage, Journal: Solar Energy Materials & Solar Cells. |

## 8 Utility Scale Power Generation / Remote area power systems: Energy Storage

This technology pathway looks at different energy storage technologies for different end use applications (utility scale power generation, remote systems and industrial process heat). The aim of this pathway is to establish which storage technologies work best in what applications to deliver the best energy solution. The technology pathway recognises the important role of thermal energy storage in enabling a dispatched energy solution (power or heat).

| | |
|---|---|
| 2021 | Sensitivity study and thermal analysis of MGA storage configurations. CSIRO restricted technical report, EP211077. |
| 2020 | Preliminary assessment of MGA storage technology for ASTRI CSP systems, CSIRO Report. |
| 2019 | On-sun Testing of Miscibility Gap Alloy Thermal Storage, Journal: Solar Energy. |
| 2018 | Techno-economic assessment of solid–gas thermochemical energy storage systems for solar thermal power applications, Journal: Energy & Fuels. |
| 2018 | Design and experimental validation of a computational effective dynamic thermal energy storage tank model, Journal: Energy. |
| 2019 | Effect of short cloud shading on the performance of parabolic trough solar power plants: motorized vs manual valves, Journal: Renewable Energy. |
| 2017 | Investigation of lithium sulphate for high temperature thermal energy storage, Conference: SOLARPACES 2016. |

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|---|---|
| 2016 | Investigation of lithium sulphate for high temperature thermal energy storage, Conference: SOLARPACES 2016. |
| 2016 | Challenges and technical assessment of a high-pressure high-temperature thermal energy storage, CSIRO Report. |
| 2015 | High-Temperature Heat Transport and Storage Using LBE Alloy for Concentrated Solar Power System, Conference: ASME 2015 9th Int. Conf. on Energy Sustainability. |
| 2014 | Solar Thermal Energy Storage Study, CSIRO Report. |
| 2014 | Cost analysis of high temperature thermal energy storage for solar power plant, Conference: Solar 2014 Scientific Conference. |
| 2014 | Coupled Experimental Study and Thermodynamic Modeling of Melting Point and Thermal Stability of Li2CO3-Na2CO3-K2CO3 Based Salts. J. Sol. Energy Eng., 136(3), 031017-031023. |
| 2014 | Wind-dependence of energy losses from a solar gas reformer, Journal: Applied Thermal Engineering. |
| 2013 | LiNO3-NaNO3-KNO3 salt for thermal energy storage: thermal stability evaluation in different atmospheres, Journal: Thermochimica Acta. |
| 2013 | Lithium-Sodium-Potassium Nitrate Salt for Thermal Energy Storage: Thermo-Chemical Evaluation in Different Atmospheres, Conference: 5th Annual High Temperature Processing Symposium 2013. |
| 2012 | The thermal stability of molten nitrite/nitrates salt for solar thermal energy storage in different atmospheres, Journal: Solar Energy. |
| 2012 | High temperature thermal energy storage systems for open-cycle solar air Brayton plant, CSIRO Report. |
| 2013 | Enhancing heat transfer in air tubular absorbers for concentrated solar thermal applications, Journal: Applied Thermal Engineering. |
| 2012 | High temperature thermal energy storage systems for open-cycle solar air Brayton plant, CSIRO Report. |
| 2012 | High temperature thermal energy storage systems for open-cycle solar air Brayton plant. CSIRO technical report, EP12817. |
| 2012 | Thermal design of a high-pressure high temperature packed bed thermal energy storage. CSIRO technical report, EP126515. |
| 2011 | Options for high temperature thermal energy storage. Advanced solar thermal energy storage technologies: a literature review - summary, CSIRO Report. |
| 2011 | Development of advanced solar thermal energy storage technologies - progress report no. 1. CSIRO restricted technical report, EP114306. |

| | |
|---|---|
| 2011 | Development of advanced solar thermal energy storage technologies - progress report no. 2. CSIRO restricted technical report, EP114308. |
| 2011 | Development of advanced solar thermal energy storage technologies - progress report no. 3. CSIRO restricted technical report, EP116230. |

## Natural gas

**Managing dispatchability is critical and using and storing gas has a role**

- AEMO forecasts integration of variable renewable energy (VRE) generation into the Australian National Electricity Market (NEM) that, by 2042, will exceed 60 per cent of electricity generation.
- Natural gas has a critical role to play in the transition to VRE over this time frame an affordable, safe, secure and dispatchable source of electricity under peak demand.
- Natural gas will have a significant role to play in stabilising and supporting the deployment of variable renewable energy in Australia.
- Increasingly the role of natural gas will be coupled with Carbon Capture, Utilisation and Storage (CCUS) in order to mitigate associated greenhouse gas (GHG) emissions.
- Gas-fired energy generation already has lower emissions than coal and offers a potential 31 per cent to 50 per cent reduction of GHG emissions depending on the generation technology used (see Whole of Life Greenhouse Gas Emissions Assessment of a Coal Seam Gas to Liquefied Natural Gas Project in the Surat Basin, Queensland, Australia. This report assesses greenhouse gas emissions of a coal seam gas (CSG) to liquefied natural gas (LNG) project in Queensland, and the relative climate benefits of using Queensland natural gas in place of thermal coal as fuel for generation of electricity in Australia. (https://gisera.csiro.au/project/whole-of-life-cycle-greenhouse-gas-assessment/)
- Natural gas will also play a underpinning transitional role as technologies for the safe and economical production and use of hydrogen evolve particularly in steam methane reforming of hydrogen and the cost trajectory to $2/kg.
- CSIRO is working with Commonwealth and state/territory governments and industry to support improving natural gas productivity, reducing emissions, and securing natural gas supply as a key element in emissions reduction strategies at scale and securing energy supply in the national interest.

**Underground Energy and Hydrogen Storage**

The follow describes storage and integration options CSIRO has been working on. A number of papers and reports are expected to be produced on these topics in the near future.

- An important but less commercialised aspect of energy storage is Underground Energy Storage (UES) that will increasingly play an important enabling technology role underpinning the transition to VRE throughout the next decade and beyond.

- Current and planned conventional energy storage are unlikely to provide enough capacity and so UES provides the potential for additional storage capacity to currently planned industrial scale batteries and pumped hydro storage.
- AEMO estimates that >15 GW of utility-scale storage will be required by 2042. Pumped hydro (Snowy 2.0 and Battery of the Nation) will provide 4.1 GW by 2030 but further low-cost capacity is needed particularly for 2-6 hours storage duration but also 12 - 24 h duration storage needed for extended VRE shortages.
- CSIRO has exceptional expertise in underground energy storage which include; (1) compressed air energy storage (CAES) in porous geological formations, underground cavities or engineered tunnels; (2) underground Thermal Energy Storage (UTES/Geo-TES) in the subsurface including storing heat in aquifers and geothermal heating/cooling capacity; and, (3) storage of hydrogen gas in subsurface formations, including depleted gas fields or engineered caverns.
- Hydrogen is a key fuel in the global transition towards lower emissions. Economical production of hydrogen and the establishment of markets will require natural gas-based generation over the next decade with the likely transition to renewable energy generation of hydrogen to increase progressively during this period.
- Geological storage of hydrogen will be required for large-scale and seasonally variable demand for energy. Australia has a significant natural advantage for geological storage of hydrogen and through this will likely play a substantial role in this energy transition. Adequate subsurface storage is also required for Australia to become a major producer and exporter of hydrogen.
- The trajectory towards increasing dependency on hydrogen as an energy source will include blending ~10-15 per cent hydrogen in natural gas reservoirs; and over the longer term the large-scale storage of hydrogen in saline aquifers and depleted oil and gas reservoirs.
- CSIRO is researching interactions between hydrogen and various rock properties (chemical, mechanical, transport and seismic) that determine optimal engineering practices to maximise efficiency of underground hydrogen storage options.

## Offshore Renewable Energy Systems and the Blue Economy CRC

The Blue Economy CRC (BECRC) was commissioned in January 2020, with the first tranche of scoping projects completed in January 2021. A number of completed scoping projects and projects underway demonstrate the avenues by which the BECRC seeks to determine the future need and potential for dispatchable energy generation and storage capability in Australia.

***Offshore hybrid microgrids support dispatchable power for offshore industry, and hydrogen production for off-take/export opportunities***

The BECRC will develop and demonstrate an off-shore, off-grid hydrogen microgrid, to meet the energy needs of offshore industry. Many coastal and maritime industry sectors are heavily dependent on diesel powered off-grid electricity. Fuel cost and availability, along with environmental (emission and spillage) risks and noise concerns are motivating transition towards renewable energy options in these environments. The BECRC is constructing a hybrid off-shore microgrid, integrating offshore energy conversion (from offshore wind, wave, tide and/or floating solar conversion technologies), hydrogen production for storage/firming and export, and battery storage, to demonstrate the opportunity for dispatchable renewable electricity generation, providing secure and reliable electricity in the offshore environment. These objectives are supported by recently completed BECRC scoping projects P3.20.001 – Hydrogen Storage and Distribution; P3.20.002 – Offshore Hybrid Power Systems review; and P3.20.003 – Energy demands of offshore industry. The outcomes of these projects are to be published in the soon to be released 2021 BECRC Research Synthesis Report.

***Utility Scale Offshore Renewable Energy in a distributed power system reduces storage needs***

Australia does not yet have an offshore wind (or other offshore renewable energy) industry, despite offshore wind being a mature/commercial technology in other jurisdictions. Australia's renewable energy integration studies, completed to date, have not considered the potential contribution of offshore wind into high renewable energy penetration scenarios in Australia's electricity system. BECRC project P3.20.007 – Opportunity for Offshore Wind in Australia, currently underway and led by CSIRO, seeks to establish the potential benefits offered to Australia's energy sector through inclusion of offshore wind. The results are expected to be published in coming months, following project completion.

Demonstrating market opportunities for offshore renewable energy, with research and innovation to support growth of a sustainable offshore renewable energy industry comprise a key component of CSIRO's strategy, delivered through the Ocean low carbon economies domain.

**As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.**

CSIRO. Unlocking a better future for everyone.