# Back to the Future: Implementing Small Scale Solar Thermal Generation with Storage

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***Abstract*— There are more than thirty-four working installations of large scale solar thermal plant with thermal storage that have been successfully implemented in high solar resource locations throughout the world. These solar thermal plants typically use concentrating solar plant with parabolic troughs or solar towers coupled with molten salt thermal storage. All are large-scale generators with capacity of fifty megawatts or more.**

**Most of the generation and storage technologies that are economically viable for large scale power plants, such as molten salt storage and turbine electricity generation do not scale down well. Small scale isolated solar thermal power plants of one megawatt and under need storage over a range of operating hours (overnight and up to three days) for a wide range of applications in the rural, mining and tourism industries.**

**This paper shall explore the design and feasibility of a practical small scale solar thermal electricity plant from both a technical and economic perspective. This work is based on real-world experience gained through a unique combination of simulation, experimental investigation and prototype plant measurement and analysis, both in Australia and in the United States.**

**The small capacity of the generation plant requires a very different approach to the generation of electricity, as turbines perform poorly for capacities of one megawatt and under. A number of different electricity generation technologies will be discussed, and the results will show that for the small-scale size of these isolated plants, high efficiency reciprocating piston steam engines, of the type that was common at the start of the twentieth century, are available that can operate efficiently without superheated steam and with low maintenance requirements, making them ideal for operating with a thermal unit that delivers only wet steam.**

**There are many possible options for the required energy storage for small solar thermal plants including physical inertia devices, batteries, pumped storage and various types of thermal storage media such as molten salts, concrete and gravel. A novel low-cost solution will be presented that uses on site materials as the ideal solution for most applications as the required materials are nearly always available.**

**Finally, the complete proposed solution and modelling results, for an economically and technically feasible solution, will be presented that includes all the required main components for a complete isolated small-scale generation plant. The proposed design will demonstrate that the combination of traditional reciprocating piston steam engines and innovative low technology storage solutions, provides a compellingly cost-effective system for a wide variety of applications.**

***Keywords – solar; small-scale; storage; steam engines***

## I. Introduction

This paper describes the history, design and proposed implementation of the small-scale solar thermal generation known as the Rural and Residential Energy System (RRES). The plan covers the manufacture and delivery of a possible total of 41,200 installations, that is 4.1% of the 1,000,000 residences at Australian country towns with population less than 10,000. That number includes residences at villages, hamlets, remote houses and farms.

Worldwide 650 million people will still be left without access to electricity in 2030. Nine out of 10 of them will be living in sub-Saharan Africa [1].

Every village in India is now connected to an electricity grid. However, grid reliability remains a huge challenge there and in many other countries. The largest nineteen blackouts have all occurred in the last 22 years [2]. The smallest affected 21 million people and the largest, in Mumbai India, affected 620 million people.

The RRESs described in this paper can resolve all these challenges and provide a local solution. Also, the technology involved is well within the skills present at most challenged locations.

The paper provides some historical background of Concentrating Solar plant and STTS plant and then describes the technology and advantages of Solar Thermal with Thermal Storage (STTS) plant. It is important to emphasize the difference between STTS and Solar Photovoltaic (Solar PV) plant. The term CSP does not adequately differentiate between STTS plant and Concentrating PV plant.

A very limited historical background of Concentrating Solar plant and STTS plant is presented in the paper. A Rural Residential Energy System (RRES) is defined as an assembly of five separate required sub-systems and three optional sub-systems.

The paper outlines a proposed business plan required to take advantage of the large market for very small scale and low-cost plant. The plan is to use mass production to drive down costs so that end users see a simple return on their investment of more than 7% per year based on a basic installed RRES costing USD 24,000. For larger energy users that could rise to above 10% per year.

## II. Historical background

In 1912 Frank Shuman installed a solar thermal plant, at Maadi in Egypt, for pumping water [3]. The plant shown in Figure 1 used water at atmospheric pressure, to store heat. A steam engine expanded steam, from the storage, to much lower pressures in a condenser.

The water that stored the thermal energy, remained at atmospheric pressure all the time. That limits the maximum thermal efficiency of the system to a theoretical maximum of 16%, with a condenser operating at 40 °C. The actual efficiency, solar to mechanical energy was probably about 7%, assuming the average trough solar to thermal efficiency was 55% and stage efficiency of 80%, a high value at that time.

Robert Mierisch had previous personal experience with the development of Solar Collector Assemblies (SCAs), in California USA working for two years with *Ausra Inc*. in Palo Alto and five years with *Terrajoule Corporation* in Redwood City and their demonstration plant near Waterford during the period from 2007 to 2015. Robert experienced for himself the serious limitations that makes the SCA designs from that era unsuitable for use in the RRES.

During 2007 and 2008 *Ausra Inc*. received approximately USD 140 millon in venture capital funding and most of that funding was spent successfully building a five megawatt (5MWe-peak) solar thermal plant located at Kimberlina, California. The plant provided steam to an existing steam turbine that was previously supplied with steam from a biomass fired boiler.

In development at the same time as the Kimberlina plant project, Robert Mierisch led a team that developed a dry cooling system using buried plastic pipes [4] and the use of thermal storage using mixtures of silt, sand, soil, crushed rock and other materials [5].

The structure of the Concentrating Linear Fresnel Reflector (CLFR), used by Ausra was necessarily very long (300 metres) and very high (17 metres). The structure did not need to be torsionally stiff. Both ends of each section, about 12 metres long, were rotated by a separate drive. The Ausra Solar Collector Assemblies (SCA) were "Direct To Steam" (DTS) type. Water was pumped in at one end and dry steam exiting at the other. A separate superheater line was planned.

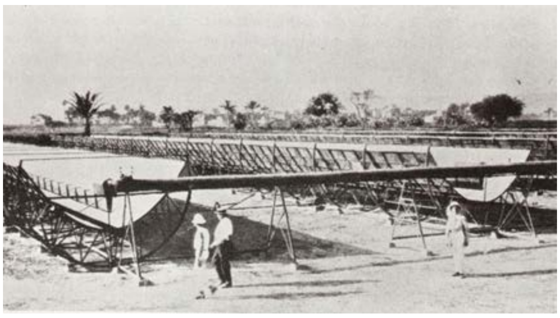

*Figure 1. Shuman-Boys Plant 1913*

The Ausra glass mirror reflectors were made and supplied flat. Then, only slightly curved, achieved by deflecting them and gluing them to corrugated steel panels. The panels were then mounted on curved rectangular hollow steel sections. The Ausra system is entirely unsuitable for installation at small scale.

Ausra did not find an acceptable alternative thermal storage approach and molten salt storage proved to be too expensive. The proposed USD 680 million plant for Carrizo Plains was abandoned when revised costings required additional financing costs of at least USD 80 million with a necessary increase to the agreed price for energy output with Pacific Gas and Electric. The plans were then abandoned and Ausra was sold to the French company AREVA, that operates nuclear power plants in France.

From 2009 to 2015 Robert Mierisch was the co-founder, director and Chief Technology Officer of the Solar Storage Company that became Terrajoule Corporation using USD 11 million in venture capital funding.

Terrajoule built and demonstrated a solar thermal power plant at Waterford, California using approximately one thousand square metre of parabolic trough collectors. A heat transfer fluid heated a steam generator, designed by Robert Mierisch that was designed to comply with ASME Section VIII. The steam generator supplied a purpose design and built high-pressure Reciprocating Piston Steam Engine (RPSE). RPSE exhaust heated a large steel vessel 12 metres long and 3.6 metres in diameter filled with water. When the vessel was heated by the RPSE exhaust, it supplied steam (at some later time) to power second and third stage Reciprocating Piston Steam Engines (RPSEs).

The design and performance of the solar thermal plant was modelled initially by Robert Mierisch using large complex spreadsheets, and then by Harley Mackenzie using Modelica, which is an open source object-oriented, declarative, multi-domain modelling language for component-oriented [6] modelling of complex systems, e.g., systems containing mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents. Using the Modelica software for modelling plant improved the iterative design process and allowed for the rapid design prototyping and analysis of other proposed applications of the solar thermal plant technology.

Stage efficiency of the Terrajoule RPSE was demonstrated to be greater than 70%. That stage efficiency compares with the highest value reported (91%) in any of the many published reports found from 1890 to 1922 [7] [8] [9] and [10]. The highest value reported was for operation on superheated steam at high pressure.

The design of the RPSE draws on the excellent work of Johann Stumpf [10] and his reporting of the work of Professor Nagel (1912) on transient heat transfer into and out of the metal surfaces in RPSEs. Considerably more detail on RPSE efficiency is detailed in the paper by Robert Mierisch [11] on the history and future of RPSE.

The Terrajoule glass parabolic mirrors were much more expensive to manufacture than the Ausra CLFR mirrors as the mirrors were more tightly curved at high temperatures to a radius of about three metres. The cheapest cost of the entire mirror SCA available in California was approximately USD 200 per square metre of aperture. Each mirror panel has four ceramic blocks glued to the back for mounting and the mirror panel edges are dressed smooth, but the glass was not toughened.

Any serious hailstorm would destroy most of the mirrors and some mirrors were broken mirror at the Terrajoule SCA field in Waterford California. Terrajoule were then required to purchase several replacement mirror glass panels, each about 1.7 metres square, for more than USD 50 per square metre.

The two solar collector lines installed for Terrajoule were each 100 metres long and driven by a hydraulic mechanism, from the middle. The structure was severely lacking in torsional stiffness. They were so flexible that bearing friction prevented mirrors at the ends from tracking effectively. That problem was never resolved, and collection efficiency remained very poor.

## III. Rural Residential Energy System (RRES)

The proposed Rural Residential Energy System (RRES) provides electricity, hot water and some winter heating. Electricity and heat to meet requirements and is available twenty-four hours a day, every day of the year.

When a larger system provides charging of one electric vehicle, every day, the RRES will provide all the winter heating required for a medium sized modern Australian house. The heating available from the RRES will be up to four times the electrical energy used.

Heat energy is usually cheaper than electricity and not all the heat available is used, especially in summer. That means the heat and electricity in the RESS will be about equal in value.

The RRES is a combination of the following five essential sub-systems and three optional sub-systems:

1. Solar Collector Assemblies (SCAs). Parabolic glass mirror panels with one axis solar tracking and inclination sensors.
2. High temperature Thermal Energy Storage System (TESS) with separate pumps for high-pressure and low-pressure piping.
3. Reciprocating Piston Steam Engines (RPSEs) connected to DC electrical generators, with speed sensors and over-speed protection.
4. Condenser system, air cooled with air pumps, ducts and diverters.
5. Solar Photovoltaic (Solar PV) plant, battery and inverter.
6. Backup boiler (Option A).
7. Backup generator (Option B)
8. Wind generator (optional).

The RRES physical layout is shown in Figure 2. The entire RRES plant is designed to fit in an area of approximately 100 m$^2$ and so can be easily accommodated on most rural sites with little impact. The distance between the TESS and the residence can be up to 48 metres. It can be much closer. Making it further away, up to 150 metres is possible, but expensive. The SCAs are 2.7 metres wide and need to be spaced about 5.3 metres apart, to limit shading.

## IV. System component detail

This section provides additional detail for all components of a Rural Residential Energy System (RRES).

The following Process Flow Diagram (Fig. 3) shows only three Solar Collector Assemblies (SCAs) and shows flows from the Hot Well that maintains the high-pressure of water in the Thermal Energy Storage System (TESS), for circulation to the SCAs.

The PFD also shows feed water pumped to the TESS for steam production to supply the Reciprocating Piston Steam Engine that drives the Generator. The Generator and the PV panel keep the battery charged to meet all the demand of the residence. The inverter produces Alternating Current to meet local demand.

The steam exhaust is condensed by the air-cooled condensers. The condensate, at about 60°C, is pumped back to above atmospheric pressure and returned to the Hot Well. Water “bleeds” from the TESS as it heats and expands. That water raises the temperature of the “Hot Well” above 60°C and up to 100°C. Any excess energy will evaporate water from the Hot Well.

Air heated by the air-cooled condensers is diverted for winter heating, when required. The hot water in the Hot Well

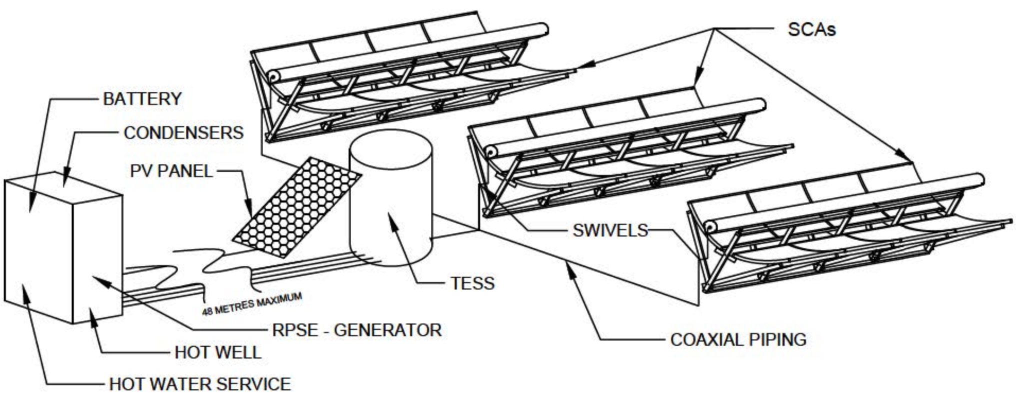


*Figure 2 - Rural residential energy system physical layout*

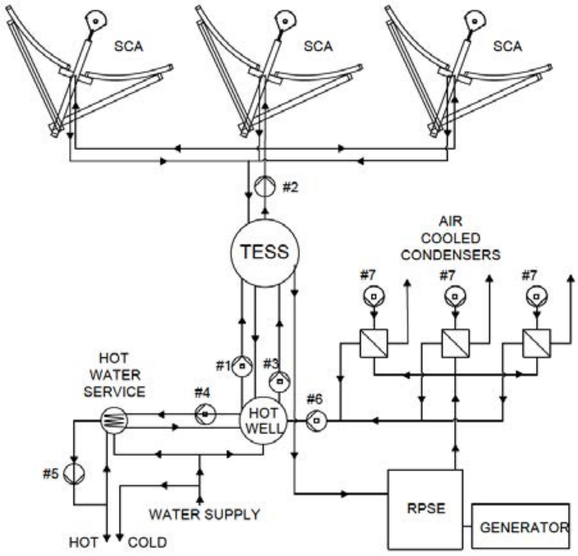

*Figure 3 - Process flow diagram for RRES*

provides heat to the Hot Water Service. It can also be used for floor heating, hot water radiators, pool heating and spa heating, where these needs are present. For the pool and spa heating additional heat exchangers are essential to limit corrosion/erosion of the plain carbon steel system.

The hot water from the Hot Well is pump circulated, with control, through a pipe coil in the Hot Water Service to maintain the set temperature of water in the Hot Water Service at the desired value, as selected by the end user from the range 40°C to 55°C.

Each RRES has at least three SCAs. An additional three are required for overnight charging of one electric car. Larger numbers of SCAs are planned for plant up to 100-kilowatt peak output. At that scale two RPSEs with 50-kilowatt peak output are ideal for reliability and high efficiency.

The SCAs are glass mirror parabolic trough type with inclined axes and each SCA has an aperture of 11 square metres, with tracking about one axis. The SCAs are designed for cyclone resistance (70 metre per second wind gusts). They are hailstone and sub-sonic bullet proof. The glass mirror will not shatter when broken.

Each RRES has at least one high-temperature Thermal Energy Storage System (TESS). One TESS can provide continuous electrical energy for a small house. Each unit stores heat sufficient for 15 kilowatt-hour electrical output. Larger systems need more than one TESS.

The high-pressure feed pump (#1) maintains the pressure in the TESS and SCAs. The water pressure is maintained at 19 MPa.

The circulating pump (#2) transfers heat from SCAs to the TESS. Temperature varies from 200°C to 360°C.

The feed Pump (#3) for the TESS water to steam circuit operates to a maximum pressure of 4.1 MPa.

The circulating pump (#4) heats the residential hot water, pool heater and spa heater, as required. The water pressure remains close to atmospheric pressure and temperatures at or below 100°C.

The Reciprocating Piston Steam Engine (RPSE) is a 5 kWe-peak DC generator that uses fixed timing automotive poppet valves with valve springs, roller cam followers and crankshaft mounted cams. The RPSE-generator speed can vary from 300 rpm to 1500 rpm.

The condensers are air cooled with air pump(s) (#7), ducts and air diverters. The condensate extraction pump (#6) pumps water and some incondensable gases from piping one metre below the condensers to the top of the Hot Well. The incondensable gases vent from the Hot Well.

The “Hot Well” water storage is a 210-litre insulated tank. Larger systems need multiple 210-litre tanks to store most of the energy from the excess feed pump flow required by regulation. The temperature is kept hotter than 65°C, by condensate from the RPSE exhaust steam and/or backup boiler flue gases and/or backup generator cooling. That prevents bacterial growth in the water. It is designed for operation to a maximum temperature of 100°C. This is the only storage that vents to atmosphere and is not pressurized.

Hot Water Service (optional) sub-system can provide mains pressure or pumped water supply pressure, with 20 litre capacity and the hot water is maintained within 1°C of a set temperature, as selected from the range 40°C to 55°C. The Hot Water Service tank is heated by circulation of water from the Hot Well. An additional circulation pump is an option to keep water in supply pipes heated, to reduce water consumption waiting for hot water to “come through”.

A backup Hot Water Boiler operating at 19 MPa is “Option A”. It is a forced hot water circulation water tube type. It has a circulation pump that is not shown on the Process Flow Diagram. Fuel recommended is firewood or LP gas. The boiler is designed to heat the TESS, not to provide steam to operate the RPSE-generator. Operating the boiler for up to 12 hours a day will provide all the backup energy required for any RRES, when the solar resource is poor. A flue gas heat exchanger provides additional heat to the Hot Well.

A backup generator Direct Current (DC) is “Option B” where the output is limited to 30 volts with a capacity of 6 kVA. An LP gas powered internal combustion engine is recommended as the fuel does not degrade over time. A small Nickel-Iron, Lithium-Ion or Lead-Acid battery, nominally 24volt and 20 ampere-hour, is sized to run the inverter with maximum output for up to four minutes during engine start-up. The system includes an inverter for 5 kilowatt-peak Alternating Current (AC) output at 240 volt and 50 Hertz. Three phase inverters (415 volts, phase to phase) are available as an option.

The Control System actuates the SCA tracking, SCA parking and the circulation pump(s) and maintains/controls the TESS temperature in the range 200°C to 360°C, the Hot Water Service temperature, the backup generator and/or the backup boiler. The control system also monitors the following: electrical demand, inverter operation, circulation pump function, RPSE speed, generator output, backup generator operation, backup boiler operation and battery voltage and current.

Any electrical demand greater than 50% peak output for more than two minutes will trigger the control system to start the steam engine. The control system will stop the RPSE-generator and/or the backup generator when electrical demand falls below 50% of peak and the battery charge level is greater than 98%. The control system will always start the RPSE when the battery charge level falls below 60%.

## V. Solar Collector Assembly selection

Solar Collector Assemblies (SCAs) currently available are not suitable for most locations in northern coastal Australia as the wind loads are too high for the structures. Also, most systems do not use "Direct To Steam" (DTS) generation. Instead, they use circulated Heat Transfer Fluid (HTF) that is circulated at much lower pressures than DTS systems where the heat transfer fluid must deliver heat to the thermal storage and transfer again to an evaporator. The DTS system is ideal for use with thermal storage, particularly at small scale and the additional cost and reduced performance of heat exchangers is prohibitive. The cost of Heat Transfer Fluids and the system to prevent oxidation and leakage (nitrogen blanket and bunds) make them unsuitable for use in RRESs.

The SCAs heat circulated water to a maximum temperature of 360°C and the water inside the solar receivers and TESS will reach pressures of 19 MPa. Little or no steam will be generated in the high-pressure water circulation piping.

SCAs structure is Pinus Radiata (MGP10 or better) trusses enclosed and capped with black High-Density Polyethylene (HDPE). This type of construction and weatherproofing keeps the structure cost to less than USD 36 per square metre, at a modest level of volume production. That compares with common, one-off, roof trusses that cost less than USD 24 per square metre. Enclosing and capping with HDPE ensures a service life of the SCAs greater than 25 years. Also, this approach allows 100% material recycling, for the structure.

Suitable glass mirrors, for the SCAs are 1.2 metres square and 3 mm thick are available from India. Delivery has been quoted for less than USD 12 per square metre delivered to the Port of Melbourne based on a quantity of one crate containing 180 pieces. The price for small quantities made in Australia is more than USD 100 per square metre. The vast difference in the price of the mirrors for different quantities is an excellent example of the economies of scale that are critical to the financial viability of the RESS design.

The parabolic trough type SCAs have two lines of four mirrors (Fig 4.) with overall dimensions, without the solar receiver, of 5.2 metres by 2.8 metres. The top half of the solar receiver is a semi-circle 310 mm in diameter with the lower half having two angled glass panels. The solar receiver is 6 metres long.

The total aperture of each SCA is just over 11 square metres. Note that the diagonal struts and support structures are omitted from the figure, for clarity.

The troughs are mounted with the axis of rotation at least 15° from horizontal as the angle is at least 15° and greater angles are recommended outside the tropics and that angle dramatically increases overall SCA efficiency. The effect on efficiency is greatest in winter, particularly outside the tropics. Also, the angle helps to keep the solar receiver pipes free of any debris, when the system is blown down and/or flushed.

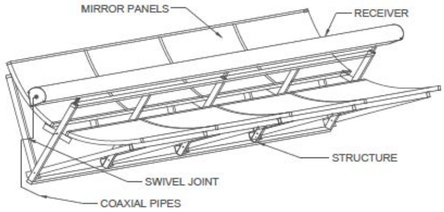


*Figure 4 - Detail of the solar collector assembly*

Solar receivers are made from painted and *Zincalume* type coated steel sheet that are 1.2 mm thick. High performance insulation fills the top half of the receivers. The receivers have two glass panels, one on each side, angled to minimize transmission losses from the parabolic mirrors on the same side. The solar receiver case weighs less than 60 kilogram and the steel costs less than USD 130. The receiver material cost adds less than USD 12 per square metre to the overall cost of the SCAs. The support for the solar receiver is on the bottom of the receiver, between the two glass panels.

A vent at the lower end of the SCAs receivers, with a High Efficiency Particulate Air (HEPA) filter cartridge attached, keeps the pressure inside the receiver very close to the pressure outside. The filter prevents dust from settling inside the mirrors and, although it will not prevent condensation, the water can drain and/or evaporate through the HEPA filter cartridge.

The glass panels of the solar receiver are in sections 600 mm long and about 205 mm wide. A seal of linseed oil putty, one millimetre thick separates the ends of the sections. Linseed oil putty is selected for its resistance to temperatures in the range -20°C to 150°C. The long sides of the glass panels are protected and sealed with High-Density Polyethylene (HDPE) extruded channel where the thermal expansion of the glass is prevented by the ends of the steel case of the solar receiver. The final step of assembly of the solar receiver applies compressive stress to the glass to prevent cracking of the putty seal when the glass cools more quickly than the insulated steel case supporting it.

The glass panels on the solar receiver may be coated to increase radiant transmissibility and would result in an increase in solar collection of at least 5%. The SCA of 11 square metres aperture has an installed cost of about USD 1,200 where the two glass panels on the solar receiver have a total area of about 2.46 square metres. The coating of panels for one SCA unit, on both surfaces, must cost less than USD 60, that is USD 12 per square metre of coated surface to provide economically justified advantage.

Mirrors 1.2 metres square and 3 mm or 4 mm thick, are subject to compressive stress in two directions. They are curved when cold and held curved by the frame surrounding them. In a test, glass curvature as tight as a radius of 500 mm caused no cracking of the mirror using a mirror that was tested with compressive stress in only one direction and a 5 mm plywood backing. It suffered no damage from five 5.6 mm (0.22 inch) diameter solid lead bullets weighing 2.59 gram (40 grain). The bullets had a velocity at impact of 300 metres per second (984 feet per second). They were directed normal to the mirror surface. The five bullets fired left only a grey smudge.

Tracking of the sun is actuated by servomotor driven recirculating ball screws. The drive control has a park-on-fault function with power from the battery, charged by the PhotoVoltaic (PV) panel. The PV panel provides most of the sunlight-hour parasitic loads. The fault circuit includes a pressure difference switch sensing flow of the water in the solar receiver tube.

Preliminary design calculations and costing for Solar Collector Assemblies (SCAs) for the Rural Residential Energy System (RRES) show that the completed SCAs can be made and installed for less than USD 95 per square metre.

The cost of the mirror mounting and surrounding frame can be less than USD 14 per square metre. To keep the price to that level, a specialized assembly set up will be needed that can process one panel, 1.3 metres square (1.2 metres square glass) every minute. Each panel will cost a total of USD 21, or less.

A specialized set up for the manufacture of the panels will is estimated to cost less than USD 160,000. If used for batches of 10,000 panels taking five weeks for production for each batch, the manufacturing investment can be recovered with less than four batches at a rate less than USD 4 per square metre of glass. Approximately seventy percent of the cost will be materials and the remainder (30% or USD 5.80 per panel) recovering the set-up cost in less than 26 weeks production.

## VI. Thermal Energy Storage System

Thermal energy collected by the Solar Collector Assemblies (SCAs) is collected during normal operation at a temperature in the range 200°C and 360°C. All the energy collected heats the Thermal Energy Storage System (TESS). The specification of a low maximum temperature allows the use of the most common and cheapest steel pipes and plates. The thermal energy stored will supply enough steam to generate up to 15 kilowatt hours of electrical output.

The cost of the TESS is much less than molten salt storage, particularly at smaller scale. It is dramatically cheaper than any battery system. Also, the effective round-trip efficiency is about 97% [13] much higher than any battery or pumped hydro. Neither of those proposed energy storage approaches produce any energy or useful by product heat.

Some low temperature thermal energy is stored, for hot water supply and residential heating, at a temperature in the range 65°C to 100°C. Excess thermal energy can and should be used for one or more of the following applications:

- A swimming pool heated to a temperature 26°C to 29°C.
- A spa at a temperature 37°C to 39°C.
- A dam at a temperature 10°C to 20°C.

The High Temperature Thermal Energy Storage System (TESS) units are less than 1.2 metres in diameter and 2.1 metres high so that 20 can be transported in a 12-metre shipping container. This geometry also makes for simple and secure mounting for risk control in a residential construction environment. They are suitable for mounting outdoors but that is not recommended. Winter heat losses are reduced when the TESS is in a house or shed and the heat losses can then be used for drying clothes all year around.

The TESS is a cylindrical container with flat ends. The internal walls and ends are steel plates at least 5 millimetres thick. The external wall is corrugated steel about one millimetre thick with galvanized or *Zincalume* type coating. The corrugations permit elastic elongation, when the inner walls are hotter.

The steel container is filled with a mixture of locally available materials that include: soil, sand, gravel, crushed rock, silt and clay. The filling can be carried out at regional centres, to reduce transport costs.

The space between the inner and outer walls are separated by a thin insulating blanket, to block thermal radiation. The space between the inner and outer walls is evacuated to limit the total thermal losses to less than 3% per day.

The pipes are nominally 20 mm bore and are arranged in concentric circles with spacing of about 180 millimetres. A total of 24 pipes are positioned by “tube plates”. The “tube plates” are spaced 150 millimetres apart and are about 870 millimetres in diameter. The “tube plates” do not contact or connect with the cylindrical inner wall.

The steel in the TESS weighs less than 400 kilograms. When filled, the total weight of the TESS is increased to about 2,800 kilograms.

Design calculations and a testing program proves that the compacted fill and steel containment acts as an elastic composite within acceptable stress ranges. The use of gravel/sand and such was proposed and modelled by Turner [12] at the Jet Propulsion Laboratory in Pasadena, California. In 2009 Robert Mierisch invented a large-scale above ground arrangement using mass produced pipe arrays [13]. More recently a patent, covering their arrangement of Turner’s approach, has been issued to an Israeli company called Brenmiller [14].

Costing of TESS indicates they can be mass produced, in batches of five hundred, for less than USD 1,300. For batches of two thousand five hundred that cost reduces to about USD 840.

## VII. Condensers

The RRES uses a condenser design suitable for automated mass production. The heat transfer is from steam condensing at 55°C to 65°C and the steam pressure will remain in the range 15 kPa absolute to 25 kPa. Cooling air is pumped through the condensers as fans at this scale do not have a high enough efficiency.

In winter one of three condensers, for a minimum system, heats filtered air to keep dust and pollen out of the residence. The other two condensers are used to recirculate and heat unfiltered air. In summer the filtered air bypasses the condensers and still reduces dust load on the house. All heated air, from the condensers, is vented to atmosphere.

## VIII. Pumps

The proposed design for the RRES includes at least six pumps. All these are more than 75% efficient as they operate with 24-volt DC supply from the small battery that is charged during the day by Photovoltaic (PV) panels. At night, the battery is kept charged by the RPSE-generator. The RPSE commonly runs about once per hour for between 3 minutes and 45 minutes with the controller operating the RPSE-generator to ensure that the battery life is maximized. All pumps are designed for life greater than 60,000 hours, with zero maintenance. None of the pumps operate more than 45% of the time and this load factor will gives a pump life of at least 15 years.

When an electric vehicle is charged overnight the RRES will need two engine-generators and they both run until the car battery is charged. An RRES designed for electric vehicle charging provides all of the residential winter heating required for a large house. In spring, summer and autumn the system provides more than enough energy for residential pool and spa heating.

The feed pump(s) (#1) maintains the high pressure in the TESS and the backup hot water boiler, if installed. Maximum pressure is 19.1 MPa and the inlet temperature maximum is 100°C. Maximum flow is 0.45 litres per min and therefore the supply required per pump is then 24 volts DC and 150W.

The circulating pump (#2) for SCAs and TESS is powered by the battery where one pump is needed for each set of three SCAs. System pressure is limited to 19 MPa and the pressure difference is 50 kPa at a flow rate of 24 litre per minute. Power supply required for the circulating pump is 24-volt, direct current and 25 watt and consumes approximately 6% of the total output of each RRES module.

A Feed Pump (#3) draws water from the hot well to maintain the water level in the steam separator in the TESS and produces medium pressure, at about 4 MPa, in separate piping in the TESS where the separate piping generates steam to drive the RPSE. When the pump is not operated, the water in the separate piping will all boil to steam and gradually superheat to the same temperature as the TESS.

The Feed Pump circulates at least 25% more water into the TESS than the steam flow rate required to operate the RPSE. The excess water flows from the steam separator in the TESS back to the Hot Well via a steam trap for that purpose. The excess water flow will heat the Hot Well from 60°C to about 100°C, over the day’s operation.

Residential supply Hot Water Service is heated by pump (#4) and draws water from the Hot Well at a temperature in the range 60°C to 100°C. This flow circuit can also be used for additional heat exchangers for pool and spa heating. Circulation pressure difference up to 150 kPa at a flow rate of 24 litres per minute. Pressure at the pump inlet will be approximately 10 kPa and all of the water returns to the Hot Well. Control of this flow keeps the hot water service tank within 1°C of the set point. This pump consumes approximately 4% of the total output of one RRES.

An optional pump (#5) keeps the water hot near each outlet, provided the plumbing has a recirculating setup. The pump runs continuously when hot water is being used and intermittently when it is not. The control system operates this pump (#5) for a minimum of thirty seconds every five minutes.

Condensate extraction pump (#6) draws condensate from the vessel one metre below the condensers. The local pressure is then at least 5 kPa greater than the saturation pressure for the condenser and the minimum condenser pressure is 15.7 kPa absolute (saturation pressure for 55°C). This pump operates with output pressure up to 120 kPa absolute.

The air pumps (#7) for condensers operate to move air through the condensers. Air pumps at this scale operate more efficiently and with less noise than a fan or fans. One of the air pumps delivers 0.2 cubic metres per second at a pressure of 250 Pa to 300 Pa. That air pump forces air through a High Efficiency Particulate Air (HEPA) filter supplying fresh air to the residence. The other two air pumps each circulate 0.7 cubic metres per second of air, drawn from the house in winter and returned to the house. The extra air pumps operate at a pressure differential of 50 Pa.

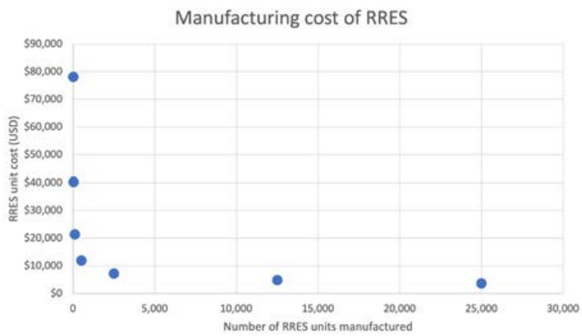


*Figure 5 - Relationship of RRES unit cost to manufacturing volume*

## IX. A PROPOSED BUSINESS APPROACH

A business plan has been formulated that incorporates a planned increasing volume of manufacture as follows:

- a first batch of four RRES units with three SCAs each and one TESS,
- second batch of twenty RRES units with three SCAs each and one TESS,
- third batch of one hundred RRES units, as above,
- fourth batch of five hundred RRES units, as above, and
- subsequent batches of five hundred RRES units.

When the batch size increases to more than two thousand five hundred RRES units, the manufacturing cost is reduced by approximately 40%. The potential market for the Australian sales volume would be a total of 650,000 RRES being is 65% of market for rural residences at towns with population less than 10,000.

The essential requirement for producing the RESS units at an economically viable price point is to rapidly increase the volumes of manufacturing and reduce the total cost of delivery of the RRES units with all of the associated sub-systems. The graph (Fig. 5) illustrates the projected reduction of RRES costs with respect to the number of RRES systems that are manufactured.

## X. CONCLUSIONS

The proposed RRES provides both electricity and heat where the value of the heat utilized by a medium sized house will be about the same as the value of the electricity.

The RRESs will have an economic service life of more than fifty years, in line with large steam power plants. The warranty period will be twelve years and simple payback time less than ten years. For larger systems, the simple payback time is less than seven years. Maintenance costs, after the warranty period, will be less than four percent of system cost.

Those figures are dramatically more attractive than any Photovoltaic system with batteries. The cost of the storage is less than USD 90 per kilowatt hour of electrical output. With larger volume production that falls to less than USD 56 per kilowatt hour of electrical output.

The total rural market for RRES, in Australia could be worth more than USD 24 billion. Worldwide the total sales of similar systems could be much more than USD 1 trillion, within the next 10 years.

The knowledge and experience shared by the authors is a remarkable opportunity to supply low cost and reliable renewable energy supply for off-grid and unreliable grid locations. There are more than 900 million people in the world with no access to an electricity grid or have unreliable grid supply.

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## REFERENCES

[1] https://www.who.int/news/item/28-05-2020-covid-19-intensifies-the-urgency-to-expand-sustainable-energy-solutions-worldwide, accessed 14 April 2021.

[2] http://en.wikipedia.org/wiki/List_of_major_power_outages, accessed 14 April 2021.

[3] Scientific American, 1914, "Feasibility of utilizing power from the sun" Vol. 110, No. 9, p. 179, February 28, 1914.

[4] Mierisch R., 2009, US Patent, US2009/0158736A1. "Thermal power plant incorporating subterranean cooling of condenser coolant", 25 June 2009

[5] Mierisch R., 2009, "Granular thermal energy storage mediums and devices for thermal energy storage systems", United States Patent Application 20090090109.

[6] https://www.modelica.org/, accessed 14 April 2021.

[7] Gebhardt G. F., 1928, "Steam Power Plant Engineering", 6th Edition, John Wiley and Sons, UK.

[8] Gebhardt G. F., 1917, "Steam Power Plant Engineering", 5th Edition, John Wiley and Sons, UK.

[9] Perry J., 1909, "The Steam Engine and Gas and Oil Engines", Macmillan, UK.

[10] Stumpf J., 1922, "The Unaflow Steam-Engine 2nd Edition", Unknown, internet based reprint.

[11] Mierisch, R., 2017, "The History and Future of High Efficiency Steam Engines". 19th Australasian Engineering Heritage Conference: Putting water to work: Steam power, river navigation and water supply. 299-315.

[12] Turner R.H., 1979, "High Temperature Thermal Energy Storage in Steel and Sand". Jet Propulsion Laboratory – California Inst. Of Tech. Pasadena, Ca., JPL Publication 80-35.

[13] Mierisch, R., 2019, "Round Trip Efficiency and Cost of Energy Storage For Electricity Grids and Microgrids", World Engineers Convention, Melbourne

[14] Brenmiller A., 2014 "Integrated Thermal Storage, Heat Exchange, And Steam Generation", WIPO, WO 2014/147491 Al.

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