The Story of RayGen

Part II – Technical Assessment Report

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For further detail, email enquiries@raygen.com.

Executive Summary

This report is the second part of 'The Story of RayGen'. Readers should acquaint themselves with '*Part I – Commercial Assessment Report*' for context on RayGen and the RayGen system.

RayGen's Solar Power Plant is a grid-scale solar-plus-storage technology. It competes with other electricity generation and storage technologies that supply power to electricity networks and/or large energy users. RayGen's technology must be cost-competitive with technologies that offer similar capabilities – including generation profile, reliability and ancillary services – to compete effectively over time.

RayGen's competitors include fossil fuel generation technologies (e.g. gas-fired generation), dispatchable renewable generation technologies (e.g. hydroelectricity, concentrated solar thermal), intermittent renewable generation plus storage technologies (e.g. solar PV panels plus batteries, solar PV panels plus pumped hydro) and stand-alone storage, both established (e.g. lithium-ion batteries, pumped hydro) and emerging (e.g. adiabatic compressed air energy storage, electro-thermal energy storage, flow batteries, mechanical storage, virtual power plants).

Solar Power Plant One (SPP1) is the flagship commercial demonstration of RayGen's Solar Power Plant 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.

The project has an estimated capital cost of $27M AUD 'turnkey'.

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1 Introduction

PV Ultra is RayGen's concentrated solar photovoltaic power technology. This technology enables capture and concentration of the sun's rays to a tower-mounted, small-area receiver. The receiver holds an array of high-efficiency multi-junction photovoltaic modules, which convert the concentrated sunlight directly to electricity. During cooling of the modules, a significant amount of the energy is captured by the receiver as low-grade heat, which is actively removed by a water-based coolant.

RayGen's Thermal Hydro uses low grade heat as a hot 'source' for an engine, which traditionally offers only very limited performance. By charging a low temperature cold 'sink', the thermal efficiency of the power cycle driven by the low-grade heat is able to be improved. Use of the engine to regenerate the 'stored' power (as cold) then enables Thermal-Hydro to operate as an energy storage system.

Combining the two systems into the 'solar hydro' technology provides renewable energy which is able to be generated and dispatched. This Solar Power Plant is scalable to suit customer and market demand, and is tailorable to specific siting and application requirements.

2 System Overview

The Solar Power Plant operates as a solar-based renewable energy generator combined with energy storage and dispatch capability. More information can be found in *Part I – Commercial Assessment Report* and an explainer video: https://raygen.com/technology.

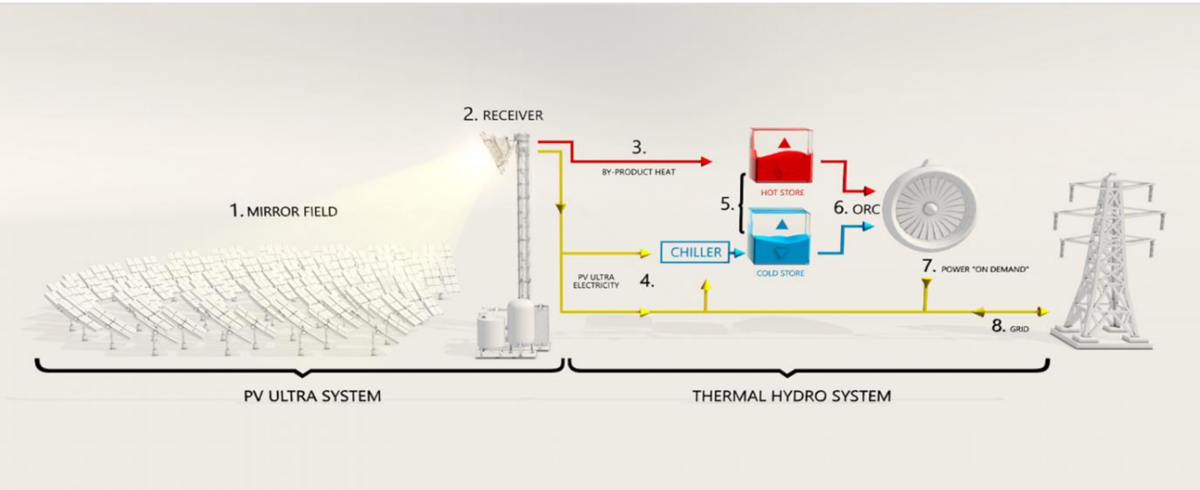

Figure 1: An overview of RayGen's solar hydro technology

2.1 Charge Cycles

The energy storage is governed by two separate charging processes 1) 'Hot-Charging' of a Hot Thermal Energy Store (TES), primarily via the cooling water from the renewable source PV Ultra, supplemented by an air-source Heat Pump, and 2) 'Cold-Charging' of a Cold TES from both PV Ultra and the grid.

'Hot-Charging' of the Thermal-Hydro system is by heating of a Hot PTES up to 90°C. This is accomplished by removing coolant from the bottom of the PTES and feeding it through the PV Ultra systems, to return at 90°C.

'Cold-Charging' of the Thermal-Hydro system is by chilling of a salt-water based TES down to 0°C. The cold sink is charged by removing coolant from the top of the PTES and feeding it through an electric chiller system to return 0°C to the bottom of the store. The cold sink is stored in a single large capacity storage vessel in the form of a closed and insulated pit, commonly referred to as a Pit Thermal Energy Store (PTES).

2.2 Power Cycle

The approach to the Organic Rankine Cycle (ORC) for this system is the use of a radial inflow turbine expander with ammonia working fluid. Ammonia has been selected as it has zero global warming potential and is also considered efficient over the planned operating temperature range of circa 0°C to 90°C.

The ORC primary heat source is the 90°C Hot Store 'charged' by PV Ultra (and an optional Heat Pump). This is used to both preheat and evaporate the cycle working fluid. The ORC cycle then makes use of the Cold Store 0°C coolant to condense the working fluid after it has undergone expansion through the turbine. This process warms the coolant and it is returned to the Cold Store.

The ORC operates at the same efficiency, regardless of ambient temperature, even on the hottest days of the year. Exhaust heat from the engine is rejected into the cold store, which provides a constant 'sink' at 0°C.

2.3 Closed loop cycles

No water or ammonia is consumed in the entire process. During storage 'charge', discharge water is removed from the hot and cold PTES, heated or cooled, and then returned at the target temperature (90°C and 0°C respectively). During storage 'discharge', water is removed at the target temperature, provides the 'source' and 'sink' for the ORC engine, and is then returned to the PTES. Ammonia transitions through several phase changes in the ORC engine but is not consumed in the process.

3 Efficiency

3.1 Storage round-trip efficiency

The round-trip electrical efficiency (RTE) of the complete cycle (from electricity to thermal storage back to electricity) can be estimated via the below relation.

RTE ≈ Efficiency of Storage Discharge x Efficiency of Storage Charge x Efficiency of Storage
≈ Power Cycle Efficiency x (Cold Sink Requirement x Cold Sink Charging Electrical Power Requirement + Hot Sink Requirement x Hot Sink Electrical Power Requirement[1]) x Efficiency of storage
$\approx \eta_{th} \times ((1-\eta_{th}) \times CoP_{Chill} + 0) \times \eta_{storage}$
$\approx \eta_{th} \times CoP_{Chill}$
≈ 12% x 6
≈ 70%

The RTE of the complete electricity-thermal storage-electricity cycle is shown in Table 1. For every 1 MWh of electricity into the chiller, RayGen generates ~6 MWh of cold from the chiller. After time in storage (where very little energy is lost[2]), the cold can be combined with heat from solar and can be converted back to ~0.7MWh of electricity, for ~70% round trip efficiency.

Two important considerations:

1. The detailed RTE calculation includes a number of other efficiency/conversion factors, as well as consideration of all pumping and other parasitic loads throughout the process. The detailed RTE is highly dynamic, as even though the ORC efficiency is not impacted by

[1] Heat is provided for free, so no electricity is required.
[2] In European district energy systems, the PTES stores solar heat energy summer to winter, and only loses 5% of the energy over 6 months.

ambient temperature, the efficiency of air-cooled-condenser (rejecting heat from the chiller cycle) is impacted by ambient temperature. The efficiency at 15°C ambient temperature is shown below in Table 1.

2. This only considers the round-trip *electrical* efficiency of the cycle, as additional energy is supplied by free low-grade heat (a waste product of solar photovoltaic production[3]).

Effective Peak Efficiency of ORC engine	12%
CoP (ambient = 15°C) of industrial chiller	6
Effective Peak RTE	70%

Table 1 - System round-trip efficiency for RayGen's storage in first-of-kind project. Later projects are expected to have a higher round-trip efficiency.

3.2 Efficiency comparison with other ETES

Other companies are commercialising electro-thermal energy storage (ETES) systems, including the Sumitomo and TSK-backed Highview Power, the GoogleX and Alfa Laval-backed Malta, ABB and MAN, Siemens Gamesa, and 1414. These companies often focus on large temperature differences, to increase the efficiency of the storage discharge (power-out from thermal turbine). Highview power operates from -196°C to ambient, Malta from -100°C to 550°C (estimated), Siemens Gamesa up to 800°C and 1414 up to 1414°C.

These large temperature differences deliver a high efficiency of storage discharge (e.g. turbine efficiency), but suffer from low efficiency of storage charge (e.g. heat pump CoP) and low efficiency of thermal storage (e.g. heat losses from storage), and can add substantial costs and complexity.

The maximum efficiency of ETES (without free heat – solar or otherwise) appears to reach a limit of about 60%:

- Highview Power: "With careful thermal integration that we've been developing over the past years, we're able to achieve a round trip efficiency of 60%."
- Malta: "the current Malta system can store and dispatch energy with efficiency of around 60%."
- Siemens Gamesa: "ETES η = 45% electricity".
- MAN Energy: "Thanks to its modular design, MAN ETES can be configured to meet specific customer needs… [with] optional re-electrification with round trip efficiency of around 50%.
- 1414: "The electrical efficiency of an electric charged TESS (TESS-GRID) is estimated to have an upper limit of 42%, with 35% practically achievable with available technologies."

By contrast, RayGen utilises a modest temperature difference of 90°C. The modest temperature difference impacts the efficiency of storage discharge (e.g. turbine efficiency of ~12%) but enables a very high efficiency of storage charge (e.g. CoP of ~6, especially with free heat from solar) and minimal thermal losses during storage.

3.3 Solar efficiency

RayGen set the world-record for a solar system efficiency with UNSW in 2014, with a sunlight-to-electricity efficiency for a laboratory prototype of 40.4%. In RayGen's commercial product, RayGen converts approximately one-third of the sunlight into electricity and two-thirds into heat (95°C hot water).

[3] This heat is uniquely captured by PV Ultra at 95°C. A typical 100MWe solar farm with a typical 15-20% panel efficiency wastes 3,500-4,500MWh of heat per day.

Within the receiver is a dense array of PV Ultra modules, with 100 multi-junction cells on each module's surface. These cells have an efficiency of 38.4%$_{DC\ STC}$. Effort has been made to maximise electrical output from the receiver, including minimising 'dead space' of the receiver (areas of the receiver not covered by cells, such as gaps between modules).

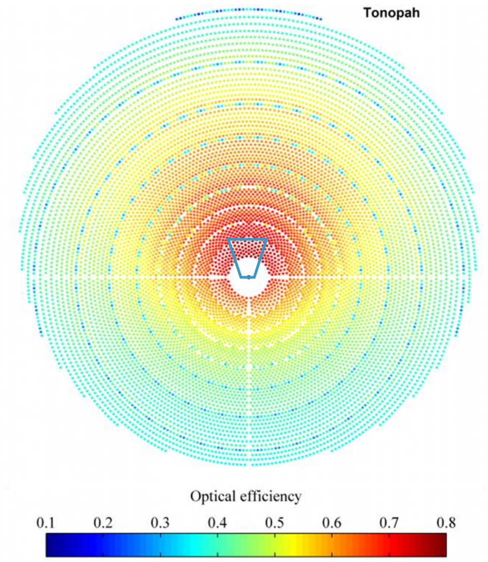

Figure 2 – Optical efficiency by heliostat location for the Crescent Dunes, Tonopah US (Rodriguez-Sanchez 2019). The highest efficiency heliostats are located closest to the receiver and expand in a wedge away from the tower to the North. Smaller towers, such as RayGen's tower, have a higher average optical efficiency than larger towers. The blue wedge approximately represents the heliostat field for a RayGen system.

Additional effort has been made to maximise the optical efficiency of the mirror field – that is, the amount of sunlight that is reflected to the receiver relative to the sunlight incident on the mirrors. RayGen's smaller tower size than typical CSP offers a distinct advantage in optical efficiency, as can be seen in Figure 2.

"The reported performance of the new system represents a significant gain in efficiency since 2016, with the optical efficiency now peaking at 85% as opposed to 75% in 2016. This places the RayGen system among the highest optical efficiency of any commercial CPV system. The system efficiency also holds constant throughout the day which is evidence that parasitic thermal effects are under control. Congratulations on the excellent results."

Letter to RayGen by A-Prof NJ Ekins-Daukes and Dr Mark Keevers of UNSW, 12 October 2018

3.4 Efficiency comparison with CSP

RayGen is often compared with concentrated solar power (CSP) power tower technologies. There are similarities – both approaches use mirrors to focus sunlight onto central, raised receivers and both systems store energy as heat.

However, RayGen is not CSP. Differentiating RayGen is:

- Electricity is generated at the receiver, using high efficiency photovoltaic modules. This electricity can be exported to the grid or used to charge nearby storage.
- Heat produced by the receiver is less than 100°C, in the form of hot water.
- The system has near-zero latency (no pre-heating is required to reach the operational temperature of the receiver).
- Tower height is ~45m, with heliostats in a small wedge from the receiver, for higher optical efficiency.
- Storage can be charged by the grid or by co-located solar and is separately operated to the solar.

4 System layout & integration of components

The Solar Power Plant is constructed from modular blocks of PV Ultra which interact with the core Thermal Hydro hub of equipment. The size and shape of the total arrangement is accordingly flexible and able to be moulded to suit site constraints. The initial Solar Power Plant One project is based on a nominal 4x PV Ultra R3 systems (4MW electrical with 8MW thermal), a 2.8 MW ORC, 2MW Chiller with Air Cooled Condenser, and a 3MW grid connection.

4.1 System Layout

Based on the nominal system sizing, a preliminary system layout has been developed. The layout includes the 4xPV Ultra R3 fields and a suitable spacing/arrangement for a centralised Thermal Hydro equipment set.

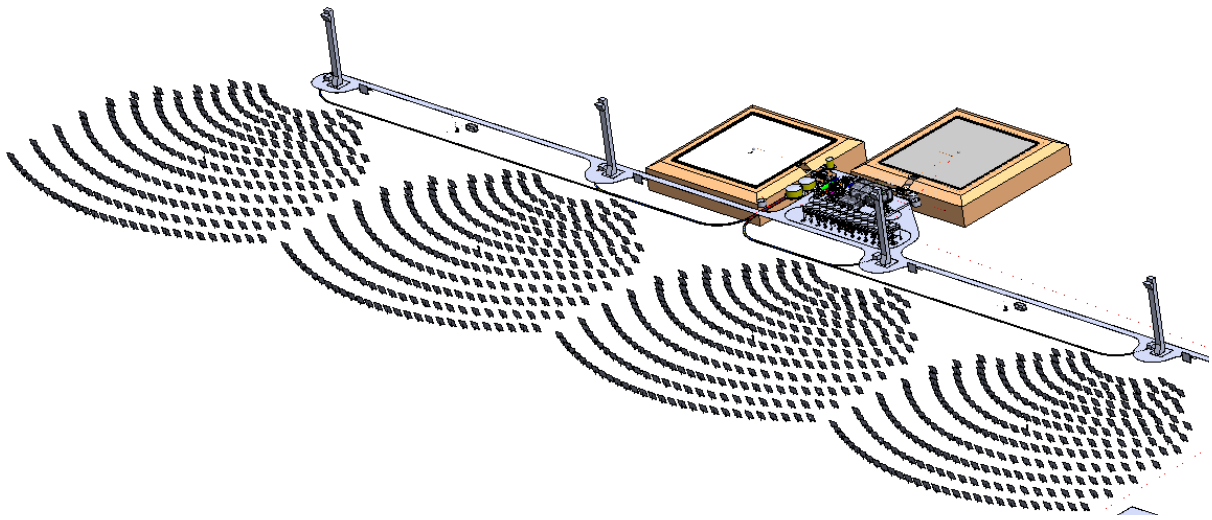

Figure 3 – Nominal Layout of Solar Power Plant One

4.2 System Components

System components include:

- RayGen Solar ("PV Ultra")
- Engine - Organic Rankine Cycle
- Chiller
- Hot / Cold PTES
- Air Cooled Condenser
- System thermal integration
- System electrical integration

The SPP1 system has been designed around a limited grid connection of 3MW due to specific site constraints. There are two primary generator types within the Solar Power Plant, being the asynchronous PV Ultra with inverter and the synchronous ORC engine.

There are several different loads within the Solar Power Plant, the most significant of which being the chiller. There are also secondary loads within the system, each of which contributes to effective operation of the generators and major loads. All loads are included in the round-trip efficiency calculation.

5 System Operation & Performance

5.1 Operating Philosophy

There are four major modes of operation for the Solar Power Plant, reflective of power flows between subsystems and the grid:

1. Export power from PV Ultra
2. Export power from Thermal Hydro
3. Charge Thermal Hydro from PV Ultra power
4. Charge Thermal Hydro from Grid power

These modes can operate independently, or in combinations: for example, exporting from PV Ultra on a sunny day (Mode 1), whilst directing excess PV Ultra power into charging of thermal hydro (Mode 3). The sizing and configuration of each individual sub-system element will determine the available mode combinations. The specific system location and configuration, as well as possible demand profile will determine the optimum operating regime.

5.2 Solar Power Plant One Performance

The optimal configuration has been developed for Solar Power Plant One based on Merchant operation/trading in the Victorian wholesale market segment of the Australian National Energy Market (NEM), as well as a variable seasonal commitment to sell $300Cap contracts (futures) as traded on the ASX. The plant typically discharges 3-6 hours from the storage system each day with additional hours to support capacity contracts.

An example week of operation of a Solar Power Plant (different configuration to SPP1) is shown in Figure 4. In this Summer operating profile excess solar power, is sent primarily to the chiller to store energy to supply to the engine during peak periods. Grid import electricity is also used to charge the cold store overnight when prices are lowest as grid import is needed to meet the daily export $300cap commitment.

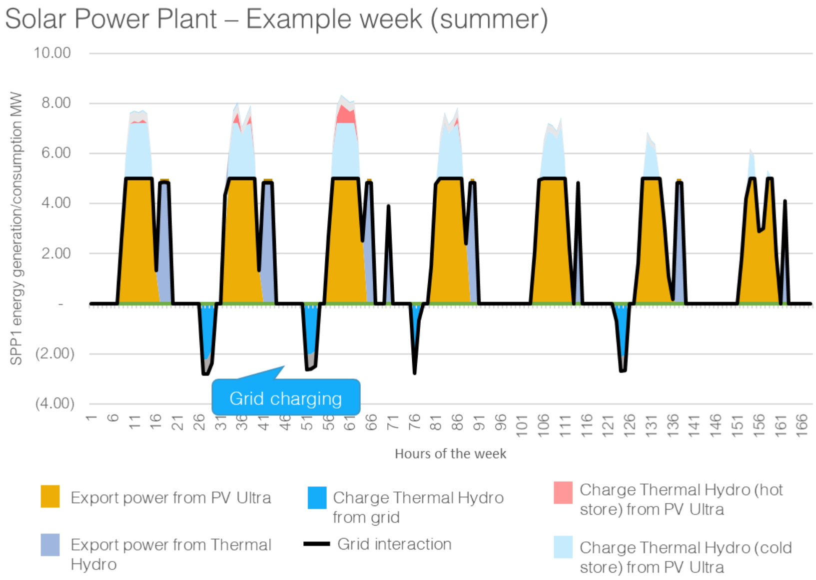

Figure 4 – Example operation of a solar power plant

6 System Cost

6.1 SPP1 capital costs

RayGen's "Solar Power Plant One" (SPP1) will realise the first-of-type deployment of RayGen's second generation PV Ultra R3 technology, and RayGen's novel Thermal Hydro product. Thermal Hydro integrates a number of commercial off the shelf solutions to create a novel electro-thermal energy storage system to regenerate electricity from PV Ultra's heat and electricity stored as a cold sink. SPP1 will see the deployment of 4x second-generation 'R3' PV Ultra systems, coupled with a first-generation deployment of Thermal Hydro, establishing the Solar Power Plant system in the energy market. This will bring the PV Ultra technology further down the cost curve following established systems in Newbridge, Victoria, whilst maximising the value of the captured electrical and thermal energy.

The project total cost is estimated at AUD $27M.

- $11M for 4x PV Ultra 1MW R3 systems
- $16M for 2.8MW / 50MWh

RayGen has established significant partner relationships for its SPP1 project with companies including Babcock and Wilcox, NIRAS, KMI, Azur Space, Egesim and Atlas Copco.

6.2 Future cost projections

6.2.1 Cost estimates

RayGen estimates a rapid cost reduction to 2030, driven by an attractive first-of-kind price ($320/kWh), a modest learning rate (10-15%) and market-average growth (37% CAGR). RayGen expects its Solar Power Plant technology to be the lowest cost dispatchable renewable solution worldwide for storage applications. A table of costs is provided in Table 2.

	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.

6.2.2 Cost reduction plan

RayGen's cost estimates are based on a detailed, initiative-level cost-out plan that has been validated by GHD. The plan was developed bottom-up with direct quotations from supply chain partners and predicted design improvements, and supported top-down with market reports, evidence from comparable projects, and application of learning rates and power laws.

The key elements of the cost reduction plan include:

- Design for manufacture: e.g. redesign components for volume manufacturing; switch to standardised specification or reduce specification; consolidate or eliminate components; transition to a new component.
- Scale and automation: e.g. transition from batch to continuous production; procure at high volume with significant negotiating power; automate assembly and installation processes; share components across large deployments
- Outsourcing to lowest cost suppliers: e.g. source components globally; establish local presence with supply chain partners; assemble components using lower cost processes.
- Efficiency and yield: e.g. improve cell efficiency, reduce optical losses and increase concentration for the solar module; ensure high yield through clean room and quality assurance practices.
- Standardised construction and commissioning: e.g. larger installations (consolidated planning, permitting and site works); standardise assembly and installation processes; establish trusted EPC partners to manage construction time and quality.
- Capacity optimisation: e.g. procure equipment at market standard capacity (e.g. most ORC units are 20-30MW for geothermal applications); add stages to thermodynamic cycle design.

"Based on the high degree of quotes received and used to develop the project estimate, the level of accuracy for the project budget is considered to be appropriate for the first project of its kind. It is considered that any possible over-run risk has significantly been mitigated, and accordingly the project has a reasonable likelihood to be delivered within the project budget inclusive of a 10% contingency as allocated by RayGen."

Independent Technical Assessment by GHD for RayGen, 2020.

6.2.3 Learning rate and power law

Empirical observations of technology costs across many industries have shown that the cost glidepath for a technology over time is related to its cumulative deployed volume and the size of the individual project in which it is used.

These observations are quantified by two values:

- Learning rate[4]. Cost reduction from cumulative deployment (e.g. supply chain maturity); and
- Power law[5]. Cost sensitivity to project scale (e.g. larger projects are lower cost).

The learning rate and power law exponent for solar and storage technologies are shown in Table 3. RayGen's advantage is that its technology is early in its growth cycle and is already competitive with incumbent PV and batteries. PV Ultra, for example, has approximately 1/400,000th the cumulative installed volume of PV, representing 19 learning rate cycles.

As RayGen grows, RayGen's individual projects are increasing in scale as the supply chain is increasing in maturity. That is, RayGen's technology cost reduction plan is impacted by *both* learning rates *and* power laws.

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[4] Learning Rate Equation: $Cost = Cost_{Ref.}(\frac{Volume}{Volume_{Ref.}})^{(1-2^{\beta})}$

[5] Power-Law Equation: $Cost = Cost_{Ref.}(\frac{Scale}{Scale_{Ref.}})^{(\alpha-1)}$

Where *Cost*, *Volume*, *Scale* are the unit cost, supply chain volume and project scale of the technology respectively; subscript $_{Ref.}$ are the reference system. β is the Learning Rate; α is the Power Law Exponent.

- RayGen's cost reduction plan for PV Ultra represents a learning rate of 10 per cent *or* a power law exponent of 0.85. If the 10 per cent learning rate *and* 0.85 power law were applied together, the compound effect would deliver an additional cost reduction for PV Ultra approximately 40 per cent below current RayGen projections.
- RayGen's cost reduction plan for Thermal Hydro represents a learning rate of 15 per cent *or* a power law exponent of 0.77. If the 15 per cent learning rate *and* 0.77 power law were applied together, the compound effect would deliver an additional cost reduction for Thermal Hydro approximately 60 per cent below current RayGen projections.

The projected costs for the Solar Power Plant imply a relatively conservative learning rate and power law forecast. There are likely many improvements and new inventions that are not already identified in RayGen's cost and performance plans, which could lead to further, faster cost reductions.

	Learning Rate, %	Power Law Exponent
Solar	**14 – 20[1]**	**0.89[6]**
Module	22 – 28[2]	
Balance	8 – 12[3]	
Batteries	**6[4] – 18[5]**	**0.92[6]**
Pumped Hydro	**Mature**	**0.7[6]**
Sources	1 - Theologitis and Masson, 2015; Hernandez-Moro and Martinez-Duart 2013, p.124; 2 - Fraunhofer 2019, p.10; BNEF, 2018; 3 - Fraunhofer 2019, p.10; Elshurafa et al. 2017, p.21; 4 - Nykvist and Nilsson, 2015; 5 - BNEF 2019b; 6 - ITP 2018 (battery for 10 hour case).	

Table 3: Learning Rate and Power Law Exponent for solar and storage technologies. RayGen's PV Ultra and Thermal Hydro have learning rates of 10% and 15%, or power laws of 0.85 and 0.77, respectively.

7 Conclusion

Cost-effective, long-duration electricity storage is critical to unlocking renewable baseload electricity. With RayGen's unique cost position and scalability, our technology can play a globally significant role in the transition toward 100 per cent renewable generation.

RayGen's technology delivers low-cost, on-demand electricity that can be sited flexibly and provides storage from one to hundreds of hours. Heat from RayGen's solar technology is crucial to unlocking the class-leading efficiency of RayGen's thermal storage.

RayGen expects a rapid cost reduction to 2030, supported with detailed bottom-up quotations and cross-checked against top-down benchmarks and industry learning rates.