RayGen's PV Ultra:

Expanding the global solar market beyond daylight power

RayGen PV Ultra
Knowledge Sharing

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Table of Contents

1 Newbridge Site – PV Ultra Pilot Demonstration Facility, 2015

Newbridge became the first site deployment of the RayGen PV Ultra technology and now has operated over a period of 30 months. The 200kW PV Ultra Pilot Demonstration was installed by RayGen at Newbridge Victoria in 2015. Finance for this project was partially provided by ARENA.

The PV Ultra tower is retailing electricity behind-the-meter to a large agribusiness in central Victoria, Australia. Newbridge has not only been an important source of data to track real-world performance, but it has doubled as a proving ground for the control software underlying the current R1-0.2MWe and the R3-1.0MWe products.

1.1 Key performance metrics

The Newbridge site consists of:

- an R1-0.2MWe power tower,
  - 207kW$_{DC}$ (at Standard Test Conditions 1000W/m^2 and 25°C)
    - 56 heliostats
    - Cell efficiency of 38%
    - DC System efficiency of 25.4%
  - 400kWth active heat capture at 60°C
    - Combined heat and power system efficiency of 75%
- central inverter, with AC output feeding the manufacturing site network to displace mains grid metered consumption,
  - Inverter 520V$_{DC}$, 415V$_{AC}$ 3 phase (97% efficiency)
- 56 self-powered, self-aligning heliostats,
- wireless mesh network for heliostat control, and
- control system and data acquisition.

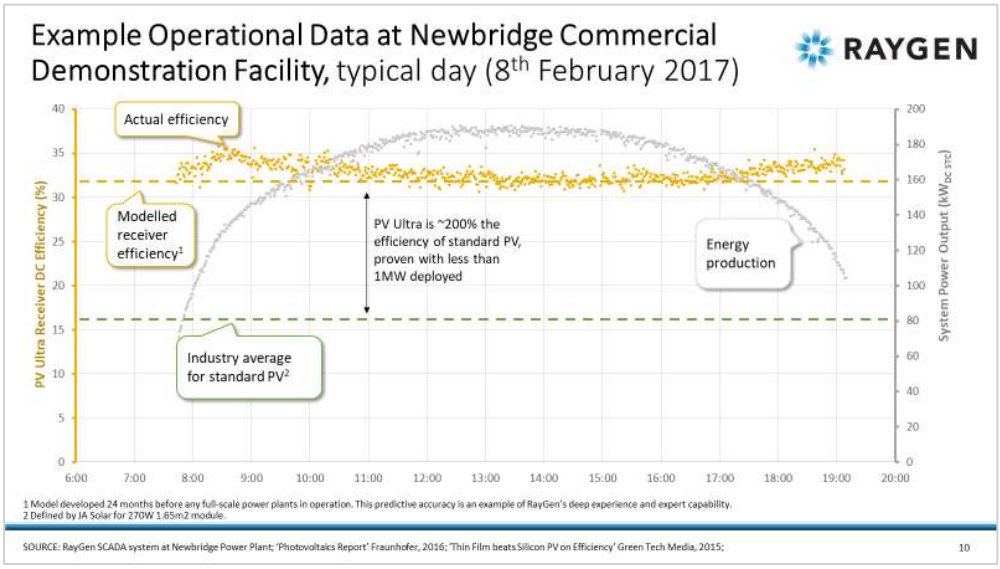

Figure 1 Operational Data at Newbridge Pilot Demonstration Facility

Data is taken at key points in the system throughout the power production process and compared with the system performance model developed during the design of the solar power-station. During a recent operational run, an availability of >98% has been achieved.

A time lapse video of the site operating is available at https://www.raygen.com/raygen-technology/

1.2 Environmental exposure

The Pilot Demonstration facility has been exposed to the environment for over 30 months of operation. The system has been exposed to and withstood extreme conditions including temperatures of -2°C to +46°C and wind speeds of 130 km/hour without damage. In addition, the Chinese site has experienced temperatures as low as -25°C. No damage has been caused after heavy rain, lightening or hail.

1.3 Technology Readiness Level progress

In early 2015, PV Ultra had a Technological Readiness Level of 7 – *'System Prototype Demonstration in an operational environment'*. Prototypes of the PV Ultra module and the PV Ultra solar field heliostats had been demonstrated at RayGen's Research and Development Facility in Bayswater, Victoria. RayGen had already set the Solar System World Record Efficiency of 40.4% with the UNSW for a PV Ultra development module (known as the 'Solar Cube').

Now in 2018, with three years of operating experience for this facility and with two further projects installed, RayGen has a Technological Readiness Level of 9 – '*Full commercial application, technology available for consumers.*'

The technology has been deployed in Australia and China:

- 0.2MW industrial agricultural business in regional Victoria, Australia.
- 0.5MW expansion of the regional Victorian site, due to finish commissioning in Q1, 2018
- 0.2MW manufacturing business in semi-urban Zhuozhou, China.

RayGen is actively in the market retailing the PV Ultra technology. The two products available are the R1-0.2MWe and the R3-1.0MWe. More information is available here: https://www.raygen.com/product-category/raygen-products/

2 PV Ultra

RayGen pioneers PV Ultra, an innovative, next generation combination of high-efficiency solar cells and low-cost mirrors.

The PV Ultra system uses a field of active mirrors (known as heliostats), which collect and focus sunlight over 600x to a tower-mounted central receiver. The receiver contains an array of ultra-high efficiency modules which are actively cooled. The modules convert the light into electricity (there is no heat turbine), and captures thermal energy from the cooling as a useful by-product. The mirrors only focus the light onto the receiver, they do not generate electricity.

2.1 Least cost solar collection

The heliostats in the 'collector field' follow the sun throughout the sky with two-axis tracking as standard. The mirrors are self-powered (with a small on-board solar power panel) and communicate wirelessly with the tower – no field wiring is required.

The mirrors are inexpensive to manufacture, to install, and to maintain. The heliostats are highly error-tolerant. They can be mounted on a low cost driven-pole and only a spanner is required to install and commission.

2.1.1 Booster heliostats

A solar field separate to the receiver makes it possible to adjust the field size according to the customer needs and the solar resource level. The solar field can be over-sized for the peak power rating without over-sizing the modules, enabling a flatter generation profile across the course of each day. The power generating and converting infrastructure can be driven to as close to full capacity as possible to maximise customer value. No other PV or CPV system has this capability (PV typically over-sizes the installed modules).

2.2 Highest efficiency solar conversion

The ultra-high efficiency module mounted in the tower is actively cooled and converts the focussed sunlight into electricity as well as heat. The module uses only the best solar cells available which are twice as efficient as conventional silicon PV cells at converting light to electricity.

In addition, the sunlight that is not converted to electricity is captured as heat and available for many applications.

Thus, PV Ultra creates useful commercial products from over 80% of the sunlight that strikes the mirrors – conventional silicon PV typically utilises less than 20% of the sunlight that strikes the panel surface.

2.2.1 Cell advantages

The electrical (photovoltaic) generator uses high efficiency III-V Multijunction space grade solar cells.

- **High efficiency**

  The current efficiency of the production cells used in the PV Ultra system is 38%. New developments for this type of cell have delivered a world record efficiency of 46% with several organisations (including NREL and Fraunhofer) currently working on 50% efficient devices. The theoretical efficiency for this type of device is in excess of 60%. The current system efficiency is approaching 26% and it is expected that these devices will be in production within the next few years and bring the *PV Ultra system efficiency to well in excess of 30%.*

  (By comparison the current record for silicon cells is around 27% with a theoretical efficiency of 30%. *Typical Silicon PV system efficiency is in the range of 12-17%*).

- **Low temperature coefficient**

  III-V multi-junction cells have a very low performance degradation with temperature increase. On a hot day, silicon cells can lose as much as 20% of nameplate, whereas PV Ultra's multi-junction cells will only lose 6% in the same conditions. This unique feature currently allows useful heat from the cell cooling system to be extracted at a temperature of 60°C without significant power loss.

- **High temperature stability**

  New multi-junction cells are under development at NREL and Arizona State University to develop cells which can operate at or above 400°C. First samples have been tested and show excellent stability. Once these cells become available the PV Ultra system will have the capacity to produce high grade heat as a by-product.

  RayGen has visited these organisations with a view to sharing knowledge and resources to accelerate the progress of this technology. RayGen can provide real-world system knowledge in manufacturing and deployment as well as providing 'on sun' testbeds to inform rapid development of production cells.

3 Lessons Learned

After construction and operation of the 200kW Pilot and the build of the 0.5MW plant, lessons have been learned through the design, supply, manufacturing, installation and operational spheres. Lessons learned include;

- Certain aspects of an innovative technology may be unclear to some component suppliers who have not worked with optics or photovoltaics. Suppliers need to be screened for their relevant capability and with appropriate education/training excellent results can be achieved.
- Tight tolerances require precision manufacturing and skilled labour. Designs which are 'error tolerant' and contemplate system assembly and operation can reduce time and cost from suppliers.

- The weather is unpredictable and site construction time can be heavily influenced by wind, rain and temperature which result in unsafe or a less than optimum working environment. The product should have a maximum degree of prefabrication and a minimum degree of on-site finesse and skilled labour requirement. This reduces cost and ensures greater certainty of cost for the installed product
- Further to the above point, minimising the parts count for erection and connection also reduces cost through consolidation and appropriate scaling of systems and subsystems.
- While it is well known that 'scaling up' can reduce cost, having an 'actual build' with a confirmed baseline case provides the means to perform a detailed sensitivity analysis which has revealed that substantial cost savings can be realised through consolidation of certain sub-systems. Scaling up of the mast, cooling system, receiver and inverter can realise a 30% cost reduction while still using the same modules, heliostats and control system.
- Plant siting is important. Apart from macro-factors such as latitude, elevation, temperature, windspeed and solar resource, local factors such as vegetation, rivers, hills and industry can have an influence on project delivery and O&M. For example, while the current Pilot is co-located with an excellent industrial partner, trucking activity produces substantial dust which can reduce the average output of the plant. Heliostat parking and washing strategies are under development to minimise this loss.
- Booster heliostats can be used to increase plant output and reduce LCOE. These are under test.
- By-product heat can be produced at 60°C and boosted to higher temperatures to increase value to the customer.

4 Status of Technology Development

During the operation, trialling and improvement of the pilot plant over the last three years, the system has been brought up to a level of consistent performance within target specification and has the capability for autonomous operation. The core technology of the heliostat field, control system, receiver, cooling system have been proven. The processes by which the system is built and deployed have also been established including; supply chain for all key components, manufacturing plant, QA/QC systems, deployment methods and O&M procedures. Along with planned enhancements and 'lessons learned' improvements have been incorporated to refine delivery processes and through 'design for manufacture' resulting in;

- Simple, accurate and repeatable heliostat design, assembly and installation processes
- Robust, intelligent control system which monitors and manages all active elements
- Automated module manufacturing with 'online' monitoring linked to QA/QC processes
- Stable and efficient modules produced at high yield
- Online system monitoring for continuous performance assessment
- System level technical readiness of TRL-9

All of the above points will be demonstrated during the 0.5 MW build and operation. Current development work on the next generation 'R3' also includes consolidation of sub-systems into a one MW field which uses the same key components and has an output of 1MWe and 2MW+ of heat. Further work is focussed on enhancement of heat extraction to provide more value to the customer.

5 Comparison with other solar technologies

RayGen's PV Ultra combines the best of other solar technologies to deliver the superior product.

5.1 Comparison with Silicon PV

The ultra-high efficiency module RayGen uses is nearly twice as efficient when compared to traditional silicon PV panels (up to 40% compared to 20%), the light is focused over 600x by mirrors onto the PV Ultra panel in the receiver. The PV Ultra panel produces over 1200x the electrical power vs regular silicon photovoltaic panels of the same area.

This means that PV Ultra is much more value intensive. Standard photovoltaic systems require 6,000m^2 of flat panels per MW. PV Ultra uses 3,600m^2 of mirrors and just 4m^2 of photovoltaic material per MW; every square metre of RayGen modules can produce 250kW of electricity and over 400kW of heat energy.

Both Silicon PV and PV Ultra systems require the same land area – however the optimised 2-axis tracking field can increase electricity yield by 15% vs standard silicon PV. In addition, the heliostats are wireless and raised off the ground, enabling dual land use, such as grazing of sheep.

Because the mirrors and tower are made using existing technology drawn from automotive and electronics manufacturing, a PV Ultra installation can have a far higher level of local content than imported solar panels.

5.2 Comparison with Concentrated Solar Power (CSP)

PV Ultra also has clear advantages over Concentrated Solar Power (CSP).

Like CSP, PV Ultra collects the sunlight using heliostats focussing light onto a tower, but that is where the similarities end. Where CSP uses a thermal receiver and complex, expensive heat turbines that require a lot of maintenance, PV Ultra uses a photovoltaic cell that requires little maintenance and upkeep.

To be efficient, CSP requires tall, massive towers over 150m high (similar to a sky-scraper over 50 storeys high).

By contrast, PV Ultra's tower is thin and less 50m high (similar to a standard light tower). RayGen has already demonstrated its commercial efficiency at 1/4MW.

5.3 Comparison with Concentrated Photovoltaic (CPV)

PV Ultra has several advantages over CPV.

All of the high-tech semiconductor components (modules) are all contained in the small factory built 'receiver'. The collector field is aligned to the receiver with software, not hardware. This means that manual field alignment is not required, software correction allows low precision hardware and low precision installation, and manufacturing tolerances can be relaxed.

The manufacturing processes for the cell modules and heliostats use existing automation technologies currently used in industry – automotive manufacturing techniques and facilities for the heliostat, and standard electronics manufacturing for the cell modules. This means that PV Ultra delivers reduced cost to scale, equipment is pre-fabricated and installation is rapid, labour costs are lower, and leveraging existing automotive and electronics manufacturing makes it easy to meet local content requirements.

A 1 MW receiver with a dense module array is just 4m^2. This allows for easy shipping, upgrades of new modules, centralised heat management system enabling heat sales, centralised power conversion that eliminates field wiring, and optimised flux management that enables constant flux.

6 Cost of PV Ultra

RayGen is now in the final stages of commissioning two PV Ultra power towers for the Newbridge Expansion Project.

The overall project includes these two new PV Ultra power towers, development of the technology design and a large manufacturing upgrade (from 8MW p.a. to 25MW p.a.) RayGen's private investment was supported by the Australian Federal Government (ARENA) and the Victorian State Government (New Energy Jobs Fund).

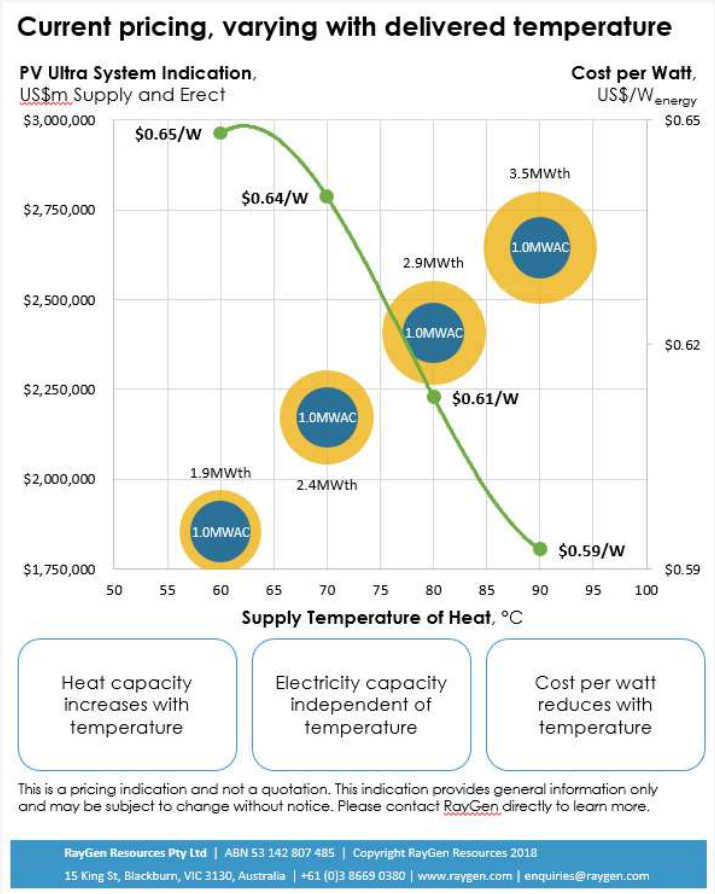

Figure 2 Current PV Ultra pricing, varying with delivered temperature

The investment in the technology design, manufacturing and the deployment of these two towers has enabled RayGen to develop an attractive commercial proposition. RayGen's system retails for less than 60c/W_{energy} with one-part AC power to two-four parts thermal heat.

The Levelised Cost Of Electricity (LCOE) for the system is US$50/MWh.

7 Markets for PV Ultra

7.1 Electricity market for PV Ultra

PV Ultra is a purpose-designed system for utility projects and large behind-the-meter C&I customers.

PV Ultra is not a scaled up domestic product. It is ideal for applications in excess of 0.25MW electricity, with co-generation heat potential nearby, in regions with moderate to high solar resource, and with land available for placing mirrors.

2-Axis tracking as standard can increase electricity production by up to 15% more electricity per annum than standard fixed plate PV.

Typical installations include:

- Utility,
- Behind-the-meter commercial and industrial customers, and
- Large community and off-grid projects.

The PV Ultra technology is not suited to rooftop applications.

7.2 Heat market for PV Ultra

PV Ultra generates heat; heat that can be used to replace existing fossil-fuel heat generation, or to create potable water using multi-effect distillation desalination. The heat sales can be used to offset the costs of the project meaning the PV Ultra system can pay for itself far more quickly than competing solutions, as well as substantially increased carbon reduction.

PV Ultra is the only tower-mounted concentrated PV technology commercially available that offers electricity and heat. The PV Ultra system generates over 7GJ of heat for every 1MWh of electricity.

- Co-generation yields higher energy revenue, higher asset utilisation and a wider product range for each solar power plant. The heat can be used to deliver:
    - Reduction in gas, diesel and other heating consumption
    - High quality water, via Multi-Effect Desalination
    - Dispatchable power, via Organic Rankine Cycle and the Kalina Cycle
    - Low cost storage, via improving the round-trip efficiency of Compressed Air Energy Storage

7.3 Other advantages

PV Ultra has potential for highest Customer Internal Rate of Return of any solar technology, with multiple additional benefits.

- **Future-proof.** With PV Ultra, the investment is guaranteed, with long-term investment protection and options for future software and module upgrades.
- **Local manufacturing.** Heliostats and mast can be manufactured and/or assembled local to the project.
- **Lighter footprint.** Heliostats do not require field wiring nor foundations. Dual-land use (e.g. grazing for sheep) as standard.
- **Highly capital efficient manufacturing.** PV Ultra requires just 3,600m^2 of mirrors, and 4m^2 of modules per MW as opposed to PV's requirement of 6,000m^2 per MW. It is also at least 10 times the capital efficiency to produce the PV Ultra modules compared to standard silicon PV panels – requiring less than US$50m per 1GW of manufacturing capacity.