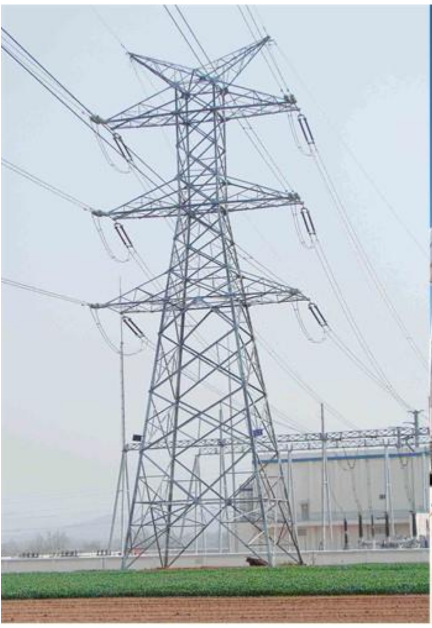
HYDROGEN RESEARCH & DEVELOPMENT IN SOUTH AUSTRALIA

Report to the Government of South Australia

November 2018



About ITP

The ITP Energised Group, formed in 1981, is a specialist renewable energy, energy efficiency and carbon markets consulting company. The Group has offices and projects throughout the world.

ITP Renewables was established in 2003 and has undertaken a wide range of projects, including providing advice for government policy, feasibility studies for large renewable energy power systems, designing renewable energy power systems, developing micro-finance models for community-owned power systems in developing countries and modelling large-scale power systems for industrial use.

The staff at ITP Renewables have backgrounds in research, renewable energy and energy efficiency, development and implementation, managing and reviewing government programs, high level policy analysis and research, including carbon markets, engineering design and project management.

ITP Thermal was established in early 2016 as a new company within the ITP Energised group, with a mandate to lead solar thermal projects globally.

About this report

The report was commissioned by the South Australian Department for Industry and Skills (DIS). It maps existing hydrogen R&D capability in South Australia and identifies opportunities to maximise this capability given local, national and international expertise and current and future hydrogen project and industry developments.

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LIST OF ABBREVIATIONS

AGIG	Australian Gas Infrastructure Group
AIST	Advanced Industrial Science and Technology (Japan)
ANU	The Australian National University
ARC	Australian Research Council
ARENA	Australian Renewable Energy Agency
ASTRI	Australian Solar Thermal Research Institute
Caltech	California Institute of Technology
CCS	Carbon capture storage
CEFC	Clean Energy Finance Corporation
CET	Centre for Energy Technology (UoA)
CHES	Centre for Hybrid Energy Systems (CSIRO Clayton, VIC)
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CNG	Compressed natural gas
CO, CO_2	Carbon monoxide, carbon dioxide
COE	Centre of Excellence
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Curtin	Curtin University
DGC	Danish Gas Technology Centre
DKK	Danish Krone
DSTO	Defence Science Technology Organisation
DLR	German Aerospace Centre
DOE	Department of Energy (US)
EPF	École Polytechnique Fédérale
ETH	Swiss Federal Institute of Technology
EU	European Union
FC	Fuel Cell
FCHJU	Fuel Cells and Hydrogen Joint Undertaking (Europe)
FCV	Fuel Cell Vehicle
FCEV	Fuel Cell Electric Vehicle
FFCRC	Future Fuels Cooperative Research Centre
FFI	Strategic vehicle research and innovation programme (Sweden)
FII	Future Industries Institute (South Australia)
Flinders	Flinders University
GHG	Greenhouse Gas
GJ	Gigajoule
Griffith	Griffith University
H_2	Hydrogen
HHV	Higher Heating Value
HIA	Hydrogen Implementing Agreement

HRS	Hydrogen Refuelling Station
HZB	Helmholtz Centre Berlin
IC(E)	Internal combustion (engine)
IEA	International Energy Agency
ISE	Institute for Solar Energy Systems
JCAP	Joint Center for Artificial Photosynthesis (USA)
JRC	Joint Research Centre
KIER	Korean Institute of Energy Research
kW	Kilowatt
LED	Light-emitting diode
LHV	Lower Heating Value
LNG	Liquefied natural gas
MCH	Methylcyclohexane
METI	Japanese Agency for Natural Resources and Energy
MJ	Megajoule
MOF	Metal organic framework
MOU	Memorandum of Understanding
MW	Megawatt (subscript e: electrical; th: thermal)
MWh	Megawatt-hour
NG	Natural Gas
NIMS	National Institute of Materials Science (Japan)
NIP	National Innovation Programme Hydrogen and Fuel Cell Technology (France)
NL	National Laboratory
Nm^3	Normal cubic metre
NREL	National Renewable Energy Laboratory (US)
PEFC	Polymer electrolyte membrane fuel cell
PEM	Proton Exchange Membrane
PROMES	Laboratoire PRecédés, Matériaux et Energie Solaire
PSI	Paul Scherrer Institute (Switzerland)
PV	Photovoltaic
QUT	Queensland University of Technology
R&D	Research & Development
RD&D	Research, Development & Deployment
RMIT	Royal Melbourne Institute of Technology
SA	South Australia
Sandia	Sandia National Laboratories
SAREI	South Australian Renewable Energy Institute
SCCER	Swiss Competence Center for Energy Research
SNG	Synthetic Natural Gas
SOFC	Solid Oxide Fuel Cell
TCP	Technology Collaboration Programme (IEA)
TEPS	Transportation Electric Power Solutions (Israel)
Tri-Gen	Tri-generation (heat, power and cooling)
TRL	Technology Readiness Level

UCLA	University of California Los Angeles
UfZ	Centre for Environmental Research
UK	United Kingdom
UMel	University of Melbourne
UniSA	University of South Australia
UNSW	Unversity of New South Wales
UoA	University of Adelaide
UoS	University of Sydney
UoWA	University of Western Australia
UQ	University of Queensland
US, USA	United States of America
USD	US dollar

CONTENTS

EXECUTIVE SUMMARY

This report has been commissioned by the South Australian Government to identify existing hydrogen research and development (R&D) capability in South Australia and the opportunities to extend this capability given local, national and international expertise, current and future hydrogen projects and industry developments.

This report is to inform the development of a *South Australian Hydrogen R&D Roadmap* and complement the *Hydrogen Roadmap for South Australia* released in 2017.

Markets for green hydrogen are all nascent but potentially very large in the coming decades. The specific opportunities for South Australia include ammonia production, hydrogen as a local transport fuel and for large-scale export.

There are currently four renewable hydrogen demonstration projects being actively progressed in South Australia. The projects target a range of end uses such as gas injection, transport, ammonia, and grid security services, and one project is to construct a testing facility with hydrogen consumed on-site. There is a proposal to establish a Hydrogen Centre of Excellence for industry-initiated research that leverages pre-existing project infrastructure and know-how.

Hydrogen related research can be broadly categorised into the areas of hydrogen production, storage, conversion, distribution, system analysis, markets and regulatory framework. Each of these areas have specific research needs and gaps which should to be addressed in order to improve the viability of hydrogen as an energy vector.

Outstanding hydrogen-related R&D capabilities and activities at the three South Australian universities include:

University of Adelaide:

- Conversion of biomass and hydrocarbon sources to hydrogen
- Renewable energy (including hydrogen) integration into industrial processes
- Nanomaterials for photo- and electro-catalysts for water splitting and fuel cells
- Chemical processes for synthesis of energy carriers and gas separation
- Combustion of new fuels
- Hydrogen injection into the natural gas network

Flinders University:

- Polymer materials for fuel cells, electrolysers and batteries
- Nanomaterials and surface science for electrodes
- Comprehensive material analysis facilities and equipment

- Technology commercialisation

University of South Australia:

- System integration, analysis and engineering
- Mawson Lakes campus hydrogen-based renewable energy storage testing facility

South Australia's local R&D capabilities are world class, applicable to a broad range of hydrogen-related research, development and commercialisation challenges, and attracting strong interest and engagement from industry. Collaborative approaches could put South Australia into the position to become a significant contributor in the future global hydrogen economy.

The three South Australian universities have capabilities that are complementary. While they are involved in various collaborations, there is scope to formalise them to assist with approaches for funding and for the universities to develop research proposals that draw on research strengths of national and international institutions. In the past, multi-university research consortiums used by the South Australian universities are a good example of a collaborative approach.

Nationally, the key research institutions with the broadest range of hydrogen capabilities are CSIRO and ANU. Others with a narrower focus include the University of Melbourne, Monash University, University of New South Wales, University of Queensland, University of Sydney, University of Western Australia, Curtin University and Griffith University. A national Future Fuels Cooperative Research Centre was established in April 2018.

CSIRO has particular capabilities in the areas of new hydrogen production methods, ammonia dissociation and fuel cell technology, while Griffith University has expertise in the area of physical hydrogen storage. ANU and University of Melbourne have particular capabilities related to the areas of hydrogen markets and regulatory framework. South Australia´s universities may benefit from national research collaborations in these areas.

Internationally, key research institutions for hydrogen related R&D include:

- USA: National Renewable Energy Laboratory (NREL), Joint Centre for Artificial Photosynthesis (JCAP), Sandia National Laboratories, California Institute of Technology, Lawrence Berkeley National Laboratory, University of Minnesota
- Germany: Fraunhofer ISE, German Aerospace Centre (DLR, Germany), Helmholtz Zentrum Berlin, Helmholtz Centre for Environmental Research UFZ
- Europe: Plataforma Solar de Almeria (Spain), PROMES (France), Swiss Competence Center for Energy Research (Switzerland), ETH Zurich and EPF Lausanne (Switzerland).
- Japan: National Institute of Advanced Industrial Science and Technology, University of Niigata, University of Tokyo, Tokyo Institute of Technology

NREL stands out due to its long-standing and broad hydrogen-related research portfolio, including production, distribution and conversion (fuel cells) technologies, fuel cell vehicles (FCVs), system analysis, as well as a leadership role in hydrogen safety, codes and standards.

The R&D capabilities in South Australia may be further enhanced and leveraged by targeting research collaborations nationally and internationally. At the national level, CSIRO could be a strong partner. Internationally, NREL stands out with a long history of hydrogen related research and a broad range of activities. Hence, early partnerships with these two organisations could accelerate activities for South Australia.

The International Energy Agency via its Hydrogen as well as Bioenergy and SolarPACES programs is a very effective forum for South Australia to stay up to date and engage with global efforts. The state is already represented in these forums, however there is scope to grow the involvement.

Currently, hydrogen R&D in South Australia is predominantly at low TRLs up to around TRL 4.[1] This has to do with the lack of a local hydrogen industry, which tends to limit R&D efforts to rather basic research. Higher TRL commercially oriented R&D can and should be stimulated through the creation of a local hydrogen market and industry in South Australia.

With regard to international research collaboration mechanisms, the long term goal of developing hydrogen exports to key trading partners such as Japan and South Korea, suggests targeting these countries for early partnerships in R&D also. For example a consortium could be formed involving South Australian, Japanese and South Korean research institutes as well as industry, with the aim to establish, evaluate and optimise a hydrogen-based fuel system in South Australia.

An obvious opportunity for capability development not only in South Australia but also Australia-wide is in the area of distribution and systems analysis to support optimal design of hydrogen infrastructure. Hydrogen can either be produced on site or produced centrally and distributed. The optimal design of a hydrogen infrastructure depends on local factors and needs, and can only be determined via detailed system modelling and optimisation. US-based institutions, particularly NREL, have pre-existing research capabilities in this area. Another area of opportunity is in research in markets and regulatory frameworks to support the uptake of hydrogen. The technical, economic and social risks associated with hydrogen infrastructure is an area deserving more research attention.

This report concludes with several considerations for further RD&D activities and for the development of a *South Australian Hydrogen R&D Roadmap*. These considerations relate to the development of a local R&D capability statement; approaches to fostering potential national and international collaborations/partnerships; support for policy analysis/development, commercial pathways for development; support for industry partnerships; requirement for future hydrogen demonstration proposals to include an R&D partner; specifically involving Japan/South Korea in collaborations; supporting international researcher exchanges to foster transfer of country expertise and participation in relevant IEA programs.

[1] TRL is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the innovation chain. TR 4 is a state of technology development of component and/or system validation in laboratory.

1. INTRODUCTION

The concept of a 'hydrogen economy' has received attention for many decades. As the world moves to increasingly embrace the reality that the whole global energy system needs to be fully decarbonised by 2050 to keep global warming below 2°C, it becomes imperative to consider approaches that not only replace fossil fired electricity generation, but also storage and transport solutions for zero emissions energy to transition the transport sector away from fossil fuels. Hydrogen is well recognised as having a vital role in this.

This report has been commissioned by the South Australian Government to inform the development of a *South Australian Hydrogen R&D Roadmap* to complement the *Hydrogen Roadmap for South Australia* released in 2017.

1.1. Context

In September 2017, the South Australian Government released a *Hydrogen Roadmap for South Australia* to focus the government's efforts to support hydrogen project deployment and investment in South Australia [1]. The release occurred shortly after the finalisation of a study by Advisian/Siemens/ACIL Allen on the technical and commercial potential for green hydrogen in South Australia [2].

The *Hydrogen Roadmap for South Australia* recommended the following policies and actions [1]:

- support for early investment in hydrogen infrastructure
- promote and attract head offices, equipment distribution, services and manufacturers
- deepen relationships with key trading partners
- unlock local hydrogen innovation
- provide a best-practice regulatory framework for hydrogen production, storage and use.

Four renewable hydrogen projects have since received funding through the South Australian Government's $150 million Renewable Technology Fund and are being actively progressed in South Australia.

A *National Hydrogen Roadmap* [3] developed by CSIRO for the Australian Government was released in August 2018. It is a response to the growing interest in hydrogen as a clean energy carrier, to develop a hydrogen economy that can extend Australia's dominance as an energy resource exporter and build on private investments in hydrogen related projects around Australia.

In parallel, a briefing paper by the Hydrogen Strategy Group, led by the Australian Chief Scientist Dr Alan Finkel, outlines potential benefits, technological pathways and key steps to converting Australia's domestic gas system to hydrogen and developing Australia into a global renewable energy exporter via hydrogen [4]. Another report, prepared by ACIL Allen Consulting, commissioned by ARENA, assessed the opportunities for the renewable hydrogen supply chain [5]. Investment in hydrogen related projects is being supported by the Australian Renewable Energy Agency (ARENA) and CSIRO programs to encourage the development of breakthrough hydrogen-based technologies and hydrogen export capabilities.

1.2. Hydrogen Technologies, Markets, Trends and Opportunities for SA

Markets for green hydrogen are all nascent but potentially very large in the coming decades. Figure 1 illustrates potential market sectors in more detail.

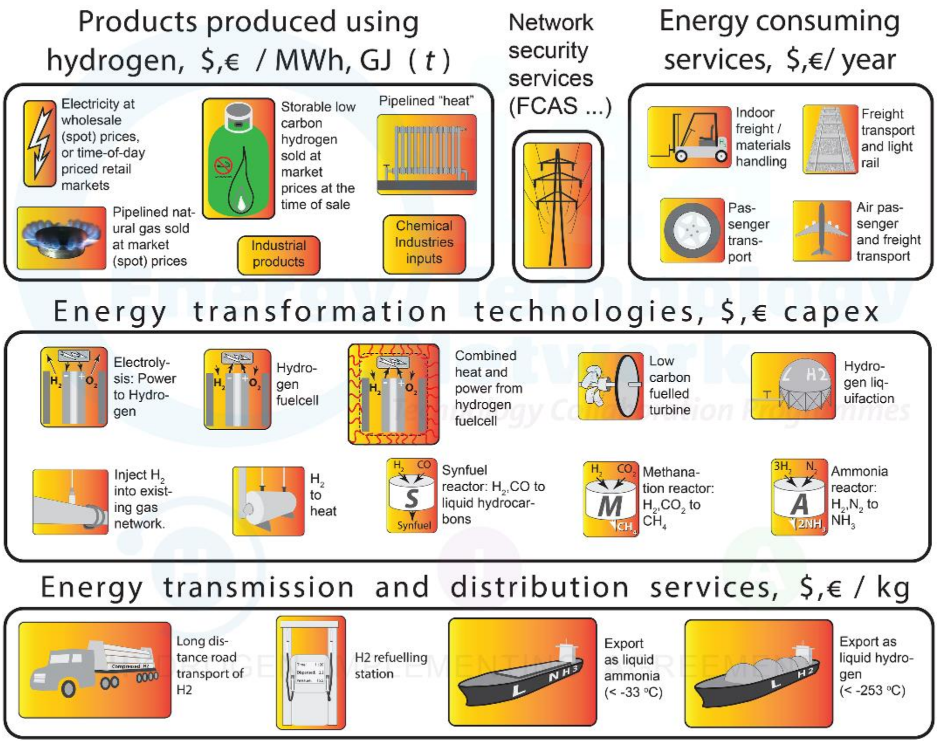

Figure 1: Hydrogen products, services, and energy transformation technologies (figure reproduced from IEA/HIA).

Most of the world's hydrogen is currently produced via steam reforming of natural gas (methane). Even at the now higher price of natural gas this potentially remains the lowest cost option, however the greenhouse gas emissions from the process are high. In South Australia there are times when the wholesale spot price of electricity is actually negative, this would suggest that depending on the amortisation of the capital cost, there should be potential for low cost hydrogen production via water electrolysis.

Hydrogen can also be produced by gasification of coal or biomass feedstocks. These pathways can be potentially combined with sequestration of CO_2 (which is produced as a by-product). If this is done with biomass, then negative net GHG emissions are achieved.

Global trends suggest hydrogen sources are diversifying and use of electrolysis to split water into hydrogen and oxygen is on the increase. There are several technologies available for electrolysis. While Polymer Electrolyte Membrane (PEM) electrolysis is less proven and more costly in terms of capital expenditure than alkaline electrolysis, it is more compact and suitable for dynamic load balancing of electricity grids with high levels of variable renewable energy. Both technologies are available commercially at the megawatt scale and increasing stack sizes are coming to the market with decreasing unit costs.

Apart from electrolysis and reforming (with CCS), it is expected that hydrogen will also be produced from bio-derived liquids and microbial conversion. Research is also underway on longer term methods of hydrogen production, including: bio-hydrogen (biological water splitting); renewable electrolysis; solar photo-electrochemical water splitting; and solar high temperature thermochemical cycles [6].

If hydrogen is produced for export, then the question of the most suitable form to transport hydrogen over long distances arises.

Japan, South Korea are among Australia’s largest customers for coal and LNG exports. These countries are also moving to decarbonise their economies and the idea of international trade in hydrogen is seriously considered. Japan in particular is exploring these ideas and has been conducting a major study that compares the specific options of; cryogenic liquid hydrogen, ammonia and using organic hydrides in a closed cycle [7]. Kawasaki Heavy Industries is a strong proponent of the cryogenic liquid hydrogen approach, and has been actively studying a potential project for producing hydrogen from Brown Coal gasification with CO_2 sequestration in the Latrobe Valley followed by liquefaction and shipping from a Gippsland port [8].

Much can be learnt from this work. Other storage approaches can also be considered. Proponents of the ammonia route point out that this is already a global industry with ship transport occurring routinely. In this sense at least one option is proven as technically feasible.

Other storage methods for hydrogen include organic and inorganic (metal) hydrides. Chiyoda, Mitsubishi, Mitsui and partners are currently constructing a demonstration plant in Brunei for the production and shipping of hydrogen via liquid methylcyclohexane as a chemical hydrogen carrier, with a dehydrogenation plant for hydrogen recovery in Kawasaki, aiming to fuel up to 40 thousand fuel cell vehicles [9].

The U.S. DOE cites durability and cost as the two primary challenges to fuel cell commercialisation. DOE has set market driven 2020 targets for successful fuel cell competition in the marketplace. The automotive fuel cell cost target is \$40/kW and the ultimate automotive target is \$30/kW. The durability target is 5,000 hrs and 8,000 hrs ultimately [10].

Manufacturers of light duty FCEVs are now launching products rather than prototypes. However, the automotive fuel cell supply chain is still immature and manufacturing occurs in low volume and 7 key components make up ~80% of the system cost.

Sale of hydrogen FCEV forklifts for industrial uses is increasing: this market segment is the “low hanging fruit” of hydrogen applications. Hydrogen powered forklifts are more cost effective than battery powered forklifts due to low refueling times. The capital cost of hydrogen powered forklifts is competitive with battery powered forklifts.

The global count of hydrogen refueling stations (HRS) that are open to the public or fleets is growing. The worldwide count of early market stations open to the public and/or fleets as at mid-2017 exceeded 200. The current leaders are: Japan, California (United States) and Germany, followed by the United Kingdom, South Korea and Denmark.

There are significant economic development and carbon abatement opportunities for South Australia through the production, use and export of hydrogen. Realisation of this opportunity would attract investment, create jobs and potentially decarbonise the State’s energy and transport sectors. It could also offer electricity grid benefits and potentially unlock new export markets to Asian economies such as Japan and South Korea.

South Australia is a world leader with renewable electricity deployment and is developing strong and economically significant export relationships, including with countries in the North Asian region. As the world transitions to lower carbon sources for its primary energy consumption, South Australia is well placed to participate in the market to provide the next generation of traded green energy commodities.

South Australia has world class solar and wind resources that can be applied to water splitting or hybrid operation. South Australia also has major natural gas resources and some brown coal resources no longer being exploited. These options could be the focus of R&D efforts along with the sequestration potential in the state.

As we will show in this report, besides these natural resources, South Australia also has local world class R&D capabilities, covering or applicable to a broad range of hydrogen-related research, development and commercialisation challenges, as well as strong interest and engagement from industry. Combined, this puts South Australia into the position to become a significant global player in the hydrogen economy.

1.3. Methodology

In order to compile this report, ITP:

- Reviewed South Australian hydrogen industry consultation materials
- Interviewed representatives of South Australian universities

- Reviewed South Australian hydrogen project developments - existing and pipeline
- Identified local, national and international R&D expertise/project experience
- Undertook capability/capacity mapping by specialisation
- Identified strengths, weaknesses and possible areas for collaboration between South Australian universities and global institutions
- Determined realistic R&D capability development opportunities for South Australia to
  - build on R&D strengths and address gaps
  - develop collaborations with world leading research
  - establish effective technology translation with local industry
- Determined other possible collaboration mechanisms and commercialisation pathways for local research in consultation with South Australian universities
- Provided market intelligence on existing/future national funding opportunities for hydrogen R&D projects

2. SOUTH AUSTRALIAN HYDROGEN POLICY AND PROJECTS

This section reviews the South Australian Government's hydrogen industry consultation materials and summarises current hydrogen project developments in South Australia.

2.1. Green Hydrogen Study

The *South Australian Green Hydrogen Study* examined the following questions:

- What role can hydrogen play in decarbonising the South Australian economy, including the transport sector?
- Can South Australia competitively produce and export Green Hydrogen?
- Is there scope for South Australia to participate in a hydrogen industry supply chain, exporting manufactured products and/or services?

The Study assumed that South Australian renewable generation would be utilised to power electrolysis to produce hydrogen from water. It then examined 11 specific pathways for how this hydrogen would be consumed. It documented its electrolysis efficiency assumptions in kWh/kg. The following table expands this to a Higher Heating Value (HHV) electrolysis efficiency.

Table 1. Green Hydrogen Study electrolysis efficiency (kWh/kg) assumptions with ITP analysis.

	Electricity consumed		Hydrogen produce		Electrolysis
Year	kWh/kg H_2	MJ/kg H_2	kg	HHV MJ	Efficiency (HHV)
2017	55	198	1	142.18	71.8%
2022	50	180	1	142.18	79.0%
2027	45	162	1	142.18	87.8%

The green power cost (Real $/MWh) implies that the financial modelling utilised the following green power costs (Table 2). The Study has limited information on the grid connection cost assumptions and how transmission and distribution costs plus marginal loss factors are included in the analysis.

Table 2. Green Hydrogen Study green power costs ($/MWh) interpreted from Figure 6, ITP analysis.

	Green power		Electricity component of H_2 cost		Natural gas
Year	**cost $/MWh**	**cost $/GJ**	**$/GJ LHV**	**$/GJ HHV**	**$/GJ**
2017	143	$39.72	$65.43	$55.32	7.39
2022	71	$19.72	$29.53	$24.97	7.06

The Study discusses an electrolysis utilisation factor of 0.8 and states, 'No attempt has been made to optimise the trade-off between the capital cost of increasing the electrolyser capacity and the ability to operate more selectively to minimise electricity cost from the grid per kg of hydrogen produced.' This implies that the electrolysis unit may be purchasing electricity from the grid at fluctuating prices.

The 'Electricity component of H_2 cost' does not include the capital and operating cost of the electrolysis plant or the necessary other infrastructure to compress, store and transport the hydrogen. The Study's assumptions for the price of natural gas illustrates the challenge for renewably produced hydrogen to displace natural gas in power generation. At $1/litre, diesel costs are $25.90/GJ which provides an indication of why transport is a promising market for renewable hydrogen.

It is also worth observing that the green power cost forecast for 2027 is now being seen in 2018 power purchase agreements.

The Study undertakes financial modelling to conclude that for 2017, of the specific scenarios tested, the potentially viable options for renewable produced hydrogen are:

- 18 MW of electrolysers to provide feedstock to produce 39 tonnes per day of ammonia to manufacture 150 tonnes per day of crystal, soluble fertilisers, and
- 1.4 MW of electrolysers to produce 0.5 tonnes per day of hydrogen to supply compressed hydrogen fuel to around 10 buses.

Looking to the years, 2022 and 2027, the Study concludes that large-scale hydrogen exports (via liquid ammonia) for transport applications become potentially viable.

R&D Implications

The Study does not discuss R&D priorities but recommends that the South Australian Government establishes a range of demonstration scale hydrogen projects focused on transport, chemicals and exports.

2.2. SA Hydrogen Roadmap

A *Hydrogen Roadmap for South Australia* [1] was developed to guide the development of a hydrogen industry in South Australia to fulfil the Government's ambition of becoming a zero-carbon emitting economy by 2050. The Roadmap also aims to be a catalyst for attracting international investment and the intellectual property needed to place South Australia at the forefront of developing a global, sustainable hydrogen industry.

The objectives targeted by the Roadmap are:

- Attract investment in hydrogen production using South Australia's renewable energy assets.
- Accelerate local demand for hydrogen as a low carbon input for transport, energy and industry.
- Unlock export markets for South Australian produced hydrogen.
- Establish South Australia as a testbed for cutting-edge hydrogen technologies.

Five action themes were developed, as follows.

1. Support early investments in hydrogen infrastructure.

   - Use South Australia Government procurement to create demand for hydrogen and incentivise investment in hydrogen production infrastructure, e.g. Adelaide Metro's hydrogen refueling station trial[2].
   - Co-invest in hydrogen demonstration projects through the Renewable Technology Fund.
   - Provide investors with up-to-date information on hydrogen technology projects in South Australia through an online hydrogen investment portal[3].
   - Case management of foreign investment through Investment Attraction South Australia and support through the Department of State Development.

2. Promote and enhance the attractiveness of head office location, equipment distribution and servicing and manufacturing in South Australia.

   - Use the Future Jobs Fund[4] to target job creation in the emerging hydrogen sector.
   - Encourage automotive industry diversification to include fuel cell vehicles.
   - Attract international conferences and events on the future development of the hydrogen industry.

[2] The tender process for a hydrogen production facility, refuelling station and a minimum of six hydrogen fuel cell buses was completed without an award of contract.
[3] www.renewablessa.sa.gov.au/topic/hydrogen (last accessed 2018-11-12)
[4] https://www.safa.sa.gov.au/all-news/Future-Jobs-Fund (last accessed 2018-11-12)

- Promote South Australia's supportive business environment.
- Provide case management for foreign investment through Investment Attraction South Australia.

3. Deepen engagement with South Australia's key trading partners.

South Australia will take a proactive approach to engaging with North Asia to promote the opportunities to invest in the development of hydrogen technologies. This includes expanding government hosted trade missions.

4. Unlock local hydrogen innovation.

- Support the commercialisation of South Australian hydrogen technologies through government programs such as the Early Commercialisation Fund[5].
- Facilitate research and industry partnerships through programs such as the Premier's Research and Industry Fund[6] and the Future Industries Accelerator[7].
- Continue encouragement of clean technology and renewable energy expertise at the innovation district of Tonsley.
- Connecting leading global hydrogen related technology and research with local industry and South Australian researchers for potential collaborative opportunities.

5. Ensure a strong regulatory framework for hydrogen production, storage and use.

South Australia works closely with other Australian jurisdictions as part of the Council of Australian Governments to ensure consistent and prudent regulatory regimes and standards. The South Australian Government is also represented on Australian Standards committees whose work encompasses hydrogen and gas safety.

R&D Implications

Action Theme 4 in the Roadmap highlights the importance of commercialisation, industry partnerships, global collaboration and the opportunities for synergies in the Tonsley innovation district.

[5] http://www.grantassist.sa.gov.au/business/program/view/8376 (last accessed 2018-11-12)
[6] https://industryandskills.sa.gov.au/science/premiers-research-and-industry-fund (last accessed 2018-11-12)
[7] http://innovation.sa.gov.au/opportunity/future-industries-accelerator/ (last accessed 2018-11-12)

2.3. Existing Announced Demonstration Projects in SA

Four renewable hydrogen projects have received funding through the South Australian Government's $150 million Renewable Technology Fund and are being actively progressed in South Australia.

Australian Gas Infrastructure Group, Hydrogen Park SA, Tonsley

In February 2018[8], Australian Gas Infrastructure Group (AGIG) was awarded $4.9 million from the South Australian Government for the Hydrogen Park SA (HyP SA) project. A $11.4 million hydrogen electrolyser demonstration project at the Tonsley Innovation District in Adelaide.

AGIG own gas distribution and transmission networks in Victoria, SA, Queensland, NSW, WA and NT. AGIG's strategy for decarbonising the gas sector is focussed on four technologies including hydrogen for injection into their gas networks and fuel cell vehicles. AGIG believes ~5-15% of hydrogen injection can be achieved with no network modification needed.

The project will involve AGIG to construct, own and operate a 1.25 MW proton exchange membrane (PEM) electrolyser. The unit will source grid-electricity to produce hydrogen. Production using on-site solar is a consideration for the future.

The main objective of the HyP SA project is to test blending of hydrogen and natural gas for reticulation in AGIG's local gas network in the commercial precinct in Tonsley. There is potential to also supply to a proposed residential development in the Tonsley area which is also serviced by AGIG network.

In the later part of 2018, AGIG are progressing a detailed front end engineering and design study, a procurement contract for long lead items including with Siemens for electrolyser supply and installation, and approvals for network connection and development and securing land.

Under the funding agreement with the South Australian government, the project has a commissioning/commercial operations date of June-July 2020 with a 5 year operating period to 2025. The installation of tube and trailer filling facilities is proposed in the 2nd phase of the project (not yet funded) to allow hydrogen to be transported and injected into other points in the AGIG network and for industry refuelling/export.

Neoen, Crystal Brook Energy Park

In March 2018[9], Neoen was awarded $1 million for a feasibility study for a renewable hydrogen production facility at the proposed Crystal Brook Energy Park. The main objective of the feasibility study is to establish if renewable hydrogen can be produced at a competitive price and to establish a demand for offtake.

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[8] www.australiangasnetworks.com.au/our-business/about-us/media-releases/australian-first-hydrogen-pilot-plant-to-be-built-in-adelaide (last accessed 2018-11-12)
[9] https://crystalbrookenergypark.com.au/neoen-awarded-funding-to-investigate-hydrogen/ (last accessed 2018-11-12)

The feasibility study will consider hydrogen produced by a 50 MW electrolyser with a production capacity of up to 25 tonnes per day for a range of end uses: gas injection, transport, ammonia.

The Crystal Brook Energy Park development is a 275 MW renewable energy facility with up to 125 MW of wind, 150 MW of solar PV and up to 130 MW/400 MWh of battery storage. Neoen submitted a development application for the Crystal Brook Energy Park in March 2018 for assessment by the State Commission Assessment Panel under section 49 of the Development Act. A decision is expected in early 2019.

The initial feasibility study has been completed and an investment decision will be made by the end of 2019. At the time of awarding funds to Neoen for the feasibility study, the South Australian Government also committed to provide a further $4 million grant and $20 million in loans should the project proceed.

UniSA, Mawson Lakes

In November 2017[10], UniSA was awarded $3.6 million from the South Australian Government to construct a $7.7m testing facility incorporating a hydrogen fuel cell, electrolyser, flow batteries, thermal energy storage and significant installation of solar PV (on buildings and single axis/tracking ground mount) at the Mawson Lakes campus. Under the funding deed, there is a commitment to a minimum size of 50 kW hydrogen fuel cell and 450 kWh flow battery, and a project completion date of July 2019.

The main driver for the testing facility is to provide technology experience to build confidence in technologies, increase exposure to technology and drive greater uptake. The facility will produce data to support multi-disciplinary research projects (e.g optimising performance, economics, energy/emissions) in new energy technologies: hydrogen, battery storage and solar.

The energy produced from the facility is intended to supplement campus needs especially at periods of peak demand. The university´s energy use is highly variable, very high when students on-campus and very low when on-holidays. The facility will likely result in frequent use of the battery and thermal water storage, with hydrogen storage used less frequently but likely for longer periods of time.

UniSA will tender for the technology and installation, and has indicated it is keen on building long term relationships with industry suppliers and providers. UniSA has existing relationships with other universities in Australia taking similar steps to be more energy self-sufficient while building their research capability in this area (e.g. Monash, Griffith University).

In the long run, UniSA will consider changing their vehicle fleet to hydrogen fuel and installing a refuelling station. It is developing a proposal near Mawson Lakes.

[10] http://www.unisa.edu.au/Media-Centre/Releases/2017-Media-Releases/Mawson-Lakes-powers-forward-with-renewable-energy-project/#.W-jmJpMzaUl (last accessed 2018-11-12).

H2U, Port Lincoln

Hydrogen infrastructure company Hydrogen Utility (H2U) is assessing the feasibility of a "green hydrogen and ammonia" demonstration plant to be built near Port Lincoln South Australia. The feasibility study is due to be completed in August 2018.

In February 2018,[11] H2U was awarded $4.7 million grant and $7.5 million loan from the South Australian Government's Renewable Technology Fund for a $117.5 million demonstration plant.

The proposed facility will integrate a 15 MW electrolyser plant, an ammonia production facility with capacity of 50 tonnes a day and 10 MW hydrogen-fired gas turbine and 5 MW hydrogen fuel cell, which will both supply power to the grid. The plant will be sited in proximity to two existing output constrained wind farms and commercial arrangements are being progressed with two proposed solar plants in the Eyre Peninsula to provide fast frequency response. The ammonia produced is targeted to be used as an industrial fertiliser for farmers and agricultural sector with field trials for ammonia production planned in the first 3 years of operation.

H2U is actively developing an ongoing collaboration with the University of Adelaide. The interest is in providing access to the facility once built and operational for post graduate projects.

H2U is interested in local universities leveraging the facilities for R&D activity more generally. H2U considers that commercial projects will drive demand for skilled technicians and professionals and has engaged with AGIG on their proposal.

2.4. Potential Project

AGIG, National Hydrogen Centre of Excellence[12]

AGIG are proposing to establish a National Hydrogen Centre of Excellence (NHy CoE) as a way of leveraging the infrastructure, partners and investment of the HyP SA. The Centre seeks to deliver on three key projects: sharing of knowledge from HyP SA, a detailed feasibility study into injecting 10% hydrogen blend natural gas to regional towns in South Australia, Victoria, ACT and a feasibility study on injecting 10% hydrogen blend and 100% hydrogen conversion of the South Australian, Victorian and ACT gas distribution networks.

Potential partners to the proposal include the South Australian Government, Victorian Department of Land, Water and Planning, Neoen, CSIRO, ANU/Evoenergy, Engie and Ausnet Services.

[11] http://www.australianmanufacturing.com.au/50111/h2u-to-build-green-hydrogen-facility-near-port-lincoln (last accessed 2018-11-12)

[12] Based on information provided to ITP by AGIG in June and November 2018.

3. HYDROGEN R&D TOPICS AND NEEDS

Hydrogen related research can be broadly categorised into the areas of: production, storage, conversion, distribution, system analysis and markets and regulatory frameworks. In this section, we briefly summarise these main hydrogen-related research areas. All areas currently have research needs and gaps that should to be addressed in order to improve the viability of hydrogen as an energy vector. In each subsection, we will also highlight some specific areas that require further research and hence provide potential opportunities for innovation.

3.1. Production

Hydrogen production processes can be categorised according to whether hydrogen is derived from water or from a biological or fossil hydrogen source, as shown in Table 3. Different methods exist to split water, including electrolysis, thermochemical processes, photo-electrochemical cells and biological organisms.

Table 3. Overview of hydrogen production processes.

Water splitting	Biomass conversion	Hydrocarbons conversion
Electrolytical	Fermentation	Gasification/Reforming
Thermo-chemical	Gasification	Pyrolysis/cracking
Photo-electrochemical		
Photo-biological		

The three main types of electrolysers are alkaline, PEM and solid oxide electrolysers. Both alkaline and PEM water electrolysers are available at Megawatt (MW) scale. In April 2017, a 3 MW PEM electrolyser stack was unveiled at Hannover Messe. A large-scale 400 MW alkaline system consisting of 187 electrolyser stacks is currently available at $450/kW USD plus housing. High temperature electrolysis splits water at 700-1000°C. The solid oxide electrolyser is the most commonly used high temperature electrolyser.

Conversion of biomass to hydrogen can be accomplished via fermentation or gasification processes, resulting in hydrogen and carbon mono/dioxides. Biomass conversion can also yield sustainable hydrogen (as the feedstock is renewable) but may involve the usage of arable land and of additional resources such as fertilizers and machinery for pre-processing.

Hydrogen can also be obtained via conversion of non-biological hydrocarbons, such as methane, coal, waste materials, etc. via gasification or pyrolysis processes, with steam reforming of methane currently being the primary way of producing hydrogen. These thermochemical[13] conversion processes can also potentially be driven using solar thermal concentrator systems to increase the hydrogen production from a given amount of feedstock.

Use of small reformers for hydrogen production via gasification of fossil and biomass feedstocks is also expected to increase. Small-scale electrolysers and reformer systems with hydrogen capacities in the range of 50-500 normal cubic meters per hour (Nm^3 /hour) are commercially available. The capital cost of small scale water electrolysers and gas reformers is comparable today (5,000-12,000 USD per Nm^3/hr), depending on the electrolyser or reformer capacity (50-500 Nm^3/hr), as well as the technology type (alkaline or PEM) in the case of electrolysers.

Hydrogen production pathways via gasification of coal or biomass feedstocks have potential to be combined with sequestration of CO_2. These thermochemical processes inherently produce a concentrated CO_2 product stream ready for sequestration. Application to biomass feedstock even has the potential to offer negative GHG emissions. This approach avoids the complex and costly process of post combustion capture that would be needed for application to fossil fuel combustion power stations.

Figure 2 illustrates the expected deployment of hydrogen production methods according to physical and time scales.

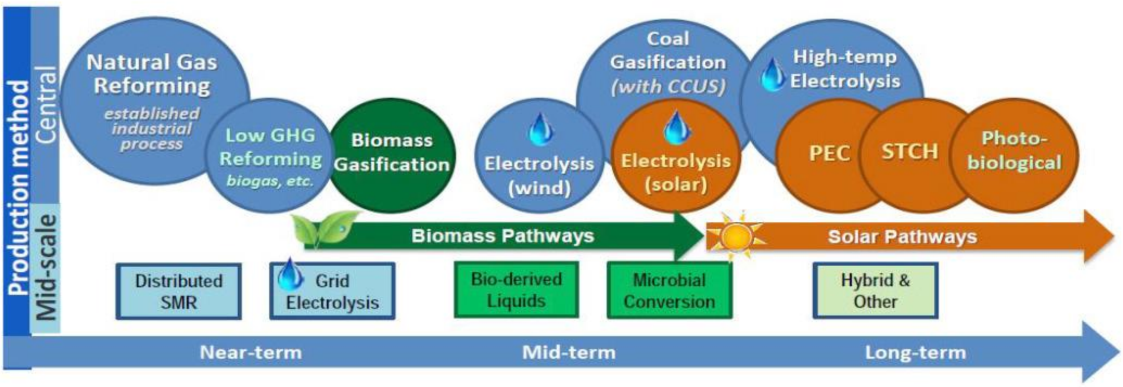

Figure 2: Future timeline for hydrogen production methods (figure reproduced from IEA/HIA).

For hydrogen production via the aforementioned processes, there is generally the need for significant improvements in energy conversion efficiencies, reductions in capital costs, and enhancements in lifetime, reliability and operating flexibility. Natural gas reforming and water hydrolysis are the most mature production technologies, while biomass conversion and photo-electrochemical and photo-biological water splitting processes are still further away from commercial readiness [11]. Cost reductions may be achieved through optimised manufacturing, reduced use of noble metals and reduced O&M costs.

[13] These thermochemical processes are not to be confused with thermochemical water splitting processes, which are typically high-temperature solar-driven and yield CO_2-neutral hydrogen.

3.2. Storage

Due to its low volumetric density at ambient conditions, hydrogen generally needs to be stored and transported in a more compact form. Storage methods can be divided into physical and chemical methods, as shown in Table 4. Physical methods include compression to pressures of around 700 bar, cold/cryogenic compression and liquefaction at below -253°C (boiling point of hydrogen). High energy densities can be achieved if hydrogen is stored in chemical form, either adsorbed at the surface of another compound (e.g. MOF-5), or incorporated into organic compounds such as methylcyclohexane, or inorganic compounds such as ammonia or hydrides. Hydrogen, can also be directly injected into the natural gas network (a form of pressurised storage combined with energy transport).

Table 4. Overview of hydrogen storage methods.

Physical	Chemical
Compressed	Adsorbed (e.g. MOF-5)
Cold-cryo compressed	Absorbed (e.g. organic compounds, ammonia, metal hydrides, MCH, etc.)
Liquid	

For compressed hydrogen storage, composite material tanks are being developed to reduce weight/enhance strength. Ongoing research needs include the following [12]:

- Research on material embrittlement, using new ad hoc fracture mechanics techniques.
- Development of stronger and lower-cost construction materials, especially carbon fibres.
- Development of an efficient and clean (i.e. without oils) 1000-bar compressor.
- The consideration of hydride-type compressors utilising waste heat or solar energy.
- Development of techniques that recover the compression energy during vehicle operation.
- Pressurised hydrogen stored inside glass spheres.

Chemical hydrogen storage allows hydrogen to be stored in liquid or solid compounds at high energy densities. Potential challenges with chemical hydrogen storage include the reversibility of the chemical reactions, side-reactions, decomposition, or incomplete conversion of reactants, material handling and energy penalties.

Ammonia is considered as a promising hydrogen carrier for exports, particularly for target markets in Japan or South Korea. It is liquid at room temperature at moderate pressures and offers higher energy density than pure compressed or liquid hydrogen per unit of volume and about half that of LNG. It only contains the abundant elements hydrogen and nitrogen.

Ammonia is a potential fuel for combustion engines (e.g. gas turbines). Alternatively, ammonia can be dissociated into its elements hydrogen and nitrogen before combustion and pure hydrogen be used in fuel cells. Recent progress with hydrogen separation membrane technology at CSIRO may facilitate this route.

3.3. Conversion

Conversion of hydrogen as a fuel primarily aims to generate electric power for either power distribution via the power grid or input to electric motors for propulsion, or to directly generate propulsion with combustion engines. In addition, combined heat and power production is an option, e.g. for industrial or residential energy use. Direct conversion to heat without power generation is thermodynamically inefficient and should be limited to industrial processes requiring high-temperature heat. Hydrogen conversion technologies are summarised in Table 5.

Table 5. Overview of hydrogen conversion technologies.

Fuel cells	Combustion engines
Proton exchange membrane	Gas turbines
Alkaline membrane	Internal combustion engines
Solid oxide	
Direct methanol	
Sulfuric and phosphoric acid	

For power generation, fuel cells promise the highest conversion efficiencies and are a major focus of research. Fuel cells offer the added benefits of no moving parts and cleaner chemical reactions, resulting in less contaminants and pollution. Major fuel cell types include polymer electrolyte/proton exchange membrane (PEM) fuel cells, alkaline membrane fuel cells, solid oxide fuel cells, direct methanol fuel cells, and sulfuric and phosphoric acid fuel cells, each having their own advantages and potential applications [13].

PEM fuel cells are suited for mobile applications due to their low operating temperature and hence fast start-up times, good dynamic behaviour and high power density. Fuel cell vehicles are already produced by Toyota and Hyundai and plans to introduce them to the Australian market were announced in 2017.

Alkaline fuel cells are among the most efficient fuel cells but are very sensitive to CO_2 impurities and require operation with purified oxygen and high-purity hydrogen. Solid oxide fuel cells operate at high temperatures of up to 1000°C and reach high conversion efficiencies. They require relatively stable load. Hence, they are well suited for stationary power and combined heat and power generation. Direct methanol fuel cells are at an earlier stage of development. They offer the main benefit of using methanol[14] as the fuel, which, being a liquid, has advantages over hydrogen in on-board storage.

Shortcomings in fuel cell technologies are currently high investment costs and limited lifetimes. Current investment costs for PEM fuel cells are in the order of 300-500 USD/kW. However, with economies of scale these costs are projected to fall to the level of conventional internal combustion engines of around 30 USD/kW.

Besides fuel cells, hydrogen can also be converted in combustion engines, including gas turbines and internal combustion engines, to generate propulsion or electric power. Vehicles using hydrogen-fuelled internal combustion engines have been demonstrated. Gas turbines operated with up to 45% hydrogen fuel content are commercially available, while gas turbines adapted to run on pure hydrogen are currently still in the R&D phase [14].

Ammonia, a chemical hydrogen storage medium, has been shown to be usable as a fuel in gas turbines. Currently, it is blended into kerosene, but tests are planned to be extended to 100% ammonia fuel content. Pure ammonia combustion would result in only water and nitrogen (the main constituent of air) in the exhaust stream (NO_x formation may occur but is expected to be controllable). Use of hydrogen or ammonia fuel in gas/steam turbine combined-cycle power plants offers the potential of energy conversion using proven large scale power generation technology with efficiencies that are comparable to the best current fuel cells. It also allows for the potential retrofit of existing power plants.

3.4. Distribution and Systems Analysis

Hydrogen can either be produced directly on site, for example at a refuelling station via electrolysis or steam reforming, or produced centrally and distributed. Local production avoids the transport and distribution costs but results in smaller, more cost-intensive hydrogen production plants, while central production and distribution benefits from economies of scale of a larger production facility. The optimal design of hydrogen infrastructure depends on local factors, such as the size and extent of the system, the density and distribution of energy sources and consumers, hydrogen quantities required, existing distribution infrastructure, etc. An optimum system configuration can only be determined via detailed system modelling and optimisation.

Compressed hydrogen can be distributed in tanks via ships and trucks or via hydrogen pipelines. Alternatively, it can be introduced and distributed via the natural gas network. Liquefied hydrogen and hydrogen contained in higher-density chemicals (see section 3.2) is transported in tanks via ships and trucks. The optimum system configuration again depends on local factors and should be determined via system modelling [14].

[14] Methanol can be regarded as a chemical form of stored hydrogen, it is synthesised from CO_2 and hydrogen.

Research topics include new materials that are resistant to long-term contact with hydrogen, as hydrogen tends to embrittle hydride-forming metals. Other research activities include long-term testing of components such as hydrogen dispenser hoses and nozzles as well as system-level analyses of hydrogen production and distribution systems to determine optimum system configurations, as well as component and system readiness levels and costs.

3.5. Market and Regulatory Frameworks

Hydrogen offers the potential for unprecedented energy exchange and storage mechanisms, both locally and globally, in centralised and decentralised energy systems, and for a wide variety of primary energy sources. As such, hydrogen has the potential to play a disruptive role in future energy systems. Despite its promise as a new universal "energy currency", hydrogen also presents significant risks, both technological and social, as well as challenges.

For these reasons, market regulations and measures for the successful uptake and use of hydrogen are essential. Some of these market regulations should target the following goals:

- Provide a stable policy framework that encourages fuel efficiency and low greenhouse gas emission technologies, to facilitate investment
- Bring down cost of hydrogen and fuel cell technologies through policy support for investment and early market deployment
- Adopt and further develop international standards and codes for the safe handling and metering of hydrogen
- Develop a clear understanding of the specific benefits of energy exchange within the economy via hydrogen

4. SOUTH AUSTRALIAN HYDROGEN R&D

This section provides a current overview of hydrogen related R&D in South Australia in 2018.

The overall field of hydrogen related R&D is so broad that in addition to specific activities noted below, all research institutions will have a wide range of capabilities and activities that are relevant but not yet explicitly identified as hydrogen related.

4.1. University of Adelaide

The University of Adelaide is actively involved in hydrogen research and development, in particular production, storage and transport and utilisation of hydrogen and its related derivatives.

Activities are largely split between the Centre for Energy Technology (lead by Professor Gus Nathan), the School of Physical Sciences (Chemistry) and the Centre for Materials in Energy and Catalysis (led by Professor Shizhang Qiao). The CET, within the Institute for Mineral and Energy Resources has a local and multi-disciplinary team of research scientific expertise in fields relevant to hydrogen and electrolysis such as engineering, chemistry and combustion.

Researchers in the School of Physical Sciences (Chemistry) undertake fundamental research into the key areas of energy usage, storage and demand, and environmental chemistry. Affiliations to the CET and Advanced Nanomaterials facilitate these projects. Aspects of this research are funded by DSTO, Adelaide Airport (through CET) and a multi-institutional $6M Science Industry & Endowment Fund grant.

The expertise within the Centre for Materials in Energy and Catalysis covers areas such as nano-structured non-precious metal and metal-free catalysts for sustainable clean energy generation and preparation of nanostructured materials for photocatalysis.

The University of Adelaide has further moved to establish a hydrogen group that is to be led by Professor David Lewis, who was previously a lead figure in the Muradel initiative that aimed to produce algae for conversion to bio crude.

The majority of the universities´ hydrogen related R&D is TRL 1 to 3, although specific opportunities are sought to develop technologies to commercialization.

Key hydrogen related activities are:

- Solar Thermochemical approaches to hydrogen production, either water splitting or gasification or hybrid fuels production; this work is based at the Centre for Energy Technology (CET) and led by Professor Gus Nathan.
- Photocatalytic approaches to water splitting for renewable H_2 production, and CO_2 conversion led by Professor Greg Metha.

- Electrocatalytic approaches led by Professor Shizhang Qiao for various energy conversion applications including fuel cells, metal-air batteries, water splitting.
- Potential on-board storage solutions for hydrogen led by Professor Christopher Sumby and Professor Christian Doonan (adsorption within designer porous materials called metal-organic frameworks, MOFs); separation of gas mixtures including hydrogen/CO_2, hydrogen and nitrogen using MOFs, or composite membranes prepared from porous materials, like MOFs, and organic polymers; catalysts for conversion of hydrogen into carrier fuels for transport (e.g. formation of methane or ammonia from hydrogen).
- Combustion processes in regimes proposed for reduced pollutant formation, solid fuel combustion, and solid fuel devolatilisation/pyrolysis, techno-economic analyses to identify the most effective and sustainable ways to produce and utilise ammonia.
- Techno-economic analysis of transportation options for renewable hydrogen such as tankers and compressed gas pipelines, and blending with gas in pipelines with downstream separation plus green hydrogen and green ammonia production.
- Development of ecofriendly biomimetic method for synthesising noble metal nano-particles and their alloy electrocatalysts, which are far smaller and more robust than currently available electrocatalyst particles. Demonstration of the use of these electrode materials in hydrogen fuel cells has the potential to significantly reduce the cost of production, thereby accelerating adoption of this clean energy technology. This knowledge has been protected by two Australian and one US Patents. The commercial prospect of the patented valuable technology led to a new spin off company NovaKat Pty Ltd, a wholly owned subsidiary of ITEK Ventures Pty Ltd, to commercialise the technology. NovaKat secured a Clever Green Grant from the South Australian Government to facilitate the Fuel Cell Electrode Prototype Development.
- The CET leads Node 4 of the $62m Australian Solar Thermal Research Initiative, which aims to lower the cost of solar fuels production by gasification and is the lead research institute responsible for the $16m ARENA funded project to introduce concentrating solar thermal into the Bayer alumina process.
- Specialisation in the technical and economic aspects of hydrogen production via solar thermal and methane reforming, which is the conventional route for hydrogen production through both ASTRI and the Bayer projects, which include techno-economics of solar methane reforming.

The University has won an ARC discovery grant that is looking at replacing CNG with hydrogen for various processes. There is an interest in ammonia combustion with other collaborations in the area of combustion. The University is considering collaboration with Liberty steel for using hydrogen in an alternative process for steel production (in place of coke) termed “flash calcining”.

The University of Adelaide has an active collaboration with Flinders University in hydrogen work (via Professor David Lewis from Flinders University[15]) and has been in ongoing discussion with H2U, in relation to the Port Lincoln project and other potential projects but there is no substantial activity as yet. The University has a collaboration with AGIG which has led to links with some UK based industry. The University has established relationships with Professor Tatsuya Kodama and University of Niigata in Japan for thermochemical water splitting.

In phone interviews, a University representative expressed the following views:

- If commercial activity in the hydrogen field is a priority, then some level of local innovation is needed to support this.
- For the State to aim for a role in the hydrogen export agenda, it was considered important to begin with the creation of some local demand for hydrogen and support the local industry with further local innovation.
- The Premier's Research and Industry Fund[16] could have a dedicated research funding round for hydrogen related work.

4.2. Flinders University

Within Flinders University, relevant hydrogen R&D activity is focussed within the Institute for Nanoscale Science and Technology led by Professor David Lewis. The main area of expertise is in materials surface science where research is occurring into high surface area electrodes (which involve adding nanotubes to roughen material surfaces and increase rates of reaction) and scumming. Other areas of work include catalysts for photo- and thermochemical water splitting and membranes for use in electrolysis.

With the combination of Electron Spectroscopy (XPS/UPS/MIES), UV-Vis Absorption Spectroscopy, Transient Absorption Spectroscopy, Photoluminescence Spectroscopy and Electrochemistry, the University is investigating a catalyst and co-catalyst system and relate electronic structure to the reactivity of catalyst systems in the reduction of CO_2 and H_2O under solar illumination. This work could present new avenues to efficient conversion of CO_2 and H_2O into fuels.

The Institute works collaboratively so the three universities in South Australia can leverage complementary expertise and provide a strong offering for R&D proposals. The solar fuels project which captures waste from combustion, adds a reaction and uses solar to stimulate a chemical reaction that creates fuel is one example of a collaboration between the three universities. This work is being led by Professor Gunther Andersson using particles at nanoscale to cluster on a surface as part of the process of producing solar fuels.

[15] It should be noted that there is a David Lewis at Adelaide and a David Lewis at Flinders, both involved in hydrogen related activities.
[16] https://industryandskills.sa.gov.au/science/premiers-research-and-industry-fund (last accessed 2018-11-12).

They collaborate with Professor Shizhang Qiao (Chair of Nanotech) at University of Adelaide and also have a strong collaboration with University of Adelaide's School of Chemistry. Through the ASTRI project, they are collaborating with QUT on using solar as an alternative in energy intensive endothermal processes.

Their main international collaboration is with the National Institute of Materials Science (NIMS) in Japan through a MOU with the Energy Division. NIMS is an internationally significant R&D institution with significant funding by the Japanese government. Their focus of activities is on batteries and hydrogen, given their use of similar polymer materials.

In terms of approaches to support hydrogen R&D, they are supportive of approaches that help to coordinate and leverage expertise across the three universities. The South Australian Renewable Energy Institute (SAREI) led by former Chief Scientist Don Bursill, now defunct, was a good model which provided "one voice" rather than individual universities´ positions. They feel this approach is important when trying to attract funding.

Support was also expressed for the idea of a Centre of Excellence, where companies contribute funds towards research that addresses their specific needs and government also puts in funding. In this way, the CoE has a way of tapping the technical expertise of universities and supporting an industry centric approach.

The University's commercialisation arm is Flinders Partners. The New Venture Institute, Flinders Partners and the various research institutes form the innovation system at Flinders University with a strong focus on engagement with industry and other stakeholders.

4.3. University of South Australia

Of the three universities, UniSA has relatively little in the way of current hydrogen related R&D work although it remains interested in an increased involvement.

UniSA's renewable energy testing facility, which incorporates hydrogen production and storage to support teaching and research projects, is discussed in Section 2.3.

Key research nodes at UniSA with some interest in hydrogen are:

- Research Node for Low Carbon Living
- Barbara Hardy Institute
- Future Industries Institute (FII)

UniSA is keen to further develop R&D activity in hydrogen and there may be scope for this to be incorporated into current research priorities and commercialisation activities which are:

- Low-carbon living
- Low-energy buildings

- Energy forecasting and grid optimisation
- Photovoltaic/thermal system for off-grid zero energy homes
- Maximising renewable energy in small community precincts
- New mobility services including the shared use of electric vehicles
- Sustainable energy
- Solar thermal technology, including testing and evaluation capabilities
- Smart energy grids
- Energy and advanced manufacturing, including sun-tracking heliostats
- Mineral and Resources Engineering – assisting mineral extraction
- Innovation and Collaboration Centre: Strategic partnership between the university, the South Australian Government and DXC Technology (DXC) supporting technology-based incubation and business growth
- UniSA Ventures: Facilitates the translation of outcomes from research into products and services that create a commercial return and have a positive impact on society.

UniSA conducts a range of research activities in autonomous & unmanned systems, systems integration & engineering, sustainable agriculture, sustainable energy, low energy housing, nanotechnology and nano-manufacturing, photonics and lasers, minerals and resources engineering, energy and advanced manufacturing, environmental science and engineering, biomaterials engineering and nano-medicine.[17]

[17] http://www.unisa.edu.au/IT-Engineering-and-the-Environment/School-of-Engineering/Research/

5. NATIONAL RESEARCH CAPABILITIES

This and the following sections provide an overview of other key hydrogen research capabilities, nationally and internationally. In addition, a list of international hydrogen-related R&D initiatives, programs and projects is provided in Annex A.

5.1. CSIRO

CSIRO has conducted major research work over many years on fuel cells, gasification, catalysis and more. This work is largely split between the sites in Melbourne (Clayton) and Newcastle.

The Centre for Hybrid Energy Systems (CHES) in Clayton, VIC, is a state-of-the-art lab with substantial expertise and capabilities for hydrogen and fuel cell technologies.

CSIRO also has expertise in membrane technology to separate hydrogen from a mixed gas stream through metallic membranes. This knowledge is currently applied to develop a low temperature membrane reactor for ammonia cracking and hydrogen separation. This would enable hydrogen to be shipped in the form of ammonia and converted back to pure hydrogen on board of vehicles.

Work has been conducted for many years on solar thermal driven steam reforming of methane. This offers a 30% reduction in CO_2 emissions whilst producing more hydrogen from the same natural gas feed. Solar thermal driven processes have been explored for gasification also. In the longer term solar thermal routes for water splitting are under development. These solar thermal paths have all been studied in an ARENA funded project Concentrating Solar Fuels Roadmap [15].

5.2. ANU

ANU has capabilities in renewables based production of hydrogen – thermochemical, electrochemical and photochemical, fuel cells, ammonia based energy storage, solar cells and nanostructured electrodes for stand-alone solar hydrogen production. Efforts related to energy at the ANU are united by the Energy Change Institute.

Research encompasses Artificial Photosynthesis, microalgal plant growth, carbon capture and storage in sediments, fuel cell components fabrication, nano-structured ceramics for thermochemical water splitting, as well as broad expertise with renewable energy Markets and Regulations. The international Energy Transition Hub collaboration aims to explore and create economic and technological opportunities from the global transition to clean energy.

5.3. Other Key Australian Universities

University of Melbourne – Current research is directed toward finding new ways of storing hydrogen at mid-range temperatures and pressures by creating lightweight, porous materials that are able to sorb and release large quantities of hydrogen under pressures much less than that commonly found in gas cylinders.

Monash University - Monash University has a long history in hydrogen production research through electrolysis, photochemical water splitting and brown coal gasification. Monash has a developing area of research in ammonia production and hydrogen storage technology including metal hydrides, nano-porous carbons and nano-grained materials.

University of New South Wales – Research at the Materials Energy Research Laboratory in Nanoscale is focussed on hydride materials for storing hydrogen, magnesium nanoparticles to enable safe storage, conversion of CO_2 for gas flues for direct conversion into liquid hydrocarbons and development of enzymatic catalysts as alternative to platinum catalysts used in PEM fuel cells.

University of Queensland - Expertise exists in advanced catalysis, gas adsorption and separation, direct carbon fuel cells and solid oxide fuel cells.

University of Sydney – Thermochemical techniques for converting biomass into useful energy and hydrogen in aviation are research interest areas.

University of Western Australia – Hazer Group is a commercial spin-off using a novel hydrogen and graphite production process developed by researchers. Current R&D activity is ammonia focussed (via a research collaboration with China National Institute of Clean and Low Carbon Energy).

Curtin University –Professor Craig Buckley’s research group works on metal hydrides, which can be used as hydrogen storage materials. In addition, Dr Buckley currently serves as the Australian executive committee member for the IEA Hydrogen Technology Collaboration Program.

Griffith University – Hosts the National Hydrogen Materials Reference Facility, a state of the art laboratory on hydrogen storage materials and embrittlement. Current projects include magnesium-based hydrogen storage materials, polymer membranes for hydrogen separation and storage, hydrogen-modified titanium-dioxide for battery electrodes, hydrogen embrittlement of high-strength steels, high-pressure hydrogen storage materials and hydrogen-modified superconductors.

5.4. Future Fuels Cooperative Research Centre

In April 2018, the Federal Government announced the establishment of the Future Fuels Cooperative Research Centre (FFCRC) to undertake research and development into new energy infrastructure for low-carbon fuels [16]. The CRC received $26.3 million in federal funding and leverages a further $64.6 million of cash and in-kind support from CRC participants. The FFCRC is led by CEO David Norman and involves six Australian universities (RMIT University, Deakin University, University of Wollongong, University of Adelaide, University of Queensland and University of Melbourne) as well as the Australian Pipelines and Gas Association, Energy Networks Australia, the Australian Energy Market Operator and state regulators from South Australia and Victoria.

The research will look at opportunities to adapt existing infrastructure for the production, transport and storage of sustainable future fuels such as hydrogen, biogas, methanol and ammonia and at necessary changes to the regulatory framework and market conditions for an accelerated uptake of low-carbon fuels. The three research programs are [17],[18]:

1. Future fuels technologies, systems and markets: This program focuses on identifying and addressing technical, policy and commercial barriers and on understanding the opportunities and developing business cases for the uptake of low-carbon fuels. Techno-economic modeling of fuels production and delivery systems and markets will be applied to identify major technical and cost hurdles and technology needs. Policy reforms required for the uptake of future fuels will be identified and proposed to government. Modeling efforts will be complemented by industry-led technology demonstration projects, such as injecting hydrogen into the natural gas network and power-to-gas conversion.

2. Social acceptance, public safety and security of supply: This program aims to understand and address social and policy context, public acceptance and safety related issues of future fuels and related infrastructure. Research is intended to cover technical, social and organisational factors and to explore global best practice regulatory solutions and adapt these to the Australian environment.

3. Network lifecycle management: This program aims to address challenges associated with the operation and maintenance of a future fuels infrastructure. Benefits of new enabling technologies from other disciplines, such as data collection and usage, new materials, additive manufacturing, etc. are explored to enhance current asset management practices.

6. INTERNATIONAL RESEARCH CAPABILITIES

Here we summarise hydrogen-related R&D expertise and activities at major institutions worldwide. This is an extract of significant activities rather than a complete overview of hydrogen-related R&D activities worldwide, which would exceed the scope of this report.

The International Energy Agency (IEA) is an authoritative source of information about hydrogen research and technology. Over more than 35 years, the IEA Hydrogen Technology Collaboration Program (TCP) has published nearly 40 documents addressing hydrogen related research topics, such as production and storage methods. Current Australian representative is Dr. Craig Buckley, professor at Curtin University. The IEA Hydrogen TCP aims to coordinate international RD&D collaboration on hydrogen. The following is a list of supported activities:

- Bio-hydrogen
- Distributed and community hydrogen
- Fundamental and applied hydrogen storage materials deployment
- Global hydrogen systems analysis
- Hydrogen-based energy storage
- Hydrogen safety
- Local hydrogen supply for energy applications
- Near-term market routes to hydrogen
- Production of hydrogen from renewables
- Water photolysis

The complete list of current and past work tasks and activities can be found at http://ieahydrogen.org/Activities.aspx (last accessed 2018-11-12). A comprehensive technology roadmap for hydrogen and fuel cells was published by the IEA in 2015 [14]. A recent publication providing an update on Global Trends and an Outlook for Hydrogen can also be found on the IEA website [19].

Other IEA organisations related to hydrogen are the Solarpaces programme[18] and the IEA Bioenergy organisation.[19]

The Hydrogen Council is a global initiative of leading energy, transport and industry companies to accelerate investment and developments in the hydrogen and fuel cell sector.[20]

[18] https://www.solarpaces.org
[19] http://www.ieabioenergy.com
[20] http://hydrogencouncil.com

The following sections include brief summaries of hydrogen-related RD&D projects and activities worldwide, based on a review of the IEA Hydrogen Implementing Agreement 2016 Annual Report, and summaries of major R&D capabilities by country.

6.1. Denmark

In recent years, 15-20% of the 1 billon DKK energy research budget in Denmark has been allocated to hydrogen and fuel cell technologies.

The FutureGas R&D project aims to optimize the future use of the gas network via safe injection of green gases. The project is funded by Innovation Fund Denmark, with participation from both the DGC and a number of European technical universities (seven partners in total).

Hylaw is a project funded by the EU Horizon 2020 framework. This project aims to tackle barriers to deployment of hydrogen and fuel cell projects in the legal framework and administrative processes (LAPS). It entails systematic description and comparison of LAPs in the eighteen (18) partner countries. Twenty-three partners from eighteen European countries are participating.

The overall objective of the BioCat Project is to design, engineer, construct and test a commercial- scale power-to-gas facility at a wastewater treatment plant (based on biological methanation) and to demonstrate its capability to provide energy storage services to the Danish energy system. The national ForskEL program funds the project and seven international partners are participating.

The Hybalance project intends to design a power-to-hydrogen plant (PTH2) for combined operations that seeks to provide both grid balancing services and hydrogen for both industry and fuel for transport in the municipality of Hobro. The plant will be used to demonstrate feasibility proof of concept and to identify potential revenue streams from PTH2 under current and future constraints (regulatory environment, state-of-art of key technologies, etc.). This project is funded by the EU Horizon 2020 Framework Program and includes six international partners.

Another project aimed to test polymer distribution pipes for hydrogen transportation. After 10 years of operation and material analysis, the field test of 100% hydrogen in polymer (PE) distribution pipes for natural gas was completed. The tests began in 2003 in order to investigate possible material deterioration and were carried out in a small grid at Danish Gas Technology Centre. Hydrogen was circulated in the grid under conditions similar to real-life operation. In order to simulate the possible outcomes for the Danish natural gas grid if it were converted to 100% hydrogen, the test grid was constructed from samples taken directly from the Danish natural gas grid.

Based on the project results, smaller hydrogen PE grids for demonstration have been put into operation in Denmark. The project results were presented at IGRC2017 in Brazil.

6.2. European Union

Under Horizon 2020, RD&D activities on hydrogen and fuel cells are structured under an industry-led public-private partnership established as a Joint Undertaking (FCHJU, www.fch.europa.eu). Its total budget for the period of 2014-2020 is 665 M€, or 95 M€/ year on average. It is further represented and promoted by the Hydrogen Europe Research association, which aims to strengthen R&D/industry cooperation, keep European industry at the forefront of innovation, participate in international regulation, codes and standards activities and support cross-cutting aspects such as safety, education, training and public information.

To identify future research and innovation needs, work in the frame of the Integrated Strategic Energy Technology Plan (SET-Plan) continues. Under the focus area Energy Efficiency and Competitiveness of Industry, the steel and chemical industries have shown significant interest in the use of electrolytic hydrogen.

6.3. France

PROMES

An example lab in France is the PROMES lab in the French Pyrenees, the oldest concentrating solar energy research lab operating today. The group of around 50 staff has conducted pioneering research in the area of solar thermochemical hydrogen production, including materials development and testing, and reactor development and testing. The lab features the world´s largest solar furnace, delivering around 1 MW or radiative power at over 10,000 suns peak concentration, as well as several smaller furnaces for small-scale material tests.

Figure 3: Solar furnace at PROMES in Odeillo, France (Source: Dave Walsh).

6.4. Germany

Overview

In 2008, the National Innovation Programme Hydrogen and Fuel Cell Technology (NIP) was established as a ten-year programme for the market preparation of hydrogen and fuel cell technology (H_2FC technology). NIP represented the starting point for more than 400 projects—from approximately 200 supported companies and scientific bodies—to be concluded by the end of 2016. As a result of NIP, German industry was encouraged to make investments totaling up to 4.5 billion € in research and development.

In this first phase, NIP has demonstrated the suitability of H_2FC technology and its fundamental marketability in various areas of application. The programme's large lighthouse projects were: the technological maturity of fuel cell vehicles, fuel cell heating devices and systems and fuel cell-based emergency power supply systems.

Most manufacturers of H_2FC products have completed the R&D phase and are now optimizing their applications in demonstration projects. German manufacturers are now offering products suitable for everyday use in the heating industry as well as in the area of critical power supply (including critical communication infrastructures). Fuel cell vehicles and the associated H_2 refueling infrastructure were introduced to the market in 2015. NIP projects have proven that the technologies are suitable for everyday use and that they meet the technical parameters of market demands. The costs of the technology could be reduced by 50–75% depending on the application. The cost of an H_2 refueling station, for example, has halved from 2 million € in 2008 to 1 million € in 2014.

R&D activities in NIP II concentrate on cost reduction through economies of scale, decreasing the weight and volume of the fuel cells as well as reducing the general system complexity. Furthermore, reliability, service life and efficiency will be increased and operating conditions improved. In demonstration projects, NIP II will achieve market preparation and technology validation of reliable products under everyday real life conditions. Another priority is customer acceptance and supplier industry motivation. Objectives for the establishment and development of the hydrogen chain in the area of energy technology include the production of hydrogen from renewable energy sources (especially through electrolysis), as well as its storage in larger quantities.

Fraunhofer ISE

The business area Hydrogen Technologies at Fraunhofer ISE offers R&D services in the research areas of fuel cell systems, water electrolysis and thermochemical processes.[21]

The fuel cells team develops and characterises cells, components and stacks and systems and peripheral components. It conducts spatially resolved characterization of cells with the aid of electrochemical impedance spectroscopy and performs modelling and simulation across all relevant length scales.

[21] https://www.ise.fraunhofer.de/en/business-areas/hydrogen-technologies.html (last accessed 2018-11-12).

The water electrolysis team has long standing experience with component and system development. Current work involves developing standardised measurement procedures for PEM electrolyser characterisation, evaluating new components and stacks for PEM cells, investigate degradation mechanisms, modelling and analysing systems involving electrolysers, conducting technological, market and cost studies, and more.

Long-standing experience in process engineering is applied to thermochemical processing of fossil and biogenic sources through heterogeneous catalytic processes, such as reforming and pyrolysis as well as hydrogen and CO_2 to liquid fuels synthesis. Goal is to make these processes more efficient and reduce CO_2 and exhaust gas emissions. The team develops and characterises catalysts, designs and executes experimental setups and models processes.

German Aerospace Centre (DLR)

DLR´s solar energy research team is the largest in the world in the field of solar thermal/thermochemical energy technologies, with teams in Cologne, Stuttgart and Jülich. The team currently has a strong focus on solar thermochemical hydrogen production.

Test facilities in Germany include a 25 kW (radiation) high-flux solar simulator (for indoor testing) and a ~20 kW solar furnace in Cologne for lab-scale tests, capable of reaching temperatures of over 2000°C for thermochemical water splitting processes. For pilot-scale testing, the Jülich test centre features a ~4.5 MW (thermal) solar tower test facility. In addition, the new research facility Synlight was recently completed, which is the world´s largest artificial sun with about 200 kW of radiative power for up to 3 parallel experiments. Besides other applications, the facility is intended to develop production processes for solar fuels, including hydrogen. In addition, DLR uses large-scale high-concentration test facilities at the Plataforma Solar de Almeria in Spain (see below), including the Hydrosol system, currently the largest solar thermochemical process for hydrogen production via water splitting.

Figure 4: DLR high-flux solar simulator (left) and solar furnace (right) test facilities in Cologne (source: DLR).

Figure 5: Solar tower (left) and Synlight high-flux solar simulator (right) in Jülich, Germany (source: DLR).

Helmholtz Zentrum Berlin

The Institute of Solar Fuels at HZB focuses on photo-electrochemical routes to split water. Work involves development of thin film and nanostructured semiconductors and catalysts and investigation of fundamental processes of charge generation, separation and transfer.

Helmholtz Centre for Environmental Research UFZ

The Department of Solar Materials at UFZ takes a multi-disciplinary approach, combining its expertise in biology/biotechnology, microbial physiology, biochemistry and biochemical engineering to explore the potential of the bio-artificial photosynthesis route to hydrogen production. This path is still at an early stage of development.

6.5. Israel

Focus in Israel is on fuel alternatives for transportation, especially using fuel cells. There are fuel cell research groups in at least seven universities throughout the country; these groups often collaborate on their work. During the last decade many fuel cell related papers were published by these groups.

In addition, there are several highly advanced industrial fuel cell enterprises conducting R&D and demonstration programs. These programs span a broad range of applications including stationary and automotive, as well as technologies such as SOFC and alkaline fuel cells and fuels such as methanol, hydrogen, etc.

The Israeli government established the TEPS group (Transportation Electric Power Solutions) in 2011 as a collaboration between industry, academia and government that promotes advanced fuel cell technologies and solutions. The government invests in and encourages private companies at various stages; supports national infrastructure; and supports international cooperation and collaboration. In 2016, the total of governmental support to these programs was about $10M.

6.6. Japan

Overview

The Japanese Agency for Natural Resources and Energy, METI released a strategic roadmap for Hydrogen and Fuel Cells which has the following targets:[22]

- Price targets for household PEFCs (polymer electrolyte fuel cells): 800 thousand yen by 2019 SOFC (solid oxide fuel cells): one million yen by 2021
- Targets for dissemination of fuel cell vehicles: About 40 thousand vehicles by 2020, about 200 thousand vehicles by 2025, and about 800 thousand vehicles by 2030, in total
- Targets for the dissemination of domestic fuel cells: 5.3 million by 2030
- Targets for the construction of hydrogen stations: About 160 stations by 2020 and about 320 stations by 2025
- Descriptions concerning hydrogen power generation
- Procurement and utilization of hydrogen generated using renewable energy by 2040

Projects include:

- Development of hydrogen utilization technologies 4.15 billion Yen in 2016 – equipment and reliability
- Development of H_2 gas turbine and supply chain 2.6 billion Yen in 2016 – 2 demonstration projects for making hydrogen with liquefied hydrogen of organic chemical hydride. 2 demonstration projects for hydrogen gas turbine and power generation for industrial use
- Development of power to gas 1.75 billion Yen in 2016 – demonstration of hydrogen produced from wind via alkaline electrolysis
- Development of fuel cell 3.7 billion Yen in 2016 – – new material structures and analysis
- Formation of “Japan H2 Mobility, LLC” (JHyM) in 2018 by Toyota, Nissan and Honda and 8 major industry companies, with the goal to build a hydrogen fuel station network across Japan, aiming at 80 stations by 2021 and further growing afterwards

Many universities in Japan, e.g. Tokyo University and Tokyo Institute of Technology, conduct hydrogen-related R&D, incl. electrolysis and fuel cells.

[22] http://www.meti.go.jp/english/press/2017/1226_003.html (last accessed 2018-11-12).

University of Niigata

An example of hydrogen-related R&D is University of Niigata´s team of researchers dedicated to solar thermochemical hydrogen production, with specialisation on materials development. The team is running experiments with a hydrogen production process in a ~100 kW solar tower facility at Miyazaki.

National Institute of Advanced Industrial Science and Technology (AIST)

The hydrogen energy carrier team at AIST at the Fukushima Renewable Energy Institute is developing and testing a combined heat and power system based on hydrogen as the fuel. The system uses a catalytic hydrogenation/dehydrogenation reaction system to store hydrogen by bonding it with toluene to form methylcyclohexane (MCH). Hydrogen is converted to power and heat in an internal combustion engine. The team has also undertaken encouraging tests of co-firing a gas turbine with methane-ammonia blends with up to 100% ammonia.

In addition, a separate team is testing components and a system aimed to balance the power grid as more and more variable renewable energy is introduced. The system involves hydrogen for energy storage, which is produced via electrolysis and stored in metal hydrides, as well as hydrogen separation membranes.

National Institute of Materials Science (NIMS)

At NIMS, the Global Research Center for Environment and Energy (GREEN) aims to apply nanotechnology in materials research to resolve environmental and energy related problems in collaboration with industries. The GREEN centre has a partnership with Flinders University via a MOA (see also section 4.2).

6.7. The Netherlands

The Netherlands’ Energy Agenda published in December 2016 includes references to hydrogen in relation to: fuel for transport and mobility; sustainable chemical industry (power-to-chemicals and high-grade process heat); large-scale/seasonal storage of renewable energy; and use of renewable gas.

In 2017 a hydrogen innovation program started called the Part Top Consortium Knowledge and Innovation on Gas (TKI Gas) with an initial budget of 0.9 M€ and a program for support of deployment of alternative fuels infrastructure 15-20 M€ (for all fuels). This is scheduled as a multi-year program.

The Netherlands has launched a national R&D project called ELECTRE, which focuses on lowering electrolyser costs (Hydron Energy, ECN). Specifically, the project seeks to determine critical electrolyser components via long-term testing and to extend electrolyser life via component improvement.

Currently, there are various national demonstration projects ongoing in the Netherlands (Groningen, Eindhoven and Arnhem). The FCH-JU bus project 3EMotion features 2 buses (of a total of six) in Rotterdam in 2017. The 'Interreg project Waterstofregio 2.0' focuses on development and demonstration of a 40 ton truck and deployment of 2 more garbage trucks. The FCH JU project H2FUTURE is currently testing 6MW PEM electrolysers. This includes deployment of a Siemens electrolyser at steel plant Voestalpine in Linz, Austria and ECN involvement in performance analysis and impact assessments.

6.8. New Zealand

Hydrogen R&D research programs in New Zealand include Unitec Institute of Technology, developing the UniQuad fuel cell farm bike. It has a Li-FeYPO4 12 kWh battery; 3 kW PEM fuel cell and 1 kg H_2 700 bar(g) fuel tank. Callaghan Innovation has commercialized HyLink^{TM}, a local hydrogen generation and storage system. This 5.5 kW_e alkaline electrolyser stores up to 80 MJ (HHV hydrogen at 3.5 bar g) underground. The hydrogen in used for heating and for a range of cooking appliances (www.hylink.nz).

6.9. Norway

Hydrogen R&D activities are covered under the ENERGIX program which has an annual budget of approximately US$52 million. Electrolysis is the main topic under Hydrogen; the Norwegian company New NEL Hydrogen is a world leading company in this field. There are also world-class R&D groups within fuel cells and electrolysis fields in Norway.

One project of special interest is a collaboration between SINTEF and companies from Japan and other countries. They are studying the possibility of producing hydrogen from wind energy and reformation of natural gas to produce reformation (which produces liquefied hydrogen) which is then transported in large LNG-type vessels to Japan or southern Europe.

6.10. South Korea

Overview

In December 2015, the South Korean government established a plan for Fuel Cell Electric Vehicles (FCEV) and Hydrogen Refueling Stations (HRS). The plan focuses on R&D, HRS, regulation, incentives and propagation, and has set the target of 10% FCEV in the market by 2030.

In August 2016, departments of the federal government, local governments and related manufacturers launched the "Hydrogen Alliance" or "H2Korea" to promote the hydrogen industry. This network will organize the working group leading the hydrogen industry. H2Korea members come from: three Departments of the South Korean government, 3 local governments, FCEV and parts manufacturers, hydrogen manufacturers and suppliers, HRS installers, public companies and Academies. Implementing and working groups were organized in February 2017.

In 2016, $34.66 million has been invested by the government: $7.77 million to hydrogen and $26.89 million to fuel cell technology. Projects include development of high pressure PEM electrolysis stack for economic hydrogen production

In February 2018, the international hydrogen energy forum was held in Seoul, South Korea, bringing together top representatives from the South Korean National Assembly with international executives from leading international oil & gas, energy, science & technology and automotive companies to discuss how to accelerate the deployment of hydrogen technologies in the region. The South Korean government announced to reduce overall CO_2 output by 37% by 2030 compared to business as usual and aims to build 310 hydrogen fueling stations by 2022.

Korean Institute of Energy Research

A major R&D institution in South Korea is the Korean Institute of Energy Research (KIER), working on sustainable ammonia synthesis from N_2 and H_2O in a molten salt electrolytic cell. KIER has previously road-tested a dual fuel passenger car that ran on a mixture of 70% ammonia and 30% gasoline.

6.11. Spain

Overview

The Spanish Strategy for Science, Technology and Innovation Program of 2013-2016 covers “Hydrogen and fuel cells” R&D initiatives as a priority topic.

The RENOVAGAS project (P2G) (2014-2016) is based on the technology of “power to gas”. This project has developed and operated a 15 kW (2 Nm^3/h) SNG plant from biogas and methanation with hydrogen produced from renewable energies. ENAGAS is the project lead; other participants include Abengoa Hidrógeno, Gan Natural Fenosa, FCC AQUALIA, TECNALIA, ICP-CSIC and CNH2. MINECO, the Spanish Economy Ministry, has funded this project. The results have proven the technical and economic viability of the “power to methane” systems. The gas produced can be injected directly into the NG network as it complies with the quality gas Spanish standards. In addition, analysis of bigger plants (scaled up to 250 kW_e) has was undertaken to inform future actions.

The AURORA project aims to develop a renewable energy mobile power system (FV+Wind+H_2 and FCs) that can be used in remote construction sites. AURORA is financed by the National Industrial Technology Development Centre (CDTI) and via a public-private partnership between Kemtecnia, Ariema Enexia, and Sacyr Construcción.

The ENHIGMA project (2016-2019) is focused on PEM electolyzer cells optimization. Funding is provided by National fundings (MINECO) and a public-private partnership between: Adix Ingeniería, Hidrógena, ITECAM, Asociación de la Industria Navarra, FLUBETECH, and CNH2.

The PLUS H2-BOAT (2016-2017) project focuses on using FC system to power a conventional ICE boat. Partners include Catalonya University and OTEM2000.

The SHIPS4BLUE (2017-2018) project analyzes the feasibility of an innovative wind-powered system, which uses wind sail technology to produce energy. Funding was provided on a regional level by the Cantabria Government and by SODERCAN S.A. Public-private partnership between: Calvo Construcciones, Montaje S.L., Bound4Blue S.L., FIHAC, and CNH2.

Plataforma Solar de Almeria

Spain has had a strong focus in R&D and industry on concentrated solar energy. The Plataforma Solar de Almeria in the south east of Spain is the world´s largest research and test centre for concentrated solar energy technologies. It has hosted many pilot-scale tests of solar hydrogen production processes. The platform is run by CIEMAT, with strong involvement by the DLR solar energy research team. The platform features solar tower, solar dish and solar furnace facilities to operate high-concentration solar thermochemical processes for hydrogen production.

6.12. Sweden

In Sweden, hydrogen actions are eligible for funding under Climate Step and the Swedish funding mechanism for pilot and demonstration projects.

The Strategic Vehicle Research and Innovation Program——Fordonstrategisk Forskning och Innovation (FFI)—is a competence centre, i.e., the result of the Swedish government's collaboration with the automotive industry and universities. This R&D program researches fuel cells and Fuel Cell Electric Vehicles (FCEVs).

The Swedish Energy Agency is financing a research project on fuel flexible gas turbines at Lund University. Hydrogen incorporation into flames under gas turbine conditions investigates co-combustion of hydrogen and simple hydrocarbons.

LKAB, SSAB and Vattenfall are aiming to develop fossil-free steel production, by substituting renewable hydrogen for fossil fuels, mostly coal, for reduction or iron ore, in the 'Hybrit' joint venture.

6.13. Switzerland

Overview

The main research institutions in the area of hydrogen are the Swiss Federal Institutes of Technology in Lausanne (www.epfl.ch), the Paul Scherrer Institute (www.psi.ch), the Swiss Materials Science & Technology Center (www.empa.ch), as well as Cantonal Universities (Geneva, Basel) and Universities of Applied Sciences (Fribourg, Winterthur, Bern).

Swiss Competence Center for Energy Research

Within the Swiss Competence Center for Energy Research (SCCER), Heat & Electricity Storage,[23] one of the focus topics is related to energy storage in chemicals, e.g., hydrogen, formic acid, methanol or syngas (CO/H_2 mixtures). The latter products can be produced using both catalytic and electrocatalytic (co-electrolysis of CO_2 and water) pathways. An economic analysis within the SCCER showed that specifically formic acid and electrochemically formed syngas (H_2, CO mixture) are products of choice using the co-electrolysis process. Recently, a novel co-electrolysis cell design was demonstrated by researchers from PSI's Electrochemistry Laboratory. This novel polymer membrane based cell design is directly fed by a humidified CO_2 gas stream, overcoming any solubility issues present so far. Based on this cell design, it is now possible to scale-up the co-electrolysis process and to demonstrate the economic viability of electrochemical transformation of CO_2 into chemical feedstock.

ETH Zurich and EPF Lausanne

Within ETH Zurich, the Professorship of Renewable Energy Carriers has been conducting R&D on solar thermochemical processes for over 20 years, particularly for hydrogen production via water splitting and conversion of carbon and hydrogen-rich feedstocks (biomass, coal, petcoke, methane, etc.) into syngas (hydrogen + CO) using concentrated solar energy. In 2015, a team including ETH Zurich, German Aerospace Center (DLR), fuels company Shell, German think-tank Bauhaus Luftfahrt, and consulting firm Arttic demonstrated the complete production path of converting water and CO_2 to jet fuel using concentrated solar energy. Facilities include two high-flux solar simulators and an outdoor solar dish test setup.

A team at the Institute for Dynamic Systems and Control, led by Professor Lino Guzzella, set the world record for fuel efficiency with a hydrogen-fuelled car (PAC-Car II) powered by fuel cells in 2005, reaching an equivalent mileage of 5385 km per litre of gasoline.[24]

Other research groups at ETH working on hydrogen related topics include:

- Professor H.G. Park: nanoscience with applications for H_2 storage, fuel cells, and solar energy conversion.
- Professor Dr. Jeroen Anton van Bokhoven: catalysts for water splitting.

[23] http://www.sccer-hae.ch
[24] http://www.paccar.ethz.ch/

- Professor C. Müller, Laboratory of Energy Science and Engineering: generation of ultra-pure hydrogen; heterogeneous catalysis.

At EPFL, the Laboratory of Renewable Energy Science and Engineering works on different hydrogen production processes, including thermochemical and photo-electrochemical routes. Research encompasses novel photoelectrodes, solar-driven electrolysis, and high-temperature electrolysis. A focus area of the lab are computational methods for material and process modelling and optimisation.

Facilities include a 15 kW (radiation) high-flux solar simulator (the same facility exists at the Australian National University) with peak concentration of over 20,000 suns, capable of reaching temperatures of over 2500°C, as well as an LED solar simulator (1 sun) with custom made photoelectrochemical test cell, potentiostat, and gas chromatography.

Figure 6: High-flux solar simulator test facility(left), LED 1 sun-simulator (right) at EPFL (source: https://lrese.epfl.ch).

Example case: Hybrid plant Aarmatt

The hybrid plant Aarmatt in Switzerland serves as an example of a demonstration plant for hydrogen-based energy storage and conversion. Built at the interconnection of the state's four grids for water, natural gas, electricity and district heating (Figure 7), the plant accesses the water network to produce hydrogen via a 350 kW PEM electrolyser producing 60 Nm^3/h of hydrogen using surplus energy from the electricity grid during high renewable energy generation. The produced hydrogen is stored in a custom-made buffer tank for controlled injection into the natural gas network. The plant further accesses the gas network in order to generate combined heat and power (1.2 MW$_e$ + 1.2 MW$_{th}$) via a 12-cylinder gas engine, complemented by a gas boiler to cover peak heat demand. The generated power and heat are introduced into the electricity and district heating networks, respectively. To overcome the current regulation of a concentration limit of 2% for hydrogen in the natural gas network, a methanation reactor will be added, which will convert hydrogen and CO_2 from a nearby water treatment plant to methane for injection into the natural gas network.

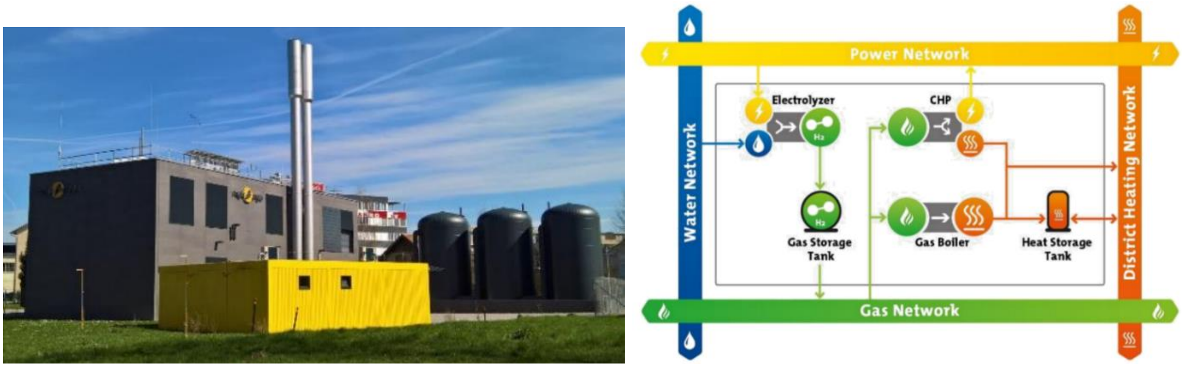

Figure 7: External view (left) and schematic layout (right) of the hybrid plant Aarmatt (source: http://www.ieabioenergy.com).

6.14. UK

In the UK, hydrogen is considered in the three major energy sectors, Electricity, Transport and Heat.

The Hydrogen Appliances Study considered replacing natural gas with hydrogen [20]. To do this, it would be necessary to develop appliances, such as boilers, hobs, ovens and industrial burners that can use 100% hydrogen instead of natural gas or methane. The aim of this study was to investigate the technical challenges and costs associated with developing such appliances and to discuss how these barriers might be addressed. It covers safety issues, training and standards (both product and installation standards), costs and timescales for the development of different hydrogen appliances for small numbers of prototype appliances (around 1,000), as well as costs and timescales for the development of appliances for large scale roll-out (around 100,000 per year).

Regarding Hydrogen and Fuel Cells, *Opportunities for Growth – A Roadmap for the UK* [21] is a new roadmap that provides an industrial strategy for hydrogen and fuel cells to play a greater role in the UK's energy mix. In developing the roadmap, E4tech and Element Energy conducted detailed analysis and a series of workshops and bilateral discussions with stakeholders. This allowed to produce 'mini-roadmaps' addressing 11 sectors in detail and to bring together the most important aspects into an overarching document with four themes.

The Hydrogen and Fuel Cell Research Hub (H2FC SUPERGEN)[25] consists of a multi-disciplinary team of academics. The core research areas are Policy, Research synthesis, Hydrogen and Fuel Cell systems, Hydrogen and Fuel Cells Safety, Education and Training, Hydrogen Storage, Polymer Electrolyte Fuel Cells, Solid Oxide Fuel Cells and Electrolysers. The Hub brings together top academics and key experts in industry ensuring that Hydrogen and Fuel Cell research can effectively scale up to support wealth and job creation. Research highlights include:

- Invention of infiltrated nanocatalysts for energy and environmental applications
- Invention of a new safety technology of explosion-free tanks & developing international safety standards
- Development of a new catalyst for oxygen reduction
- A new method of testing electrocatalysts for PEFCs
- Development of new techniques to analyse PEFCs
- Development of materials for lower cost & lower CO_2 hydrogen production

[25] http://www.h2fcsupergen.com

6.15. USA

Overview

Progress in DOE-funded research in 2016 includes the following projects.

The DOE “Hydrogen at Scale” (H2@Scale) concept, coordinated by the Fuel Cell Technologies Office,[26] was introduced in 2015 to address the potential of hydrogen production to enable resiliency of the power generation and transmission sectors, while simultaneously serving multiple domestic industries and reducing U.S. emissions. Preliminary analysis performed by the national laboratories on the H2@Scale concept indicated that wide-scale use of electrolytic hydrogen could reduce U.S. petroleum consumption by about 1.2 billion barrels per year. An in-depth analysis is now underway to project future price points of electrolytic hydrogen, and thereby more accurately estimate future demand and value proposition.

The Hydrogen Station Equipment Performance (HyStEP) testing device was developed to validate operation of new hydrogen stations. The open-source designs, developed by Sandia National Laboratories and the National Renewable Energy Laboratory, can be used to accelerate hydrogen fueling station deployment.

Researchers at UCLA and Caltech demonstrated that altering nanoscale wires from a smooth surface to a jagged could dramatically reduce the amount of precious metal used as fuel cell catalysts.

Research at Sandia National Laboratories led to a patented polyphenyline membrane for PEM fuel cells that operates over a wide temperature range and lasts three times longer than comparable commercial products.

Researchers at Stanford University developed solar cells that, after electrolysis, capture and store 30 percent of the energy from sunlight into stored hydrogen.

National Renewable Energy Laboratory

NREL conducts a comprehensive range of hydrogen-related development, integration and demonstration activities, covering the areas of hydrogen production, delivery, storage, as well as fuel cell technologies for both stationary and mobile applications. Production methods include biomass fermentation, photobiological and photoelectrochemical water splitting and renewable electrolysis (with electricity from solar, wind, etc.). NREL has been involved in the on-road testing of hydrogen fuel cell vehicles, such as buses (Figure 8), cars and forklifts.

In addition to fundamental research, technology and system development and validation, NREL engages in safety, codes and standards developments for hydrogen-related equipment and applications in buildings. Projects also cover manufacturing processes for high-volume

[26] https://www.energy.gov/eere/fuelcells/fuel-cell-technologies-office (last accessed 2018-11-13).

production, as well as system and market analyses to draw different commercialisation scenarios and promote market deployment.

NREL fosters collaborations with industry to better understand the practical challenges to improve their products. It also collaborates with other competence centres nationally and internationally, such as the European Commission's Joint Research Centre (JRC) Institute of Energy and Transport, on hydrogen-related technologies, such as gas sensors, and offers technical support in the development of international codes and standards.

Figure 8: Hydrogen fuel cell electric bus tested by AC Transit in California in collaboration with NREL (source: NREL).

Sandia National Laboratories

Sandia NL have had a pioneering role in R&D of solar thermochemical fuels processes (including water splitting). In the field of solar fuels, the teams at the Livermore, CA and Albuquerque, NM campuses work on new perovskite redox materials to operate water splitting cycles at lower temperatures and higher efficiencies. The team at Albuquerque has also developed and tested solar reactor prototypes. The centre in Albuquerque, NM, features a solar tower, a solar furnace and a small indoor high-flux solar simulator, as well as solar dish research facilities.

California Institute of Technology

Caltech has had long-standing expertise in the area of solid-state ionics with applications as electrolyte materials in fuel cells, batteries and other electrochemical devices (Professor Sossina Haile, now Northwestern University). Another group, led by Professor Nathan Lewis, specialises in solar fuels production via artificial photosynthesis. This work in now coordinated at the Joint Center for Artificial Photosynthesis (JCAP). In addition, the group led by Professor Harry Gray, conducts research in the area of inorganic catalysts for electrocatalytic water splitting.

Lawrence Berkeley National Laboratory

The Energy Storage and Distributed Resources Division within the Energy Technologies Area at Berkeley Lab[27] involves four focus areas that all relate to hydrogen. These areas are:

Toward Carbon-Free Transportation Technologies, focussing on technologies that enable the transition from fossil to renewable fuels, including fuel (incl. hydrogen) generation, fuel cells, and batteries.

Grid Tools to Allow Renewables Penetration, focussing the challenges associated with the developing electricity grid and the increasing coupling of transport with the grid and provides tools to enable demand response.

Discovery Tools to Enable the Future, aiming at developing tools to support smart technology developments, such as new material developments.

From Lab to Market, fostering collaboration with industry nationally and internationally on the development of new technologies such as fuel cells and batteries, and supporting commercialisation efforts.

University of Minnesota

Solar fuels related research is undertaken at the Universities of Minnesota in Twin Cities and Duluth by Professor Jane Davidson and team and by Professor Nesrin Ozalp, respectively. Research encompasses new materials fabrication and testing, process and heat and mass transport modelling and analysis, as well as reactor engineering and characterisation for water splitting and biomass conversion processes. Professor Ozalp additionally serves as Associate Professor for Mechanical Engineering at KU Leuven in Belgium.

[27] https://esdr.lbl.gov/

7. CAPABILITY/CAPACITY MAPPING AND OPPORTUNITIES

This section provides analysis of research capability strengths in South Australia, as well as nationally and globally and discusses some potential collaborations which could be promoted between South Australia and the rest of the country and the world. Further, South Australian hydrogen product developments are reviewed and some ideas of commercial R&D pathways are provided. Finally, future R&D funding opportunities are also discussed.

7.1. Mapping of R&D Capabilities

Figure 9 provides a non-exhaustive map of hydrogen-related R&D capabilities in South Australia, Australia and worldwide.

South Australia is well positioned to play a significant role in the area of hydrogen-related energy technologies, both as an innovative hub for hydrogen-related technology developments and as a national and global hydrogen production, usage and export centre.

South Australia´s three major universities all have capabilities relevant to hydrogen. The University of Adelaide has the broadest range of capabilities of the three South Australian universities. The university has expertise on various hydrogen production processes, including solar thermochemical, electrolytical and photocatalytic water splitting, as well as biomass and hydrocarbon conversion. It further has expertise with hydrogen storage in chemical form (e.g. ammonia, hydrocarbons), energy conversion via fuel cells and combustion, renewable energy integration in industrial processes and system analysis capabilities. Hence, the university appears to be well positioned to play a leading role in hydrogen-related R&D projects, both locally and globally.

Flinders University´s capabilities are primarily centred around nanotechnology applied to enhanced electrodes for electrolysis and fuel cells and new membranes for electrolysis cells. The university has broad analysis facilities for material characterisation that may be leveraged for new material developments. The university also has expertise in photo- and thermochemical water splitting. The Australian Industrial Transformation Institute led by Professor John Spoehr is focused on helping companies adapt to the changing times and has a particular focus on implementation of next generation industries, which is highly appropriate for the hydrogen economy.

University of South Australia´s capabilities related to hydrogen R&D appear to be more limited and mainly include a renewable energy technology testing facility (see section 2.3) and expertise in systems analysis and integration.

South Australia appears to have little ongoing research in the area of physical hydrogen storage and distribution, which are covered by Griffith University.

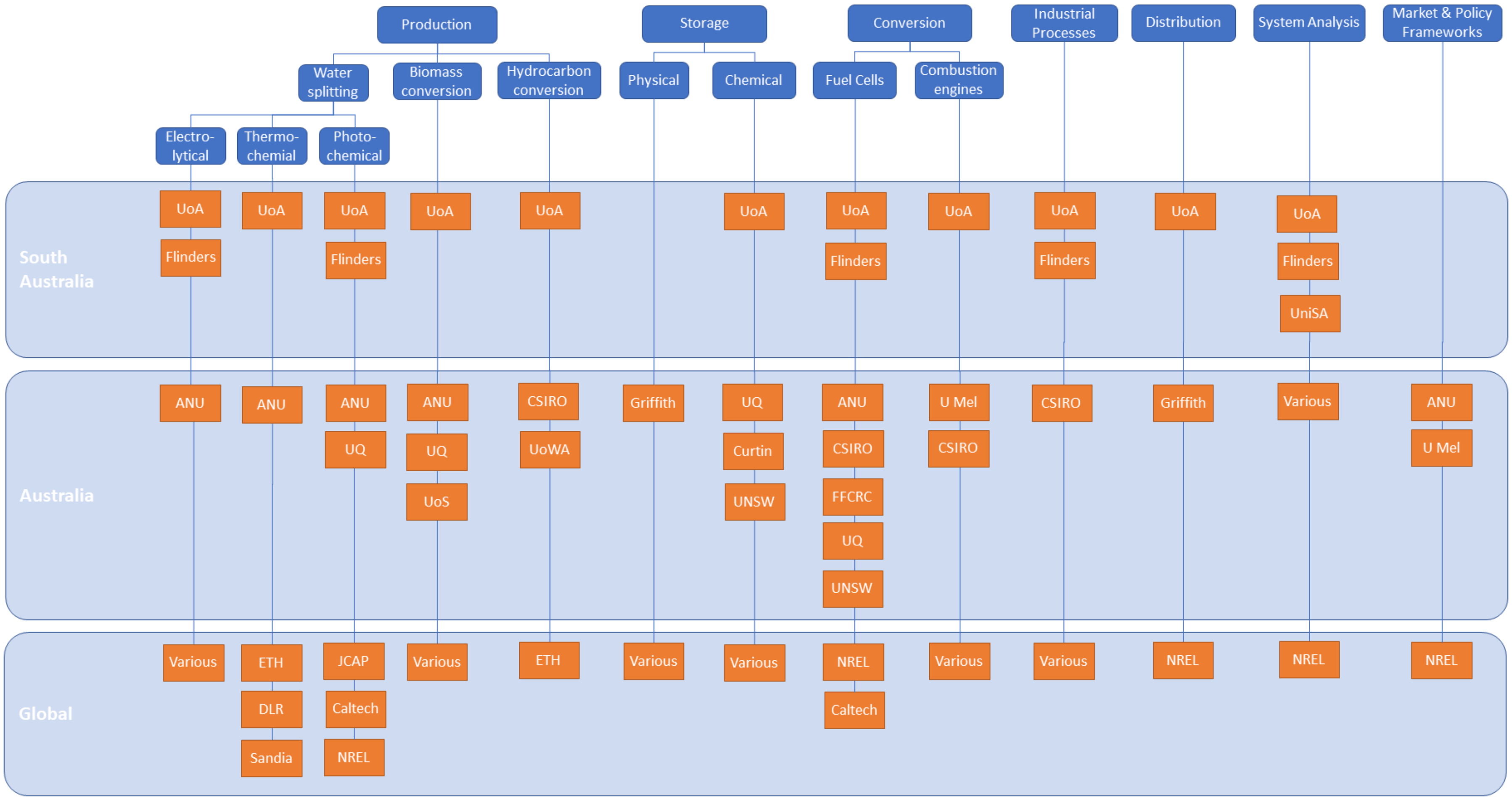

Figure 9. Mapping of hydrogen-related R&D capabilities in SA, Australia and worldwide.

There appears to be little experience with hydrogen-specific distribution technologies and hydrogen system analysis in South Australia and nation-wide.

No competence centre for the areas of hydrogen markets and policies has been identified in South Australia. In these areas, the University of Melbourne and ANU appear to have broad capabilities and South Australia may be well advised to draw on these resources.

Nationally, several of the major Australian universities have expertise with hydrogen-related technologies and, as such, may offer opportunities to partner with South Australian universities to conduct complementary research and to leverage knowledge and facilities.

The National Renewable Energy Laboratory in Colorado, USA, is one of the largest and broadest centres for hydrogen R&D globally. It offers expertise on different production methods, as well as on storage, infrastructure and hydrogen vehicles. It includes safety, codes and standards as one of its research areas, which may be a topic to collaborate with for South Australian government and researchers.

Other international centres for hydrogen-related research are found in the US, Germany, France, Switzerland, Japan, South Korea and other countries. These institutes and labs may offer complementary knowledge for South Australian research projects and may be suitable as partners.

It is important to keep track of international developments. In view of the potential large size of a hydrogen economy and the existence of competence centres around the world, it is important to carefully select and define the niche that SA is to play in this global industry.

The IEA hydrogen program is a very efficient way of doing this, as well as the SolarPACES and Bionergy programs and others. The various programs have different membership and representative structures. SA researchers already have a presence. A greater involvement in more tasks would be a very cost effective approach to increasing the engagement with international developments.

7.2. Research Institution Collaborations

In view of the relatively small South Australian economy, a concerted effort is recommended, in which universities and companies work hand-in-hand to create innovation and pioneering projects. Past consortium approaches by South Australian universities for funding applications provide a good example. At the national level, the Future Fuels Cooperative Research Centre aims to fulfil this purpose.

ANU appears to have in-depth expertise with the fundamental science of hydrogen production and storage methods. These teams may be considered as partners in novel technology development projects. On market-related topics, the ANU appears to offer a broad range of experts on Energy and Security, Energy Economics and Policy, and Energy Regulation and

Governance. The ANU Energy Change Institute may be a good first point of contact to coordinate with and explore possible collaborations.

Internationally, the National Renewable Energy Laboratory stands out as a high-profile research institute for hydrogen related research. The NREL appears to have broad research competences with regard to hydrogen and appears to be open to share its knowledge and facilities and collaborate with international partners.

In addition, the IEA HIA (http://ieahydrogen.org/) is one of the most long-standing and authoritative resources regarding hydrogen-related knowledge, technology and market-related topics, which should be consulted for background information in any hydrogen-related R&D project.

In order to benefit from existing knowledge and experience with hydrogen technologies and avoid “reinventing the wheel”, infrastructure and facilities overseas should be considered and visited. Much can be learned from previous projects, to fast track the development in South Australia and avoid unnecessary mistakes. The hybrid plant Aarmatt in Switzerland may be one example for a reference plant. It has been built with the intention of serving for educational purposes and could be a useful source of technical information and practical know-how.

7.3. Commercial R&D Pathways

The planned first small government transportation fleet powered by hydrogen appears to be an important step as a validation and demonstration project, as a first step towards building a domestic hydrogen value chain, to gain first-hand experience dealing with hydrogen, to acquaint society with this new form of energy supply and gain broad acceptance, and as a showcase for the technology and for South Australia as a global technology pioneer. It also offers an opportunity to learn about the challenges and limitations of current state-of-the-art hydrogen technologies and may provide insights about how the hydrogen value chain may be improved through innovation.

Other countries and states like California, Germany and South Korea already have hydrogen fuel infrastructure in place that may serve as references, for example the Toyota Tri-Gen facility in Port of Long Beach, Los Angeles. But also here in Australia, for example at Hyundai´s HQ in Sydney and in the ACT, hydrogen fuel stations have been operated or will be deployed soon.

The scope for innovation is not limited to the primary technologies required for the production and distribution of hydrogen and hydrogen derivatives, but may also include enabling technologies, such as smart metering and safety monitoring systems, or new and improved hydrogen-related service offerings, as well as IP and know-how related to the design, construction and operation of hydrogen infrastructure.

7.4. Current and Prospective R&D Funding Opportunities

There are a range of options to source funding for hydrogen R&D efforts.

ARENA

At the national level, the Federal Government is the main source of hydrogen R&D funding through ARENA. ARENA's ability to commit funding from its current allocation ceases in 2022. Due to time taken to contract projects it is expected that the remaining rounds will be announced before 2020. ARENA supports R&D through competitive time limited rounds. While there are no funding rounds currently open, there is growing national and international interest developing in global renewable hydrogen supply chains. As electricity systems achieve higher levels of renewable energy penetration, the possibility of energy commodity trade is a logical progression in the economic agendas of State Governments.

Exporting renewable energy is an ARENA investment priority. In 2017, ARENA consulted with industry and researchers on where it should direct funding to boost the chances of building a renewable exports industry. In late 2017, ARENA opened a funding round for R&D into potential export supply chains for hydrogen and carrier materials. Full applications closed in May 2018 and the round was well subscribed. In September 2018, ARENA announced the award of $22.1 million to 16 research projects.

In July 2018, ARENA announced $1.5 million to ATCO to trial the production, storage and use of renewable hydrogen in a microgrid at Jandakot, Western Australia. In September 2018, ARENA announced $7.5 million to Jemena for a demonstration of hydrogen production and injection into gas networks in Sydney.

ARC

The Australian Research Council is open to hydrogen-related research. The ARC Linkage program promotes national and international collaborations among research institutions and industry in research and innovation. The ARC Discovery program aims to enhance excellent basic and applied research by individuals and teams. It is most suitable for early TRL fundamental research. Additional grant schemes include the ARC LIEF, supporting critical large research infrastructure, equipment and facilities, the ARC DECRA for early career researchers and ARC Future Fellowships for outstanding mid-career researchers.

CEFC

The CEFC and ARENA jointly manage the Clean Energy Innovation Fund which has $200 million to support early stage and emerging clean energy technologies, including hydrogen. The focus of the Fund is on technologies which have passed the R&D stage. Thus the CEFC would not support R&D explicitly however its investment in potential projects can be leveraged in various ways.

Department of Industry, Innovation and Science

The Federal and Victorian Governments are supporting The Hydrogen Energy Supply Chain,[28] a trial of hydrogen production in the Latrobe Valley in south-east Victoria for export to Japan. The project is led by Kawasaki Heavy Industries (KHI), working with Electric Power Development Company (J-Power), Iwatani Corporation, Marubeni Corporation and AGL. Construction is due to be completed by 2020 and the project will operate for one year.

Infrastructure developed under the project may provide future opportunities for renewable based hydrogen projects.

Other State Governments

In May 2018, the Queensland Government announced it would be undertaking a $750,000 study into the potential to produce and supply renewable hydrogen in Queensland.[29] This is a significant study that may lead to R&D activity in Queensland. South Australian researchers could seek out opportunities to partner on projects where capabilities are complementary.

[28] https://archive.industry.gov.au/resource/LowEmissionsFossilFuelTech/Pages/Hydrogen-Energy-Supply-Chain-Pilot-Project.aspx (last accessed 2018-11-13).
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8. CONCLUSIONS AND RECOMMENDATIONS

South Australia has taken the initiative to be the first mover in Australia in engaging with the renewed global interest in hydrogen. If the use of hydrogen as an energy vector grows as expected, it will become a massive global industry. R&D efforts will grow in parallel and target all aspects. Ultimately all states and countries would be expected to be involved at some level in such trends.

South Australia does have, through its existing activities, world class capabilities and projects in this area that can serve as a foundation for further growth and securing an important and valuable share of activity for the state.

Outstanding hydrogen-related R&D capabilities and activities at the three South Australian universities include:

University of Adelaide:

- Conversion of biomass and hydrocarbon sources to hydrogen
- Renewable energy (including hydrogen) integration into industrial processes
- Nanomaterials for photo- and electro-catalysts for water splitting and fuel cells
- Chemical processes for synthesis of energy carriers and gas separation
- Combustion of new fuels
- Hydrogen injection into the natural gas network

Flinders University:

- Polymer materials for fuel cells, electrolysers and batteries
- Nanomaterials and surface science for electrodes
- Comprehensive material analysis facilities and equipment
- Technology commercialisation

University of South Australia:

- System integration, analysis and engineering
- Mawson Lakes campus hydrogen-based renewable energy storage testing facility

Collaborative approaches could put South Australia into the position to become a significant contributor in the future global hydrogen economy.

In addition, the South Australian Government is currently funding four pioneering demonstration projects:

- The Hydrogen Park SA, Tonsley, aiming to demonstrate production of hydrogen and injection into the natural gas network
- A feasibility study of a large-scale 50 MW renewable hydrogen production facility at the proposed Crystal Brook Energy Park, conducted by Neoen
- A new hydrogen-based energy storage facility at UniSA, Mawson Lakes, to build technology know-how, confidence and relationships with suppliers
- Feasibility study of a 15 MW hydrogen electrolyser plant combined with power and ammonia production at Port Lincoln, by H2U.

These projects are at a comparable level with current international developments and are important steps for South Australia to become a significant player in the hydrogen economy.

The R&D capabilities in South Australia may be further enhanced and leveraged by targeting research collaborations nationally and internationally. At the national level, CSIRO combines a long track record related to hydrogen technologies, and could be a strong partner, for example for new hydrogen production methods (see section 5.1), ammonia dissociation and fuel cell technology. Internationally, NREL stands out with a long history of hydrogen related research and a broad range of activities, including several hydrogen production methods, storage, distribution and policies. In particular, NREL appears to be a leader in the US and internationally on hydrogen-related standards, codes, and regulations. Hence, early partnerships with these organisations could accelerate activities for South Australia.

The International Energy Agency via its Hydrogen as well as Bioenergy and SolarPACES programs is a very effective forum for South Australia to stay up to date and engage with global efforts. The state is already represented in these forums, however there is scope to grow the involvement.

Currently, hydrogen R&D in South Australia is predominantly at low TRLs up to around TRL 4.[30] This has to do with the lack of a local hydrogen industry, which tends to limit R&D efforts to rather basic research. Higher TRL commercially oriented R&D can and should be stimulated through the creation of a local hydrogen market and industry in South Australia. This would stimulate research-industry collaborations and innovation along the hydrogen value chain that, in turn, reinforces the local industry. One way of achieving this could be through the creation of local demand for hydrogen and related infrastructure by introducing a number of FC power generation systems and FCEVs. In addition, the South Australian Government could take the initiative to build and operate a first small hydrogen distribution system across the Adelaide metropolitan area. This would allow for example local transport services (e.g. taxis) to switch to FCEVs.

With regard to international research collaboration mechanisms, the long term goal of developing hydrogen exports to key trading partners such as Japan and South Korea suggests targeting

[30] TRL is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the innovation chain. TR 4 is a state of technology development of component and/or system validation in laboratory.

these countries for early partnerships in R&D also. For example a consortium could be formed involving South Australian, Japanese and South Korean research institutes as well as industry, with the aim to establish, evaluate and optimise a hydrogen-based fuel system in South Australia, including hydrogen production, distribution and use in FCEVs. This would allow for first-hand experience with hydrogen technologies and knowledge exchange and could stimulate local innovation in hydrogen-related technologies. Hydrogen Mobility Australia are aiming in this direction and the four projects listed above are significant steps towards this goal.

SA Hydrogen R&D Roadmap

The South Australian Government has plans to draft a *South Australian Hydrogen R&D Roadmap*. The following specific issues could be considered in the development of such a document:

- The potential to develop a local capability statement in hydrogen R&D. The capability statement would articulate the complementary capabilities of the universities as identified in this report. Joint approaches are already evident informally, so the capability statement would primarily be a formalisation and would assist with approaches to external funding bodies (e.g. for future R&D rounds by ARENA) and other potential project collaborators.
- Scope for local institutions to develop relationships with national institutions to bridge a gap in South Australia´s research competencies in physical hydrogen storage and distribution.
- Scope to encourage development of expertise in hydrogen-specific distribution technologies and hydrogen system analysis, hydrogen markets, policies, market deployment and commercialisation pathways. In particular, NREL as one of the largest and broadest centres for hydrogen R&D. Other international competence centres for hydrogen-related research in the US, Germany, France, Switzerland, Japan, and several other countries exist. These institutes and labs may offer complementary knowledge for South Australian research projects and may be suitable as partners.
- The potential for the South Australian Government to collaborate with universities to keep track of international developments in the hydrogen value chain. Given the potential large size of a hydrogen economy and the existence of competence centres around the world, monitoring of developments could help identify niche opportunities for South Australia in this global industry. Policy expertise is important to the development of a hydrogen economy in South Australia, and could be fostered in government and in research institutions. One stream for investigation could be to review and adopt current international standards, procedures and legislation related to hydrogen.
- For future funding programs, requiring any future hydrogen demonstration proposals to include an R&D partner in their funding bids
- Specifically involving Japan / South Korea in research collaborations

- A relatively cost-effective way of keeping up with international developments would be for South Australian researchers to actively participate in selected IEA programs, in particular the Hydrogen, Bioenergy and Concentrated Solar Power Technology Collaboration Programmes. This would provide access and involvement in the latest hydrogen-related R&D topics and increased international exposure.
- Supporting international researcher exchanges to foster transfer of country expertise. Again, a relatively inexpensive initiative would be to support South Australian researchers to travel and spend time at world-leading research institutes overseas, to give them access and exposure to the latest developments in the world and an opportunity to form connections for potential collaborations.
- To build confidence in building a domestic hydrogen value chain, in addition to supporting small demonstration projects in the production and distribution of hydrogen and hydrogen derivatives, support could be targeted at enabling technologies, such as safety monitoring and detection systems, new and improved hydrogen-related service offerings, or IP related to the design, construction and operation of hydrogen-related infrastructure.

Going beyond the R&D agenda, to further advance the South Australian strategy towards becoming a centre for hydrogen, an updated and refined *South Australian Hydrogen Roadmap* could be initiated by the government, that assesses and prioritises different options such as target market (e.g. grid support, natural gas network, fertiliser industry, export, etc.), preferred hydrogen storage solution (e.g. liquid hydrogen, ammonia, methylcyclohexane, etc.), the design layout of a hydrogen infrastructure in South Australia, etc. Different scenarios could be developed and assessed in terms of their economic benefits and technical feasibility.

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