The Story of RayGen

Part I – Commercial Assessment Report

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For further detail, email enquiries@raygen.com.

Executive Summary

The electricity grid of the future will have sufficient storage to shift energy from when it is produced to when it is required, and much of this storage will be over 6-8 hours. An energy grid reliant on solar and wind energy requires long-duration storage that can store energy for hours, days or weeks and be deployed cost-effectively at large scale around the world.

"Grid-scale electricity storage will be a critical element of Australia's future electricity system. Broad deployment of storage will facilitate more low-cost solar and wind electricity in the grid. Storage will also provide system security services and be a source of reliable, dispatchable electricity. It can reduce pressure on electricity prices by meeting peaks in consumer demand."

– Low Emissions Technology Statement, Australian Government

RayGen Resources Pty. Ltd. (RayGen) has developed a world-first approach that will deliver zero-carbon mid-merit and baseload generation at lowest cost. RayGen originated, designs, and develops our proprietary, patented solution, and is supported by investors that include AGL, Photon Energy, Schlumberger and Chevron. Additional due diligence has been conducted by MIT, ARENA, Aurecon and GHD.

RayGen's solar hydro delivers low-cost, on-demand electricity that can be sited flexibly and provides storage from one to hundreds of hours. Solar hydro consists of RayGen's proprietary PV Ultra – concentrating photovoltaic tower solar co-generation – and electro-thermal energy storage (ETES). The ETES technologies include water-based pit thermal energy storage (PTES), organic Rankine cycle (ORC) turbines and industrial chillers.

RayGen stores energy as a temperature difference between two water reservoirs – one heated to 90°C and one cooled to 0°C. This temperature difference of 90°C stores the equivalent energy of a Pumped Hydro system with a height difference of 1,000m. The round-trip efficiency of the electricity storage is boosted with by-product heat from solar co-generation to a class-leading efficiency of 70-80%.

RayGen's approach has several advantages that differentiate it from competitors. The water-based storage can be delivered more cheaply than batteries for applications over four hours, with near zero-marginal cost to extend duration (simply extend the pit storage and add more water). The insulated water reservoirs can be sited more easily than pumped hydro, with few requirements on local topology and no need for a vertical displacement between the reservoirs. The modest operating temperatures can be delivered more cost-effectively and with less risk than the extreme temperatures of typical ETES and concentrated solar power (CSP). The high efficiency photovoltaic solar tower is competitive on price and performance to typical PV, but with additional heat co-generated as a by-product of cooling the photovoltaic modules (and this heat is integral to the efficiency of the storage).

RayGen is building a flagship 4MW solar, 3MW/50MWh (17 hour) storage project in Carwarp, Australia. The project commenced construction in early Q2 2021 and will be commissioned in Q2 2022, delivered with 40-50% local content that includes more than 25% expenditure with contractors in the Mallee region. The world's highest efficiency and highest power solar modules are manufactured by RayGen for this project in Nunawading, Australia. The project has an executed offtake with AGL for electricity and grid services.

At AUD $320/kWh for 50MWh of storage, this first-of-kind project is competitive with recent 'big' battery projects, which are often $700-1,100/kWh per unit of storage. $2.75m/MW for 4MW of solar is high for a solar project but remains competitive with other small-scale solar projects sub-5MW, and is expected to fall below $1.20m/MW for larger-scale projects.

RayGen has ambitious plans to grow deployment and cut costs. RayGen's strategy is to become a globally significant renewable systems integrator and original equipment manufacturer (OEM), supplying our technology to large-scale renewable energy projects in Australia and around the world.

RayGen has commenced feasibility studies for larger projects, typically 200MW solar with 100MW/1,000MWh of storage.

RayGen expects a 50-70% unit cost reduction from the first-of-kind 4MW solar, 3MW/50MWh SPP1 project to these larger 200MW solar, 100MW/1,000MWh storage projects (known as Solar Power Plant Two, or SPP2).

ARENA has been critical to RayGen's success, through four previous grant programs beginning May 2012, and support for this current program. Prior grants supported RayGen to deploy PV Ultra solar towers, scale module manufacturing capacity and improve receiver performance. The $10m of grants to 2019 were leveraged with private investment better than 2:1 and have supported employment of over 30 full time employees at RayGen, with more jobs created at local construction and supply chain partners.

The Australian Government has a target of under $100 per MWh for firm electricity supply from storage available for eight hours or more. RayGen expects to meet or exceed this target from the next project (SPP2), with prices from $98 to $44 per MWh.

RayGen's technologies can play a globally significant role in the transition toward 100 per cent renewable generation. The following commercial assessment report introduces our company, our technology suite, our flagship project, and our growth plans to those who are interested in learning more about RayGen.

This report is the first in the series of 'The Story of RayGen'. The second report, 'Part II – Technical Assessment Report' provides additional detail on the RayGen system. This report has been compiled solely for information purposes to share knowledge generated in this project with the wider market only. RayGen does not make any representation or warranty as to the accuracy or completeness of the information contained in this report. RayGen shall not have any liability to the recipient or any person resulting from the use of this report.

Contents

1 Introduction

A low- or zero-carbon electricity grid must be able to shift energy from when it is generated by the sun or wind to when it is needed by consumers. Moving toward 100 per cent renewable power will require novel long-duration storage solutions that can store power cost-effectively for hours, days or weeks and be deployed at large scale around the world.

RayGen is an Australian technology company that has developed an innovative grid-scale generation and storage solution that provides affordable, on-demand, renewable electricity. RayGen's solar hydro delivers low-cost, dispatchable electricity that can be sited flexibly and provides storage from one to hundreds of hours.

Solar hydro consists of RayGen's proprietary PV Ultra, a concentrating photovoltaic solar co-generation tower, and electro-thermal storage, comprising water-based pit thermal energy storage, organic Rankine cycle turbines and industrial chillers.

RayGen's technologies will play a critical role in moving toward 100 per cent renewable generation. RayGen expects its technology will be the lowest cost dispatchable renewable solution worldwide for all storage applications greater than four hours and cost-competitive with lithium-ion batteries for one- to four-hour storage applications.

1.1 About RayGen

RayGen Resources Pty Ltd was founded in 2010 with a vision "to accelerate the global transition to renewable energy with RayGen as the technology provider of choice". The company now has 35 employees, primarily in engineering.

RayGen is the original equipment manufacturer (OEM) of PV Ultra and the system integrator of solar hydro. RayGen's strategy is to become a globally significant technology provider, supplying large-scale renewable energy projects in Australia and around the world. RayGen follows the example of global, capital-efficient OEMs such as Siemens, Vestas Wind Systems and Caterpillar. The PV Ultra module and plant control software are in-sourced by RayGen with the remainder of the system sourced through existing, at-scale suppliers. RayGen develops and manufactures its high efficiency PV Ultra modules at our 25MW manufacturing facility in Melbourne, Australia.

RayGen set the world record for solar system efficiency, of 40.4%, with the University of New South Wales in 2014.

2010	–	Company founded
2012	–	Bayswater Test Facility commissioned (capacity for one module and two heliostats)
2013	–	Commissioning of R&D module manufacturing line (8MW_{AC} p.a. capacity)
2014	–	World Record for solar system efficiency (40.4%) for ‘solar cube’, set with University of New South Wales (UNSW)
	–	Grand Prize in Global Cleantech Cluster Awards, Switzerland
2015	–	Commissioning of two PV Ultra towers; one 250kW tower in Newbridge, Victoria, Australia and 250kW in ZhuoZhou, Hebei, China
2018	–	Commissioning of two further PV Ultra systems (2x 250kW) in Newbridge, Victoria
	–	Commissioning of module manufacturing facility (25MW p.a. capacity)
	–	Secured $4.8M from the Australian Renewable Energy Agency and $2.0M from the Victorian Government New Energy Jobs Fund
2019	–	Release of RayGen’s ‘Solar Power Plant’ solar plus storage
	–	Commenced development of Solar Power Plant One (SPP1) storage project located in Carwarp, Victoria
2020	–	Secured $3.0M ARENA funding toward feasibility and development of Solar Power Plant One
	–	Secured strategic partnership with Photon Energy for development of large-scale Solar Power Plant Two, nominally 200MW solar, 100MW/1,000MWh storage
2021	–	Financial Close on 50MWh Solar Power Plant One
Q1	–	Financial Close on 100MW p.a. manufacturing line expansion
	–	Series C round closure, with multiple strategic partners

Figure 1: RayGen’s PV Ultra plant at 1477 Yorkshire Rd, Newbridge, Victoria, Australia. Pilot tower (right) built in 2015 with 0.25MW_{AC} (0.75MW_{energy}); Commercial Expansion (left and centre) built in 2018 with 0.5MW_{AC} (1.5MW_{energy}). The site remains active for local farming – a flock of sheep can be seen feeding within the field.

1.2 Solar hydro product overview

RayGen's solar hydro delivers renewable, on-demand, electricity generation and is intended for utility-scale grid-connected deployments at a similar scale to solar and wind projects. Solar hydro's power (MW) and storage (MWh) capacity is flexible and can be configured to suit a desired generation profile.

For electricity utilities, independent power producers, large industrial energy users and hydrogen exporters, RayGen's solar hydro technology offers a configurable asset than can meet a range of needs:

- Firm, mid-merit to baseload generation, offering reliable displacement of natural gas and coal with renewable power;
- Storage capacity, with the ability to time-shift other renewables and avoid congestion; and
- High power quality, with synchronous generation and fast ramp time, supporting grid security and ancillary services.

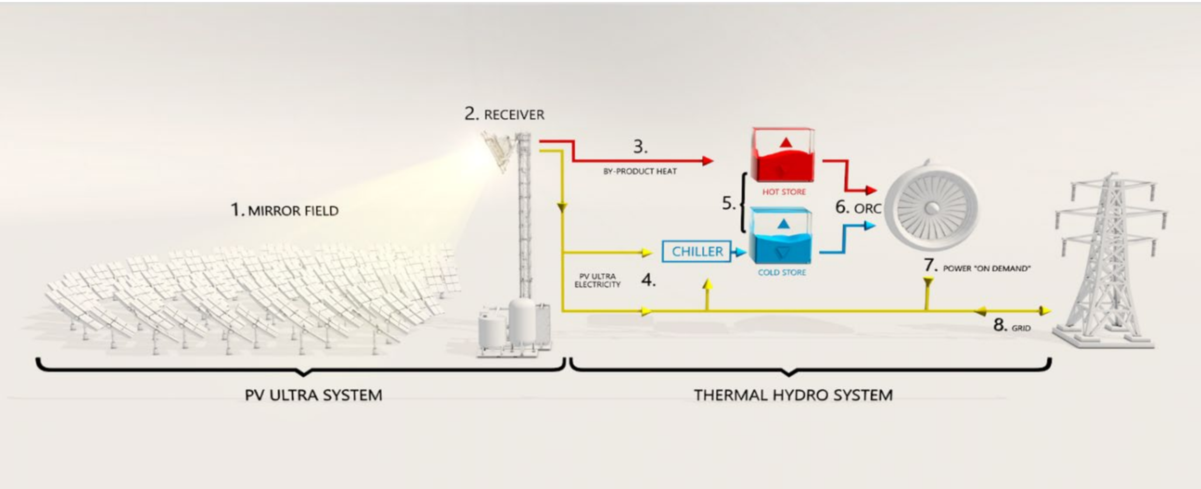

Figure 2: An overview of RayGen's solar hydro technology

RayGen's solar hydro is best introduced by the video at www.raygen.com/technology.

The technology schematic is shown in Figure 2: An overview of RayGen's solar hydro technology, and described below:

1. A field of mirrors concentrate sunlight onto a tower-mounted receiver. Inside the receiver is an array of PV Ultra concentrated photovoltaic modules, that are high-efficiency and actively cooled.
2. PV Ultra's modules converts sunlight to power with approximately 90% efficiency – 30% to electricity and 60% to heat.
3. Captured hot water is stored in an insulated water reservoir known as pit thermal energy storage (PTES).
4. Electricity is used to chill water in a second, cold PTES, or is directly sold to the grid.
5. The insulated reservoirs maintain a temperature difference of 90°C, storing energy with a volumetric efficiency equivalent to a Pumped Hydro system with a height difference of 1,000m.
6. The stored difference in temperature is used to drive a heat-to-power engine known as an organic Rankine cycle engine (ORC).
7. This engine provides the grid with reliable, on-demand power and option for baseload power.

8. The solar and storage operate independently, and the storage can be charged by the solar or by the grid.

Three proven technologies are integrated to form solar hydro – PV Ultra, PTES and the ORC/Chiller.

1.2.1 PV Ultra

RayGen is the inventor, designer, retailer and operator of the world's only concentrated photovoltaic power tower system, known as PV Ultra. At the core of the system is the ultra-powerful PV Ultra module.

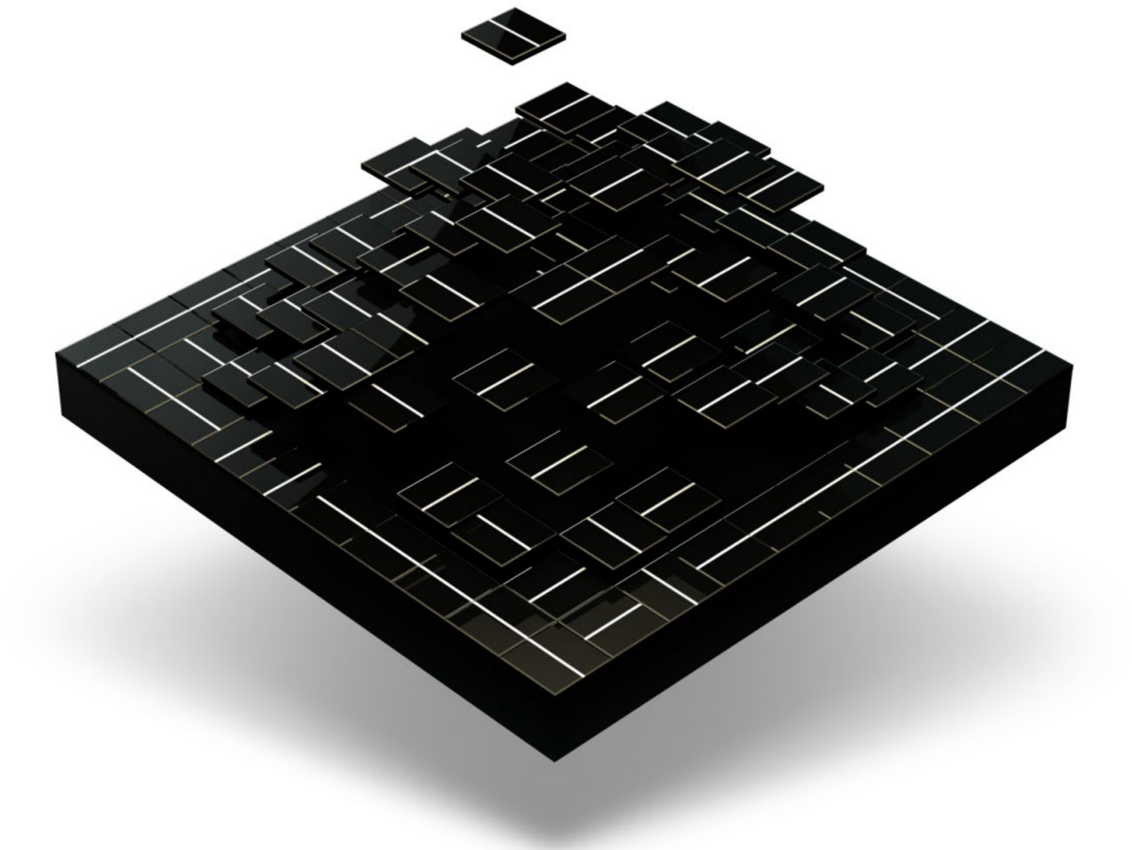

Figure 3: Stylised, expanded view of a PV Ultra module. Approximately to scale.

The PV Ultra module, shown in Figure 3, is a world-leading technology. The module measures just 10cm x 10cm (4" x 4") and has a rated power capacity of 2,500W electricity and 5,000W heat – that's 7,500W! In the current generation PV Ultra 'R3' system, 441 modules (arranged 21x21 for a 4.4m^2 surface area) form a 1MW$_{AC}$/3MW$_{cogeneration}$ receiver – just 4m^2 per MW of electricity.

RayGen's module has the highest conversion efficiency and highest energy density of any terrestrial solar product commercially available. On the surface of each module is an array of 100 multi-junction cells, each with an efficiency of 38.4%$_{DC\ STC}$. The modules have RayGen's proprietary and sophisticated thermal management system to prevent overheating.

PV Ultra modules are almost 2,000x more powerful than ground-mounted photovoltaic (PV) systems by surface area. One square metre of PV Ultra modules delivers 250,000W electricity plus 500,000W heat; by contrast, a square metre of typical PV panels will deliver approx. 150W of electricity.

The PV Ultra module is designed and tested to IEC 62108. RayGen has almost 7 years of in-field operational data of PV Ultra modules, as well as an environmental chamber for accelerated testing and a solar furnace for other reliability tests.

Figure 4: PV Ultra field at Newbridge, Victoria. A field of dynamic mirrors (lower left) focus sunlight onto photovoltaic receivers (upper right).

PV Ultra co-generates electricity and heat by using mirrors to focus sunlight onto a photovoltaic receiver containing RayGen's highly efficient PV Ultra modules. Electricity is generated in the photovoltaic receiver and a closed-loop water cooling system captures and stores heat as a useful by-product.

Figure 4 shows two of three PV Ultra-R1 fields at RayGen's Newbridge plant. This previous generation 'R1' system[1] consists of 68 sun-tracking mirrors (heliostats) focusing light onto a central $1m^2$ receiver atop a 25m mast. Each R1 receiver contains 100 PV Ultra modules and has the total capacity of $250kW_{AC}/750kW_{cogeneration}$. RayGen's pile-driven heliostat design enables dual-use grazing agriculture within PV Ultra fields (see earlier Figure 1). Heliostats reflect light, eliminating heat island concerns associated with ground-mounted solar photovoltaic systems.

1.2.2 Pit thermal energy storage (PTES)

RayGen stores energy as a temperature difference between two water reservoirs – one heated to 90ºC and one cooled to 0ºC. This temperature difference of 90°C is equivalent to a Pumped Hydro system with a height difference of 1,000m.[2]

Figure 5: Operating examples of Pit Thermal Energy Storage for district energy applications in Denmark. L-R $60{,}000m^3$ Dronninglund; $110{,}000m^3$ Gram; $203{,}000m^3$ Vojens.

Energy is stored in insulated water storage pits, known as PTES. PTES was commercialised for seasonal storage of renewable heat for northern European centralised district energy networks

[1] The R3 receiver has the same PV Ultra module dimensions, but a greater number of modules, than the R1 system.
[2] Using simple comparison $mC_P\Delta T$ with $\rho g\Delta h$ and assuming water, 15% heat-to-power efficiency and 95% gravitational potential energy-to-power efficiency.

(Wiltshire, 2015). PTES offers low-cost infrastructure (excavated, insulated pits) that can be scaled to large capacity easily, and much greater siting flexibility than typical pumped hydro reservoirs. Over one million cubic metres of PTES systems have been built worldwide, with potential for over twenty million cubic metres of large-scale heat storage for district heating applications (Denmark Monitoring, 2019). Figure 5 shows three PTES installations in Denmark.

PTES is highly efficient, with minimal thermal losses. Facilities in Denmark store solar energy from summer sun to heat towns in winter and retain over 90 per cent of the thermal energy after six months storage (PlanEnergi, 2019).

The hot reservoir is heated by the by-product heat from the PV Ultra system, with additional heat supplied via a heat pump if required. The cold reservoir is cooled using an electric chiller, supplied with electricity either from PV Ultra or imported from the grid.

1.2.3 Organic Rankine cycle (ORC) and chiller

RayGen's energy storage is charged by an industrial chiller and discharged using an organic Rankine cycle turbine. While the heat-to-power discharge is low efficiency (typically below 15%), the power-to-coolth charge is very high efficiency (CoP of 6 or more), leading to a round-trip efficiency of approximately 70% for the first deployment.

The components of the central thermal plant – chiller, ORC, heat exchangers, air cooled condensers, and optional heat pump – are common, everyday equipment. ORC systems are widely used in industrial waste-heat-to-electricity generation and in low-grade geothermal applications with 3.2GW installed worldwide (see Figure 6). The ORC operates similar to a steam turbine: the working fluid (pressurised ammonia) is boiled (by hot water), creating pressure to spin a turbine and generate electricity. Then, the vapour is captured and recondensed by cold water to complete the closed loop cycle. The ORC always operates between the same temperatures from two insulated water reservoirs (no impact of ambient temperature) and the closed loop process does not consume water or ammonia.

Figure 6: Operating Examples of Organic Rankine Cycle engines. Clockwise: 7.8MW Veyo Utah; 112MW Pamukoren Turkey; 139MW Olkaria III Kenya; 5MW Turboden Italy; 100MW Ngatamariki NZ; Exergy Turkey.

1.3 Features

1.3.1 Synergy of RayGen's solar with RayGen's storage

RayGen is not the first company to propose electro-thermal energy storage, and there is wide commercial availability of the components of RayGen's storage. Other companies actively developing ETES include the Sumitomo and TSK-backed Highview Power, the GoogleX and Alfa Laval-backed Malta, ABB and MAN, Siemens Gamesa, and 1414.

However, no other company proposes electro-thermal energy storage with a round-trip efficiency above 70% or has a first-of-kind project under construction that will deliver 50MWh for AUD $16m.

"Do you need RayGen's solar for your storage? Could the heat for storage be produced by a solar-PV powered heat pump or sourced from an industrial waste heat facility?"

Frequently asked question.

The key to RayGen's storage efficiency is the free heat from RayGen's solar.

With free heat, the round-trip *electrical* efficiency of RayGen's storage is over 70%; without free heat, a heat pump is required and the round-trip electrical efficiency is less than 25%. A low round-trip efficiency causes storage to be prohibitively expensive on most occasions, even if the electricity is provided by low cost solar[3].

Any heat source can boost RayGen's storage – though a lot of free heat is required. A 100MW RayGen storage facility operating for four hours per day has a daily heat requirement of 2,500MWh at 90°C; ten hours per day would require more than 6,000MWh. Most waste heat streams in industry produce a fraction of this requirement. Large-scale thermal generation facilities, such as coal, gas and nuclear, currently produce enough heat in sufficient quantity to meet this requirement. However, these facilities face an uncertain future and are generally designed to have a lower outlet temperature than 90°C. Most existing waste heat streams are far from the solar rich renewable energy zones where large scale long duration storage is required.

Existing solar farms waste a lot of heat. A typical 100MWe solar farm with a typical 15-20% panel efficiency wastes 3,500-4,500MWh of heat per day. That is a lot of wasted heat! The design of the standard PV panel makes it infeasible to capture this heat from existing solar farms – there are prohibitive parasitic and thermal losses from pumping a working fluid (e.g. water) to capture heat over such a large surface area.

There is only one large-scale source of low cost heat in solar rich renewable energy zones – RayGen's PV Ultra. PV Ultra is competitive with typical solar PV on an electricity only basis (e.g. $/MWhe or $m/MWe). The heat is generated as a by-product, so is effectively free.

1.3.2 Integration with other heat streams

RayGen is evaluating project opportunities that are co-located with other heat streams. These include heat streams from the cooling water of thermal power plants, and heat produced by hydrogen electrolysis and ammonia synthesis. The heat from these projects increases the heat available for RayGen's storage.

RayGen is also evaluating project opportunities that are stand-alone and heat is only provided by RayGen's co-generated solar heat stream. RayGen typically includes a small heat pump, to provide spare capacity when insufficient heat is available, and to take advantage of uncommon but lucrative arbitrage opportunities (negative pricing, local-area grid congestion and price spikes).

[3] For example, a storage plant with 15% round-trip efficiency that sources electricity from solar at $40/MWh can only profitably discharge when the price is over $250/MWh.

1.3.3 Asset lifetime and electronic waste

Solar hydro has an anticipated lifetime of over thirty years. PV Ultra modules have a lifetime over twenty years and can be upgraded cost-effectively (just 4.4m^2 module area per MWe) when higher performance versions become available. Storage components do not degrade with cycling, depth of discharge or operating temperature. The operating software can be updated over-the-air.

Solar hydro produces 99 per cent less electronic waste (e-waste) than an equivalent PV-plus-battery project. RayGen replaces a large of array of silicon photovoltaic panels and electro-chemical battery cells with a system mostly comprised of water and mirrors and a small, power-dense photovoltaic module array.

1.3.4 Intellectual property protections

The concepts of RayGen's solar hydro (Solar Power Plant), PV Ultra and electro-thermal energy storage (Thermal Hydro) are original ideas of RayGen and remain the intellectual property (IP) of RayGen. PV Ultra, Thermal Hydro and the Solar Power Plant are protected by many patents. RayGen in-sources the manufacturing of PV Ultra modules to protect core IP and ensure quality.

1.4 Collaboration with ARENA

ARENA is a world-leading proponent of project-led innovation, and RayGen and ARENA have collaborated on several innovative projects. Investors into RayGen's recent Series C capital raise, including AGL, Photon Energy, Schlumberger and Chevron, relied on data from RayGen projects supported by ARENA, including operating plant data and feasibility studies.

RayGen first collaborated with ARENA (then the Australian Solar Institute) in May 2012, on a project to deliver the first PV Ultra tower and heliostat field. This project lasted to 2015, and lessons from this project were immediately applied to an upgrade of the pilot receiver and the establishment of an 8MW p.a. robotic manufacturing line, completed in 2016. Next, RayGen built two new PV Ultra towers (the 0.5MW Expansion), and scaled manufacturing to 25MW p.a. Across these projects, the power per square metre of the receiver increased by 50% (160 $kW_{DC\ STC}$ to 244 $kW_{DC\ STC}$).

Project	Years	ARENA Funding	Total budget	Power per sqm., kW	Deployed modules	Mfg. scale, MW/yr	Storage, MWh
Central Receiver CPV Pilot Project Stage 2	2012-15	$ 1.75	$ 3.63	160	100		
Central Receiver CPV Pilot Project Stage 3	2015-16	$ 2.92	$ 5.84	210	100	8	
RayGen Resources PV Ultra Commercialisation Project	2017-19	$ 5.75	$ 11.60	244	300	25	
Solar Power Plant Phase 1	2019-21	$ 3.00	$ 6.00				
Solar Power Plant Phase 2*	2021-22	$ 15.00	$ 40.00	244	2064	125	50

*Recently started

Table 1 – ARENA's support to RayGen across 5 projects. The first four projects received $13.4m of grant support to deliver $27.1m of projects.

In 2019, in response to feedback from the market, RayGen pivoted the commercial offer and added electro-thermal energy storage to the core offering. ARENA supported this move with grant funding for project development of the 50MWh SPP1, including the design and execution of an offtake with AGL. ARENA recently confirmed funding for the second phase of the SPP1 project: which will see delivery of this large project and further expansion of the manufacturing facility to 125MW p.a.

2 Electricity Storage Market Overview

2.1 Global need for long duration storage

A major challenge facing the global electricity sector is how to integrate intermittent renewable generation while preserving the reliability, security and affordability of electricity supply. Grid-scale energy storage will play a key role in the transition from baseload energy generation provided by fossil fuels to a reliable power supply underwritten by renewable generation.

A literature review of six market studies, summarised in Figure 7, demonstrate that most energy storage required is over six to eight hours, with very little requirement for ancillary services.

	US electricity market today[a]		Opportunity for storage in US market[1]		
	% of generation-related energy market costs	**Generation-related energy market costs, USD p.a.**	Storage response requirements	**Estimated US addressable storage opportunity[2]**	Average storage duration
Ancillary services[3]	2 - 3%	**$ 5 b**	Milliseconds +	**25 GW / 15 GWh[a]**	0.5 hours
Capacity payments[4]	20 - 25%	**$ 50 b**	At least 4 hours	**70 GW / 432 GWh[b]**	6 hours
Energy	Approx. 50%	**$120 b**	Market bidding		
			➢ 55% VRE	**100 GW / 800 GWh[c]**	8 hours
			➢ 70% VRE	**230 GW / 2,300 GWh[d]**	10 hours
			➢ 80% VRE	**450 GW / 5,400 GWh[e]**	12 hours
			➢ 90%+ VRE	**8,100 GWh[f]**	18 + hours
Congestion and loss, and other grid charges[5]	20-25%	**$ 50 b**	Co-located long duration with VRE	*Majority of grid storage ideally located near VRE zones or consumer loads*	
	100%	**$ 225 b**			

RayGen can address all markets, with multiple revenue streams for each project

VRE – Variable Renewable Electricity
1 Electricity only assessment. Does not include Power-to-X (e.g. hydrogen) or increased electrification industry, transport.
2 This list is not mutually exclusive. US accounts for approximately one-seventh of all electricity generation capacity.
3 Includes Primary Frequency Response; Regulation; Contingency (Spinning and Non-Spinning); and Ramping.
4 Capacity payments are to all generation capacity. Addressable opportunity focused on peak shaving.
5 Does not include customer charges for grid connection (transmission and distribution costs), which typically account for approximately 50% of a customer's energy bill.

a NREL 2019, 'An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind'
b NREL 2019, 'The Potential for Battery Energy Storage to Provide Peaking Capacity in the United States'
c NREL 2017, 'Timescales of Energy Storage Needed for Reducing Renewable Energy Curtailment'
d Argonne National Labs 2016, 'The value of energy storage in decarbonizing the electricity sector'
e Carnegie 2018, 'Geophysical constraints on the reliability of solar and wind power in the United States'
f Zerrahn 2018, 'On the economics of electrical storage for variable renewable energy sources'
Reports scaled using market data from NERC's '2018 Long-Term Reliability Assessment'

Figure 7: Opportunity for storage in US market by energy service, in power MW and energy MWh.

A report by the German Institute for Economic Research (Zerrahn, Schill, & Kemfert, 2018) estimates that, to achieve a 90 per cent renewable grid, the average duration of storage required exceeds 18 hours. That is, per installed MW unit of storage, markets need an average of 18 hours of storage to:

(a) avoid excessive renewable curtailment, and
(b) ensure reliable delivery of electricity at any time of day, at any time of year.

Figure 8 shows their analysis of a pathway to 90 per cent renewable generation for a case study of the European electricity market. The analysis includes optimisation of storage, wind and solar capacity, and accounts for renewable curtailment of 22 per cent.

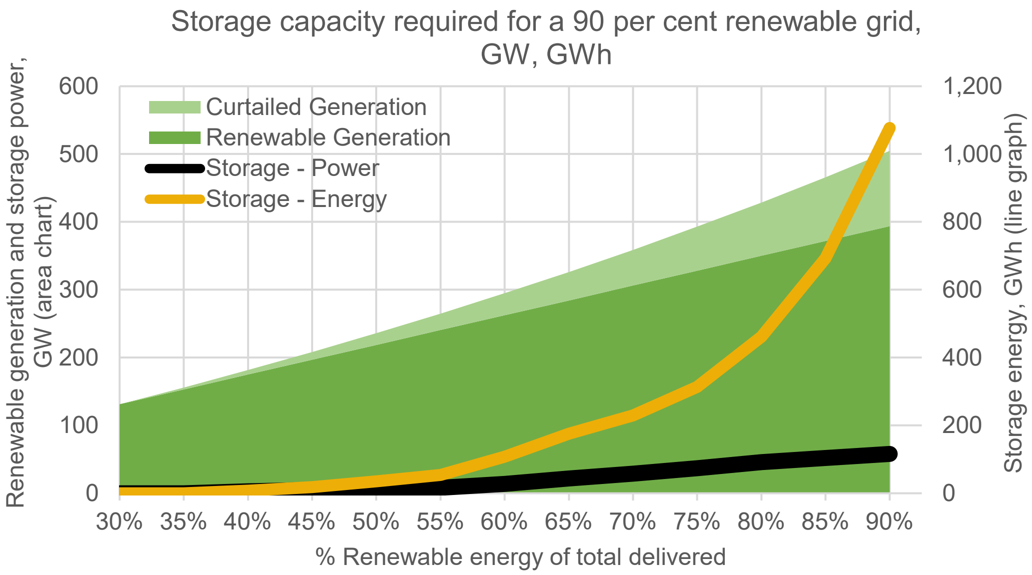

Figure 8: Storage capacity (GW, GWh) required for a 90 per cent renewable grid (Zerrahn, Schill, & Kemfert, 2018)

The market requirement for long duration storage contrasts with the current developer focus on the short duration ancillary services market. Project developers have focused battery projects on the ancillary services market, with 75% of revenue for US battery projects from ancillary services. 70% of the Hornsdale Power Reserve (aka 'Tesla Big Battery') is contracted by the South Australian Government to supply power for just ten minutes (RenewEconomy 2017). The market for ancillary services is finite, and will be quickly overwhelmed, as warned by market experts (Figure 9).

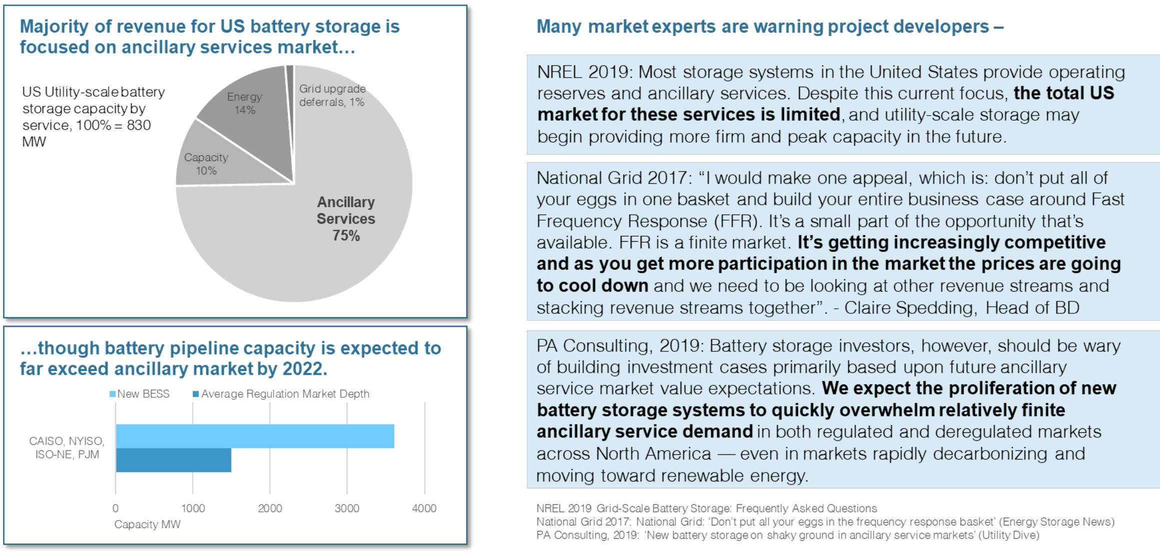

Figure 9: Focus of storage projects on ancillary services will be short-lived.

RayGen will participate in the ancillary services markets with our synchronous generation and fast response, but the profitability of RayGen's projects is not dependent on ancillary services revenue.

2.2 Australian need for long duration storage

In its latest Integrated System Plan, the Australian Energy Market Operator (AEMO) identifies that 5GW of storage with 4 to 12 hours' duration will be needed by the mid-2030s to replace retiring thermal generation and balance renewables (AEMO, 2020). With approximately 14GW of coal-fired capacity expected to retire by 2040, coal asset retirements alone create the need for almost 1GW per annum of new baseload generation capacity over the next two decades, to replace over one-third of Australia's total electricity generation requirement (ENA, 2019).

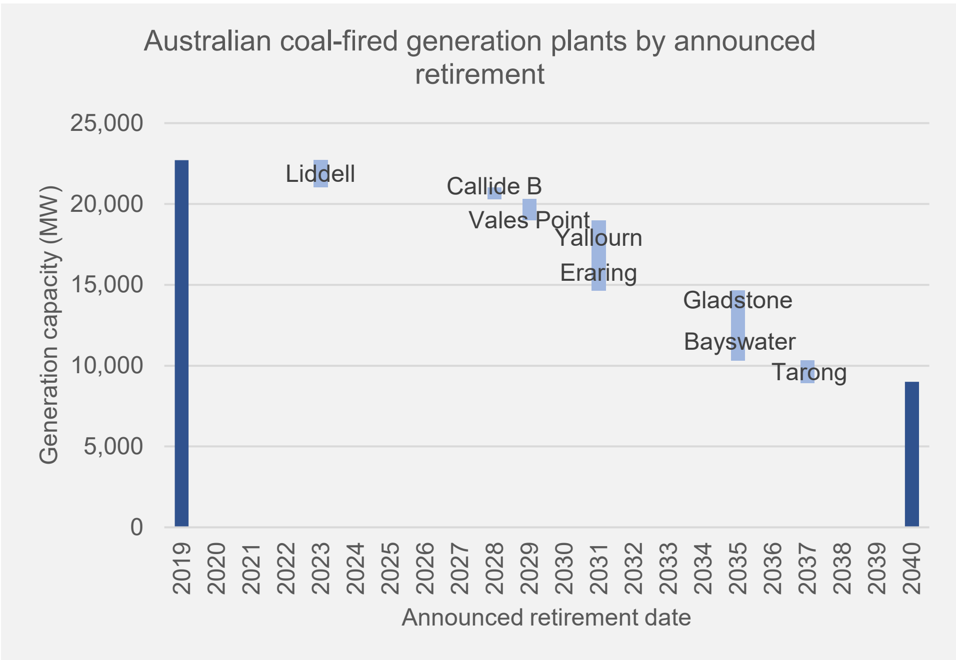

Figure 10: Australian coal-fired generation plants by announced retirement date (AEMO, 2019). Recent announcements have brought some retirements forward.

Coal currently accounts for 75 per cent of electricity generation in the Australia's National Electricity Market (AER, 2019). Figure 10 shows the expected closure dates of Australian coal-fired power stations from 2020 to 2040 (AEMO, 2019).

2.3 RayGen's total addressable market

RayGen estimates that our addressable market is currently US$24 billion p.a., growing to US$149 billion p.a. in 2030 at an annual growth rate of 37 per cent.[4] RayGen considers the addressable market for solar hydro technology to be utility-scale solar-plus-storage projects in global locations with moderate to good solar resource. This addressable market is a sub-set of the overall market for solar and storage, growing from 21 per cent in 2020 to 47 per cent in 2030 (see Figure 11).

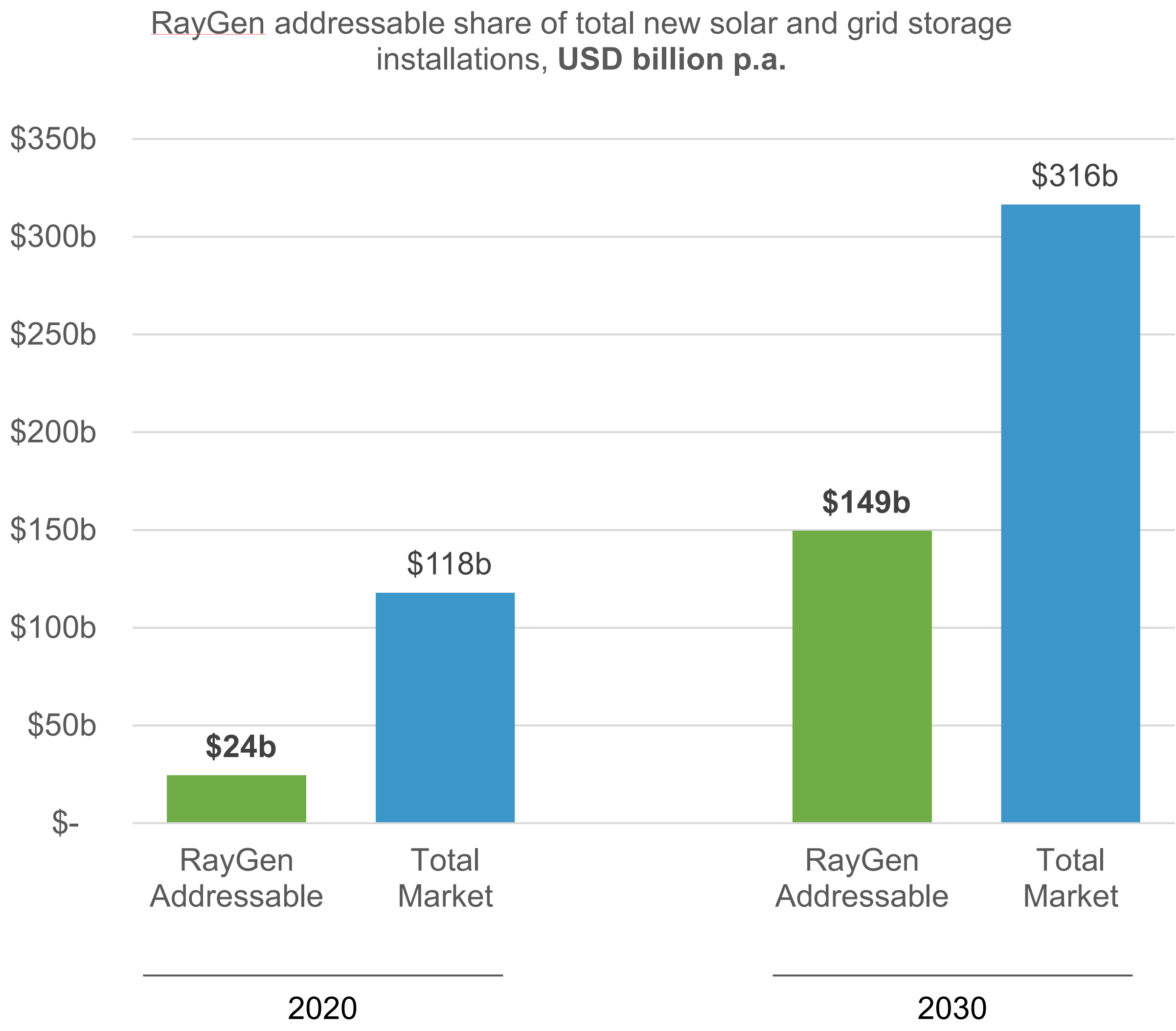

Figure 11: RayGen addressable share of total new solar and grid storage installations (DNV GL, 2019)

The worsening market value of solar electricity – whose correlated generation suppresses market prices and frequently leads to supply curtailment – is a primary driver of storage adoption. In select markets, such as California (Figure 12), there is already a rapid transition from intermittent renewable projects to hybrid renewable-storage projects. Just three provinces in China (Inner Mongolia, Qinghai and Shaanxi) are expected to account for 63% of all solar and 81% of all storage in China by 2030 (LBNL, 2020).

[4] RayGen's total addressable market model is based on DNV GL's (2019) report, *"Energy Transition Outlook, 2019 – a global and regional forecast to 2050"* and supporting dataset.

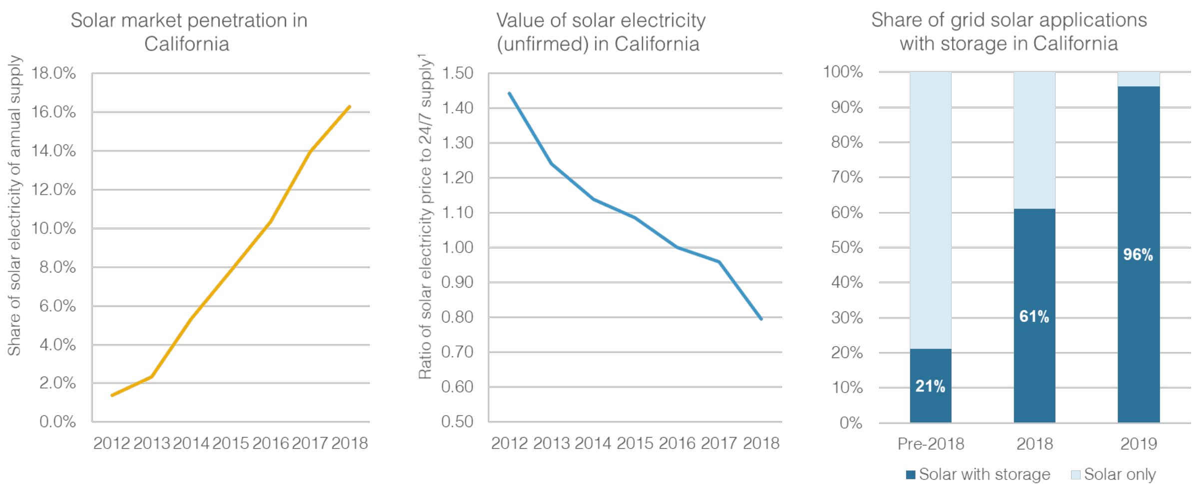

Figure 12: Californians have responded to solar oversupply and falling prices with a new project pipeline that is 96% solar-plus-storage (LBNL, 2019) (LBNL, 2020)

2.4 Long duration storage opportunities

There is a window of opportunity for a new technology that can cost-effectively deliver long-duration storage and be unconstrained by geography. Existing technology solutions – pumped hydro and lithium-ion batteries – are limited by how effectively they can deliver long duration storage.

2.4.1 Pumped Hydro Energy Storage

Today, electricity storage is dominated by pumped hydro energy storage (PHES) technology. Pumped hydro accounts for over 95 per cent of operational storage capacity (IRENA, 2017). Over 160GW of pumped hydro capacity was operational as of 2017 – more than 16 times all other forms of storage combined – with over half of that capacity in China, Japan and the United States (IRENA, 2017).

Although pumped hydro can supply long-duration energy storage cost-effectively, the technology is constrained by geography. The main limitation for pumped hydro is the need for a large vertical elevation at reasonable proximity between upper and lower water reservoirs. As the market need for long duration storage grows exponentially, it will be an escalating challenge to find appropriate sites to provide new PHES capacity. Pumped hydro's geographical constraint also introduces additional challenges – including the common requirement for significant transmission infrastructure from a renewable energy zone to the PHES, and the concern for impact to ecologically sensitive areas.

2.4.2 Battery Energy Storage

Long duration storage is well beyond what most battery projects are designed for today. Current battery installations typically provide somewhere from a few minutes up to four hours of storage. The primary purpose of these projects is typically to provide grid ancillary services: supporting power quality and bridging short term gaps in supply caused by sudden outages. As previously mentioned, 70 per cent of the Hornsdale Power Reserve's capacity is contracted by the South Australian Government to supply power for ten minutes (RenewEconomy, 2017).

The long duration business case for batteries requires a significant reduction from current prices and an increase in durability. Batteries are unlikely to provide the long duration storage (tens to hundreds of hours) required to enable the effective replacement of baseload fossil fuel generation with reliable renewable generation.

2.4.3 Emerging energy storage technologies

Globally, venture investors are beginning to recognise the need for new technological solutions that will provide affordable, long-duration storage and siting flexibility.

In 2019, over US$200m of venture capital was invested into emerging technologies that deliver long-duration storage, including: $110m for Energy Vault's gravitational energy storage, led by Softbank

Vision fund; $40m for Form Energy's 'aqueous air battery', led by Breakthrough Energy Ventures and EniSA; $37m for Hydrostor's Advanced Compressed Air Energy Storage, led by Arctern Ventures; and $30m for ESS Inc's iron flow battery, led by Breakthrough Energy Ventures and Softbank Energy.

2.4.4 Cost comparison with competitors

A cost comparison is provided in Appendix I. The table compares RayGen projects with utility-scale lithium-ion batteries and virtual power plants.

3 Solar Power Plant One

3.1 Project overview

Solar Power Plant One (SPP1), locally known as the RayGen Power Plant Carwarp (RPPC), is the flagship commercial demonstration of RayGen's solar hydro technology. SPP1 will have a capacity of 3MW grid connection, 4MW solar and 3MW/50MWh (17 hours) storage and will operate as a grid-connected generator in the Australian National Electricity Market (NEM). The project will be located in Carwarp, north-west Victoria with COD Q2 2022.

3.2 Project objectives

In building SPP1, RayGen has the following objectives:

(1) Demonstrate RayGen's Solar Hydro as a fully operating system. Prove performance and scalability of RayGen's PV Ultra and Thermal Hydro technologies in an integrated plant.

(2) Secure Solar Power Plant Two and future project pipeline. Attract customers, suppliers and financial investment for large-scale Solar Hydro projects and develop future pipeline.

(3) Optimise Solar Hydro technology. Incorporate lessons learned in designing, constructing, operating and maintaining SPP1 into future projects (SPP2+) to deliver cost reduction and performance improvement.

When determining the scale, configuration and design of SPP1, these three objectives for long term value creation were prioritised ahead of immediate project economic returns.

3.3 System configuration and location

Solar Power Plant One consists of:

- 4MW solar – 4x 1MW PV Ultra systems; and 2x 2.2MW SMA Inverters. The 4MW of solar electricity also co-generates 8MW of heat.
- 3MW engine and grid connection – 2.8MW ORC engine (synchronous generator); 3MW grid connection to 22kV distribution network; and 2MW chiller for charging of Thermal Hydro storage.
- 50MWh electricity storage (17 hours) – 2x 17,000m^3 pit thermal energy stores; one hot, one cold. Each PTES has capacity for over 300MWh of thermal energy.
- Operations and maintenance facilities, which will house the on-site centralised plant control system (SCADA).

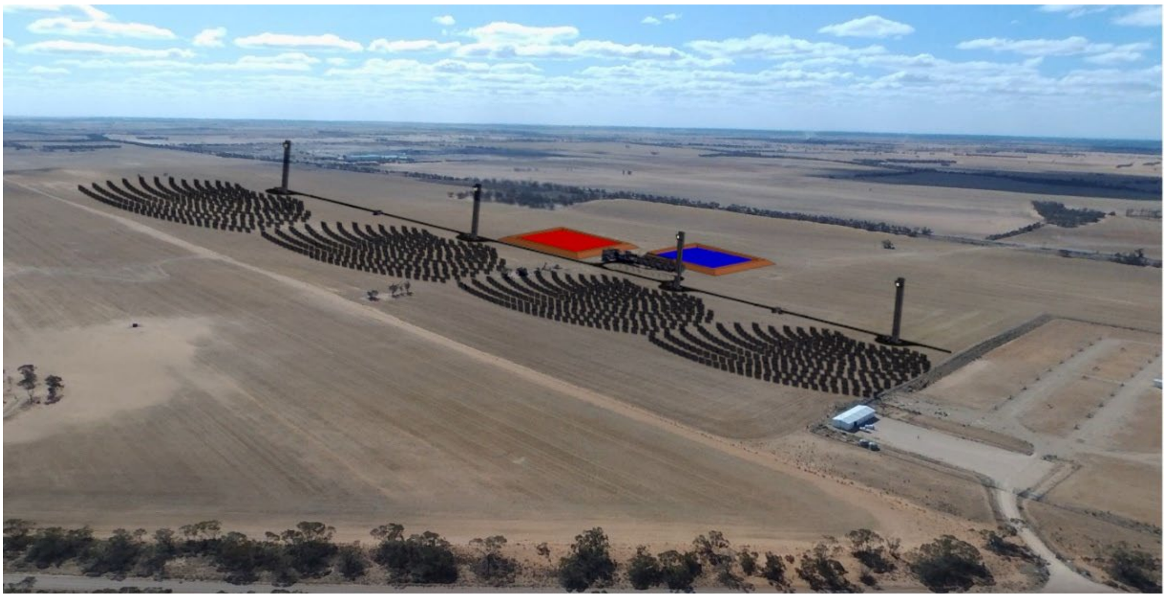

Figure 13: Rendering of Solar Power Plant One at Carwarp, Victoria. Four PV Ultra fields and central Thermal Hydro system. This project will be located on non-irrigated farmland 36km south of Mildura, 3km east of a bio-energy plant and 2km south-west of Carwarp township (population 70).

The SPP1 project site is located in Carwarp, Victoria. Figure 14 shows an image of the site.

Figure 14: View from border of site.

3.4 System operation

The Solar Power Plant has significant flexibility in its operating regimes as it can act as both a generator and a load for the grid, offering both grid-attached storage capacity and spinning reserve for firming of variable demand/generation sources.

For Solar Power Plant One, a discrete set of operating modes will be enacted which can operate independently, or in combination:

1. Synchronous Generator for grid – Export power from Thermal Hydro via ORC turbine;
2. Asynchronous Generator for grid (option for synchronous condenser) – Export power from PV Ultra via inverter;
3. Load for grid – Charge Thermal Hydro from Grid via chiller; and
4. Limited / No grid interaction – Charge Thermal Hydro from PV Ultra

Figure 15 shows SPP1's response to a worsening duck curve. SPP1's operating profile changes significantly in response to price signals, decreasing export from PV Ultra during solar hours and increasing export from Thermal Hydro in the higher-price evening peak.

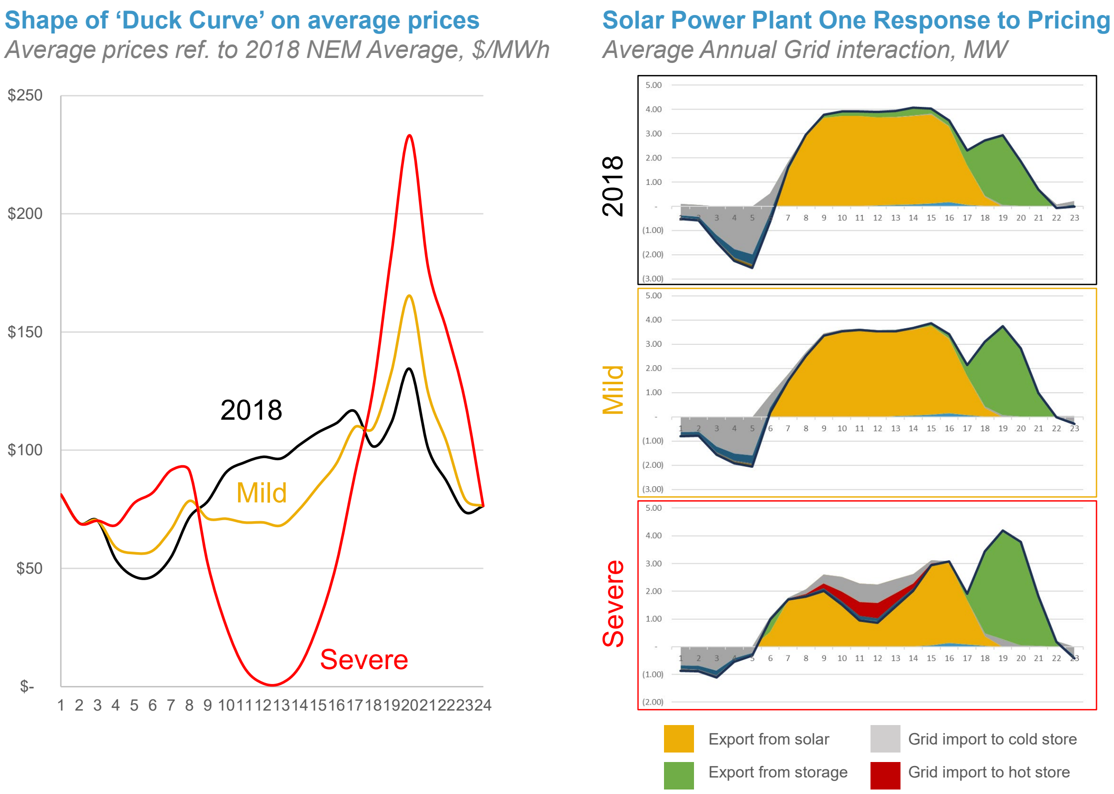

Figure 15: The Solar Power Plant is resilient to the 'duck curve'

3.5 Summary financial analysis of SPP1

3.5.1 Capital cost

RayGen presently has a total estimated capital cost of $27 million AUD ('turnkey'), for capital equipment procurement and installation. Between 40 and 50 per cent of the project will be sourced in Australia, and as much as 25 per cent will be sourced locally to the Mallee region.

The total project cost of AUD 27M turnkey is estimated as:

- $11m for 4MW of solar ($2.75m/MW); and
- $16m for 3MW/50MWh of storage ($320/kWh).

$320/kWh per unit of storage is competitive with recent 'big' battery projects, which are often $700-1,100/kWh per unit of storage. $2.75m/MW is high for a solar project, but competitive with other small-scale projects sub-5MW.

3.5.2 Generation

Based on detailed SPP1 performance modelling, RayGen expects SPP1 to export between 6,000 and 7,500MWh per annum from its 3MW grid connection. SPP1 will import approximately 200 to 1,000MWh per annum. RayGen's techno-economic model uses ten years' meteorological data for Mildura, Victoria from the Australian Bureau of Meteorology and aligned marked data from the Australian Energy Market Operator. Export volumes are influenced by electricity price.

3.5.3 Expected revenue

RayGen expects SPP1 to achieve attractive net revenue per annum on a merchant basis, with year-on-year variation influenced by meteorological conditions and increasing solar market penetration (worsening 'duck curve'). A revenue premium for storage exports results from SPP1's dispatchability, meaning the timing of export can be optimised to take advantage of peak price periods.

SPP1 was initially modelled as a merchant generator with access to four revenue streams:

- Wholesale market export – earning the spot price in Australia's National Electricity Market (NEM) for the Victorian region. Grid imports are also at the wholesale market spot price.
- Capacity trades – ASX electricity capacity futures (quarterly base load $300 cap), an ASX-traded option price received.
- Large scale generation certificates (LGCs) – LGCs are a market mechanism of Australia's Renewable Energy Target to incentivise renewable energy generation. The assumed value of these certificates is low.
- Frequency control and ancillary services (FCAS) – RayGen expects to register SPP1 for FCAS contingency services once the plant is operational. RayGen's technology provides a synchronous generator and load that can ramp up and down in seconds.

RayGen has executed an offtake agreement (with annual license fee) with AGL which is commercial-in-confidence. SPP1 will include RayGen's dispatch controller that will provide autonomous plant control in line with our customer's objectives.

3.5.4 Operating and maintenance costs

Operating costs comprise network use of system charges, fixed and variable operating costs and maintenance costs associated with the plant and equipment. These costs are commercial-in-confidence.

RayGen will employ three full time personnel for on-site operation and maintenance of the Solar Power Plant system at Carwarp. Staff will monitor the various HMIs for the plant from a central control room, will respond to specific requests from the customer, and will conduct most routine inspection and maintenance activities for the plant. This staffing requirement is specific to this first-of-kind project, as RayGen's experienced on-site personnel will provide observations and feedback for the development process of much larger projects.

Figure 16: Site supervisors reviewing operating data from autonomous control system at Newbridge.

Maintenance activities will be undertaken by a combination of RayGen site operators, third-party service providers for routine inspection of safety critical devices and systems, and third-party maintenance via service agreements for specific elements of the plant.

Major service intervals are equipment dependent but typically in the order of 10-15 years.

4 100MW p.a. manufacturing expansion

4.1 Project overview

RayGen will install a new 100MW p.a. module manufacturing facility, expanding its installed manufacturing base five-fold, from 25MW p.a. to 125MW p.a.

RayGen is seeking a 1,000m^2 warehouse for facility – approximately 300m^2 for the production line and 700m^2 for staff amenities, stores, and other services. It is expected this facility will be located close to existing RayGen engineering staff.

When operating at full capacity, this facility will employ 40 staff and produce 40,000 modules per annum. Commissioning of the facility is expected to occur by late 2022.

Figure 17: Existing 25MW p.a. manufacturing facility in Nunawading, Victoria Australia.

4.2 Advantages of PV Ultra manufacturing

Just two shipping containers of RayGen hardware (+ RayGen software) unlocks 200MW of solar and 1 GWh of storage ($400M of value). This contrasts with typical solar panels, which would require approximately 2,500 shipping containers of panels and 100 containers of batteries.

The cost to scale PV Ultra module manufacturing is low, at an estimated one-twentieth of the capital requirement per watt of typical silicon PV modules. PV Ultra modules also have high transportability, making Australia a suitable manufacturing hub for global export.

RayGen expects to retain in-sourcing of software development and manufacturing of PV Ultra modules as our business scales. RayGen's high-value, high-complexity PV Ultra modules are difficult to replicate but low cost to scale. In-sourcing of these components is central to RayGen's intellectual property protection strategy and quality assurance; and delivers a high return on invested capital (ROIC) for RayGen. The balance of system components for PV Ultra and Thermal Hydro are procured from an outsourced supply chain of global and local supply partners.

5 Future projects

5.1 Future cost projections

RayGen expects its technology will be the lowest cost dispatchable renewable solution worldwide for all storage applications greater than four hours and cost-competitive with lithium-ion batteries for one- to four-hour storage applications. RayGen estimates a rapid cost reduction to 2030, driven by an attractive first-of-kind price, a modest learning rate (10-15%) and market-average growth (37% CAGR).

The advantage of RayGen's system is that it can be 'scaled-*out*' not 'scaled-*up*' to larger projects. The solar components – heliostats, modules, receivers and towers – do not change in unit size. Larger projects simply have a greater number of these components than smaller projects. Scaling-out ensures unit cost reduction in the supply chain, and de-risks the transition from smaller to larger projects.

A table of costs is provided in Table 2, with additional discussion provided in *Part II – Technical Assessment Report*.

	Solar Power Plant One	Solar Power Plant Two+		
	2020/1	2022/3	2025/6	2030/1
Grid export capacity, MW	3	100	100	100
Solar capacity, MW	4	200	200	200
Storage capacity, MW	3	100	100	100
Storage capacity, MWh	50	1,000	1,000	1,000
Storage duration, hrs	17	10	10	10
Total project cost, A$m	27	400	310	240
Total solar cost, A$m	11	240	180	140
Total storage cost, A$m	16	160	130	100
Solar unit cost, A$/kW	2,750	1,200	900	700
Storage unit cost, A$/kW	5,333	1,600	1,300	1,000
Storage unit cost, A$/kWh	320	160	130	100

Table 2: Cost reduction for RayGen's technology over time.

5.2 Cost of firm electricity

The Australian Government has a target of under $100 per MWh for firm electricity supply from storage available for eight hours or more. RayGen expects to meet or exceed this target from the next project (SPP2). Batteries may never meet this target.

To evaluate the LETS target, RayGen developed a comparison model for a nominal 200MW 24/7 baseload project, supplied by wind, solar and storage at a location near the Kogan Creek Coal Power Station in Queensland[5]. The comparison was between RayGen solar-plus-storage vs PV + batteries, using NREL's latest and lowest cost forecast for batteries. Both systems also used wind.

[5] Project is wind + solar + storage. Reference location at a power plant in Queensland (Darling Downs Solar Farm and Coopers Gap Wind Farm). Assumes 98% minimum offtake compliance for 24/7 baseload. Project lifetime of 30 years, 80% debt at 8%, 20% equity at 12%, 30% tax rate, 20 year depreciation using variable declining balance method, 2.0% CPI, 1% annual O&M. Battery costs from NREL ATB 2020 (lowest case); wind and solar PV costs from CSIRO GenCost 2020-21. The model applied variable round-trip efficiency for RayGen's storage dependent on heat availability (heat from RayGen solar, or from heat pump powered by curtailed electricity). Any electricity not used to meet the contract was curtailed. The system was solved using a GNG Non-Linear solver.

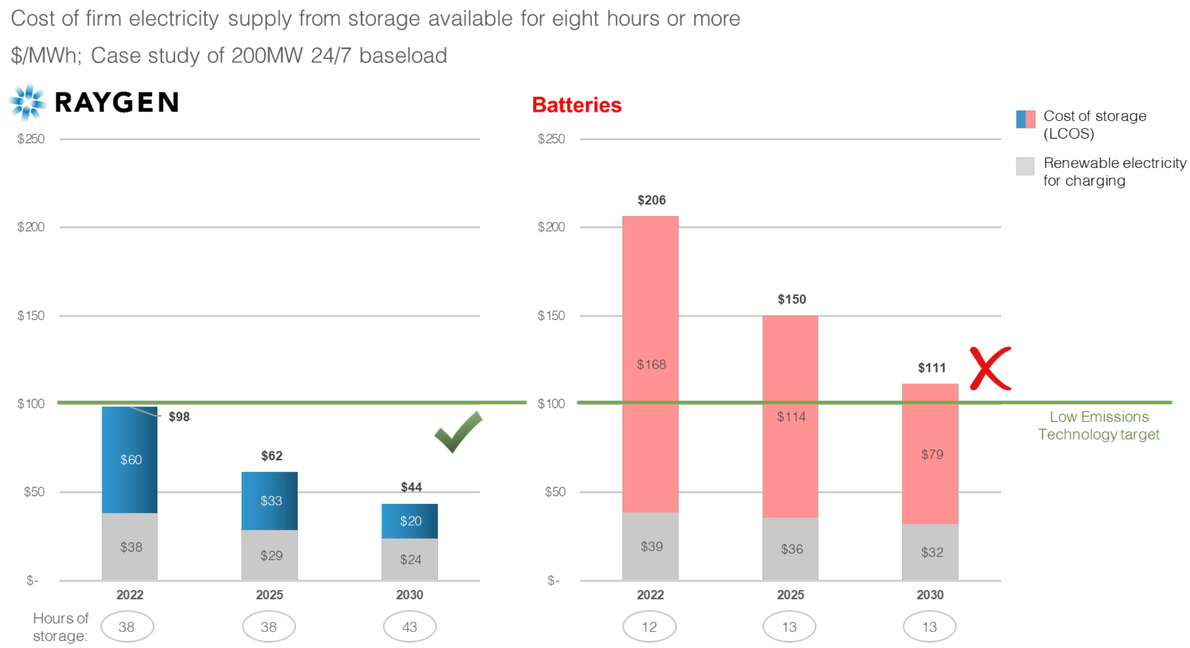

Figure 18 – Cost of firm electricity supply from storage available for eight hours or more, estimated with NREL's latest and lowest cost forecast for batteries.

RayGen meets the Government LETS target with a lower cost of storage than batteries, even as the optimised RayGen configuration includes ~40 hours of storage to batteries' 13 hours.

As can be seen in Figure 19, it is the cost of adding hours (duration) of storage to a project (the 'storage – energy' component) that differentiates RayGen's projects from PV + batteries.

RayGen has a very low marginal cost of adding hours (duration) of storage to a project. To add more hours of RayGen storage, one must simply dig a larger hole and add more water. RayGen is *already* less than $10/kWh for each additional hour of storage, whereas the lithium ion industry has a *long term target* of approximately $140/kWh.

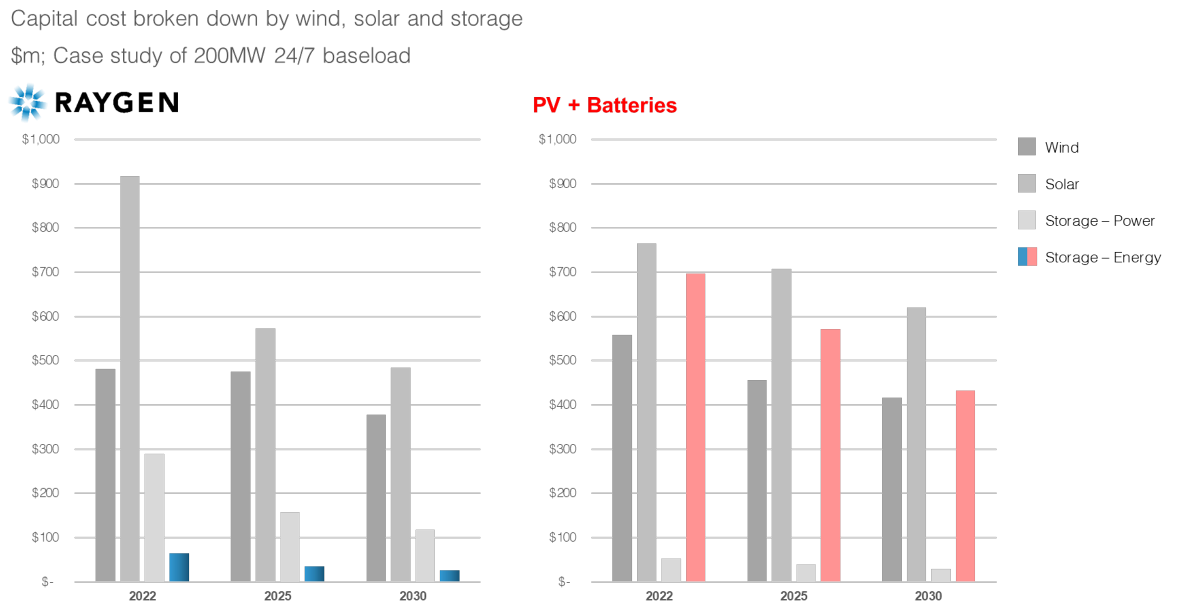

Figure 19 – Capital cost broken down by wind, solar and storage. Storage is broken out into power component (does not vary with duration) and storage component (varies with duration).

The lower price of electricity from storage drives a lower price blended PPA from a hybrid wind/solar/storage project supplied by RayGen (Figure 20) than typical PV + batteries. Both a

RayGen and a non-RayGen project will directly export variable renewable electricity at a cost of $20-40/MWh. However, a RayGen project ($44-98/MWh) will export firmed renewable electricity via storage at less than half the cost of batteries ($111-206/MWh). This leads to a lower cost blended PPA for RayGen ($65-37/MWh) than PV + batteries ($85-62/MWh) – an overall advantage of 25-40%.

This comparison uses a hypothetical case study of a 200MW 24/7 baseload project and is sensitive to financial assumptions and model design. Studies of levelised cost of electricity and storage (LCOE/S) can be useful for comparison, but issues include lack of standardised assumptions and methodology[6], a focus on cost not value[7], and a lack of consideration of the costs of transmission and distribution in the total cost of delivered energy to a customer.

RayGen is developing projects in the Australian market to receive a commercial offtake and realise market competitive returns on capital (targeted to exceed 10% project-level pre-tax IRR unlevered).

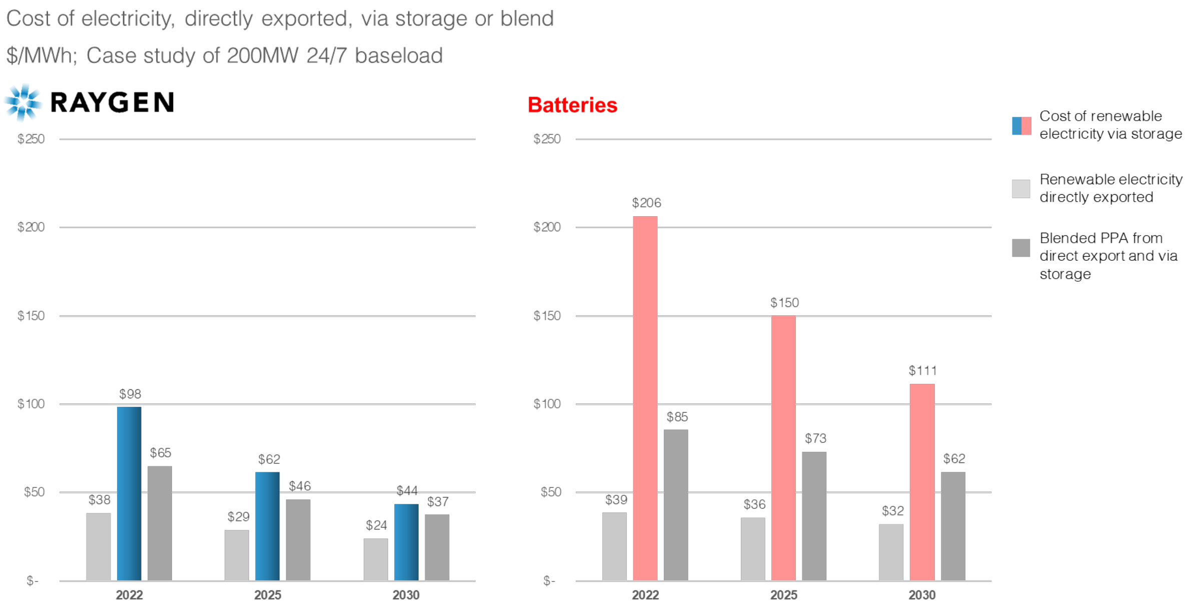

Figure 20 – Cost of electricity broken into renewable electricity directly exported, firmed renewable electricity via storage, and the blended PPA of both direct export and firmed via storage.

6 Conclusion

Cost-effective, long-duration electricity storage is critical to unlocking renewable baseload electricity. With solar hydro's unique cost position and scalability, RayGen can play a globally significant role in the transition toward 100 per cent renewable generation. Over the next 24 months, RayGen's primary strategic goal is to achieve full commercialisation of our solar hydro technology.

Solar Power Plant One (SPP1) is the flagship commercial demonstration project of RayGen's integrated solar and storage technology, planned for construction and operation in the Australian National Electricity Market. The Solar Power Plant One (SPP1) project has been developed with primary specifications of $3MW_{AC}$ grid connection; $4MW_{AC}$ and $8MW_{thermal}$ of PV Ultra co-generation; and 3MW/50MWh (17 hours) storage. The current design has a total estimated capital cost of $27 million AUD turnkey.

[6] Lazard's much cited LCOS figures assumes that taxable losses are immediate cash payments (not accrued to offset future losses). Cash flow = EBITDA – Levelised Debt Service + Tax Benefit. Lazard assumes that tax losses for the individual project can be offset against a portfolio tax profit, so the tax losses are cash income, and not accrued. This unusual treatment has a larger impact on LCOE/S than a 20-30% cost reduction in the underlying project capital cost.
[7] Solar is the lowest cost energy source on an LCOE basis, but its intermittent generation during the congested midday peak means it also is the lowest value energy source (recent project write-downs demonstrate this issue).

Solar Power Plant Two (SPP2) will be RayGen's subsequent project. SPP2's nominal specifications are 100MW$_{AC}$ grid connection, 200MW$_{AC}$ and 400MW$_{thermal}$ of PV Ultra co-generation, and 100MW/1,000MWh storage (10 hours).

RayGen expects its Solar Hydro technology will be the lowest cost dispatchable renewable solution worldwide and will meet the Australian Government LETS target of $100/MWh for eight hours or more of storage.

7 Appendix I – Small utility-scale storage projects

Table 3: Comparison of SPP1 Thermal Hydro with similar scale storage projects using established lithium ion technology

Technology	Thermal Hydro	Utility Lithium Ion				Virtual Power Plants	
Project	**SPP1**	**Wattle Point**	**Ballarat**	**Gannawarra**	**Hornsdale**	**Planet Ark**	**AGL**
Status	Shovel ready	Operating	Operating	Operating	Operating	Operating	Operating
Location	Aus	Aus	Aus	Aus	Aus	Aus	Aus
Storage MWh	50 MWh	8 MWh	30 MWh	50 MWh	129 MWh	3 MWh	7 MWh
Power MW	3 MW	30 MW	30 MW	25 MW	100 MW	3 MW	5 MW
Hours	17 hours	0.3 hours	1 hour	2 hours	0.8 hours	1 hour	0.7 hours
AUD – Total	$16m	$30m	$33m	$37m	$91m	$14m	$20m
AUD/kWh$_{total}$	$320/kWh	$3,750/kWh	$1,100/kWh	$740/kWh	$710/kWh	$4,790/kWh	$2,860/kWh
AUD/kW$_{total}$	$5,000/kW	$1,000/kW	$1,100/kW	$1,500/kW	$900/kW	$4,800/kW	$4,000/kW

8 Glossary

Abbreviated term	Term
AC	Alternating current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
ASX	Australian Stock Exchange
BOOT; BOO	Build, own, operate, transfer; Build, own, operate
CER	Clean Energy Regulator (Australia)
CFD	Contract for difference
COGS	Cost of goods sold
COTS	Commercial off the shelf
CP/CoP	Coefficient of performance
CSP	Concentrated Solar Power (also known as Concentrated Solar Thermal)
CST	Concentrated Solar Thermal (also known as Concentrated Solar Power)
CPV	Concentrated photovoltaic
DC	Direct current
DC,STC	Direct current, standard test conditions
DLF	Distribution loss factor
DNI	Direct normal irradiance (solar resource)
DUoS	Distribution use of system charges
ETES	Electro-thermal energy storage
HVAC	Heating, ventilation and air conditioning
IEC	International Electrotechnical Commission
IRR	Internal rate of return
kW	Kilowatt (1,000 watts)
kWh	Kilowatt hour (1,000 watt hours)
MLF	Marginal loss factor
MVA	Megavolt ampere
MW	Megawatt (1,000,000 watts)
MWh	Megawatt hour (1,000,000 watt hours)
NEM	Australian National Electricity Market
NER	National Electricity Rules
NSP	Network service provider
NUoS	Network use of system charges (sum of TUoS and DUoS)
ORC	Organic Rankine Cycle engine
PCB	Printed circuit board
PHES	Pumped Hydro Energy Storage
PPA	Power purchase agreement
PTES	Pit Thermal Energy Storage
PV	Photovoltaic
RET	Renewable energy target
ROIC	Return on invested capital
RTE	Round trip efficiency
SCADA	Supervisory control and data acquisition (plant control software)
SPP1	Solar Power Plant One (5MW grid/ 10MW solar/ 50MWh storage)
SPP2	Solar Power Plant Two (10MW grid/ 200MW solar/ 1,000MWh storage)
SPPX	Solar Power Plant X – future, large scale Solar Power Plant project
SPV	Special purpose vehicle
THES	Thermal Hydro Energy Storage
TUoS	Transmission use of system charges
VoLL	Value of lost load

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