Feasibility of Solar Power for Remote Mining Camps

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The potential for climate change due to the effects of greenhouse gases and increasing demand for limited oil resources have prompted Rio Tinto to explore alternative energy sources for their operations. Solar power has become a very important industry because of this and Rio Tinto Technology Division has funded research into finding the most effective solution to a solar plant. This paper researches the different technologies needed to implement a solar powered remote camp such as batteries and photovoltaic panels. Solar designs have been made that compare these technologies in order to find both the most elegant and the most cost effective solution.

1. Introduction to Solar Power

Solar power has been in widespread use for decades, but in the last few years the demand for solar power has increased dramatically due to an increased environmental awareness, specifically the effect of greenhouse gas emissions on climate change. Due to this increase in demand, solar technologies are evolving at a rapid pace. The technology faces problems which are unique to using solar, and which require innovation and creativity to overcome in order to permit implementation into the larger market.

1.1 Photovoltaics

The photovoltaic (PV) effect is widely utilised in solar power, and many different designs have been created to take advantage of this. The PV effect occurs when photons hit a semi-conductor surface and the photons contain enough energy to jump an electron from the valance band to the conduction band, where the electron can now move freely. This free electron can transfer energy to where it is required (Sze, 2002).

There are many different semi-conductor materials that use the PV effect to produce energy. Table 1 lists and compares these technologies practical efficiency, laboratory efficiency and their cost to mass produce. The large difference between laboratory and practical efficiencies, typically 10% or more, means that research and development of these technologies can improve practical efficiencies dramatically as well as lowering production costs (Valera, 2003).

Comparison of Solar Cell Efficiencies			
Cell Type	**Laboratory Efficiency**	**Practical Efficiency**	**Cost per Watt Peak ($/Wp)**
Mono-chrystalline Silicon	24.0%	14-21%	$4.35
Poly-chrystalline Silicon	20.0%	13.0-15.0%	$4.17
Amorphous Silicon	14.0%	5.0-7.0%	$3.72
Sliver Cell Silicon	17.7%	12.60%	-
Cadmium Telluride	27.0%	20.0%	$4
Copper Iridium/Gallium Diselenide	19.90%	10.0-12.0%	$7
Gallium Arsenide	47.0%	30.0%	-

Table 1: Comparison of solar cell efficiencies and production costs.

1.2 Producing Power Using Photovoltaic Cells

There are many different PV technologies. These PV cells must be utilised in a power system in such a way to produce as much power as possible. To do this, there are three different sorts of solar arrays used to produce large scale power.

1. Flat plate
2. Parabolic dish collector
3. Power tower

Flat plate cells are the most common sort of cell and are widely available for homes and businesses. Large power plants use thousands of connected cells to generate the necessary power for the grid and produce energy at from anywhere between 60W to 300W per square meter. This type of solar farm takes up large, flat areas, as well as using large amounts of expensive solar panels. Although economies of scale will reduce the costs of these solar farms, it is usually around $5-7 per watt in building costs (Valera, 2003).

Parabolic collector dishes, such as in

Figure 1, use mirrors to concentrate the light onto a small PV plate at the front of the dish. Mirrors are much cheaper than PV cells and are therefore used extensively in dishes. As more sunlight is focused onto these PV cells, the cells efficiency can increase by as much as 20% from a concentration of 1 sun to 1000 suns i.e. raising efficiency from 14% to 17% (Frank, 1980). This efficiency increase is only possible for specially designed cells though. The concentration point can reach up to 1000°C and heat reduces efficiency and degrades the cells, so an effective cooling system is necessary to prevent damage and increase efficiency.

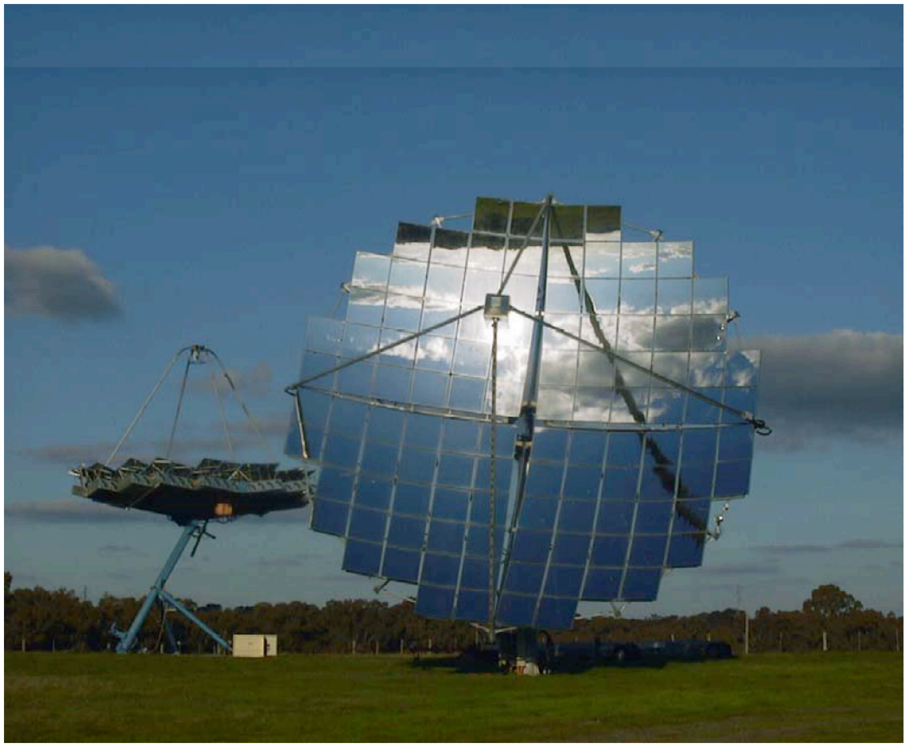

Figure 1 CS-500 parabolic dish collector by Solar Systems based near Bendigo, Victoria

The power tower is a similar concept to the parabolic collector, but the mirrors are on the ground, and focus the light on a single tower. The power tower facility shown in

Figure 3 is a planned development by Solar Systems to be constructed in Victoria. This tower is expected to cost $420 million, producing 154MW. This means that the cost is $2.7 per Watt, much cheaper than other technologies.

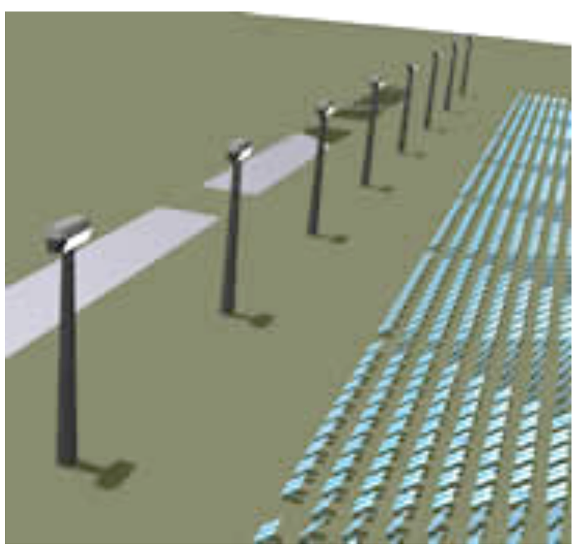

Figure 3: Proposed solar plant in North West Victoria by Solar Systems

2 Batteries

Batteries store energy in chemical form and are currently the best form of energy storage due to their high energy density, long cycle life and high efficiency. Energy density is how much energy is stored per kilogram or per litre. Higher energy densities are preferable as transport of the batteries is easier, and smaller areas are needed for storage. Long cycle lives indicate how many periods of charging and discharging the battery can withstand. Longer lifecycles mean that the batteries do not need to be replaced as often. Efficiency is defined as

$$Efficiency = \frac{Output}{Input}$$

The efficiency of a battery is measured by calculating the energy that a battery can output divided by the energy required to return the battery to its original state.

2.1 Lead-Acid Battery

The lead-acid battery is the most common battery because it is simple, cheap and efficient (McChesney, 2000). Lead-acids are a very mature technology to the point that further research is expected to provide little in extra energy storage or efficiency. Economies of scale no longer produce benefits, leaving their current cost at approximately $500/kWh of energy.

Lead-acids have many disadvantages though, being that they cannot fully discharged without damaging the battery, the reaction produces hydrogen gas, there is a relatively high self-discharge and the electrodes eventually corrode as they take part in the reaction. Also, the lifecycle of the battery is only 2500 cycles, approximately 7 years.

2.2 Sodium Sulfur Battery

Sodium sulfur (NaS) batteries have much better qualities than traditional lead-acid batteries. The sodium is the anode, and the sulfur is the cathode. Cell discharge occurs when the liquid sodium is channelled between the beta-aluminate electrolyte, and the safety tube.

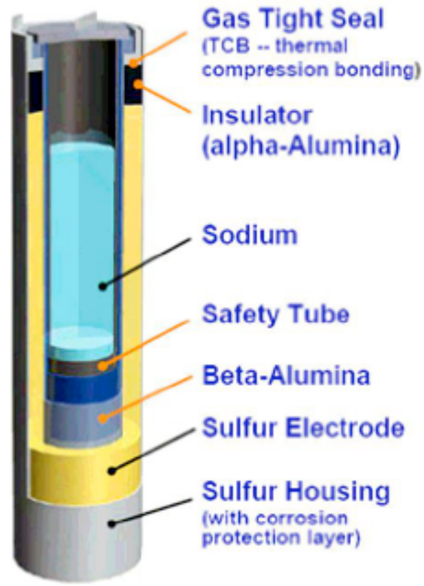

Figure 5: Diagram of the NaS battery (Wen, 2006)

NaS batteries have a high energy density, being 151Wh/Litre, about 3 times the density of lead-acids. It has high charging efficiency (89%) with no self-discharge and has a long cycle life. It can last 6500 (18 years) cycles at 65% discharge, 4500 cycles (12 years)when discharged to 90%, or 2500 cycles (7 years) when 100% discharged (Bito, 2005).

Safety is a concern as sodium is corrosive and contact between sodium and sulfur is highly explosive. Current designs severely limit the reactive surfaces between the sodium and sulfur via the beta aluminate and the small channel across which electrons flow from the sodium to the sulfur. The cells run at around 300°C so proper ventilation is required, though the high temperature means that it is resistant to temperature changes in its operating environment. The battery itself is 98% recyclable however, thus preventing contamination of the environment after the batteries useful lifetime (Bito, 2005).

As the density of NaS batteries are so high, the leave a much smaller footprint. They are unaffected by ambient temperature, have a long lifecycle, quick response (full charge to full discharge in 1ms), minimal maintenance (3 hours per 430kWh module), no emissions or vibrations and is highly reliable. NaS batteries are currently commercially available and are suitable for large scale, non-mobile operations. When mass produced, the costs are expected to fall to AU$160/kWh.

2.3 Vanadium Redox Battery

Both the electrodes of the Vanadium Redox Battery (VRB) are a vanadium solution but at different oxidation levels, being that the vanadium ions in the solution contain different amount of electrons. Therefore, any inadvertent mixing of the electrolyte will not greatly affect the stack. For example, if the electrolytes mix, then there is simply less energy stored and recharging the battery produces a heat. After this happens, then the cell acts as if there was no leakage (Shibata, 1999).

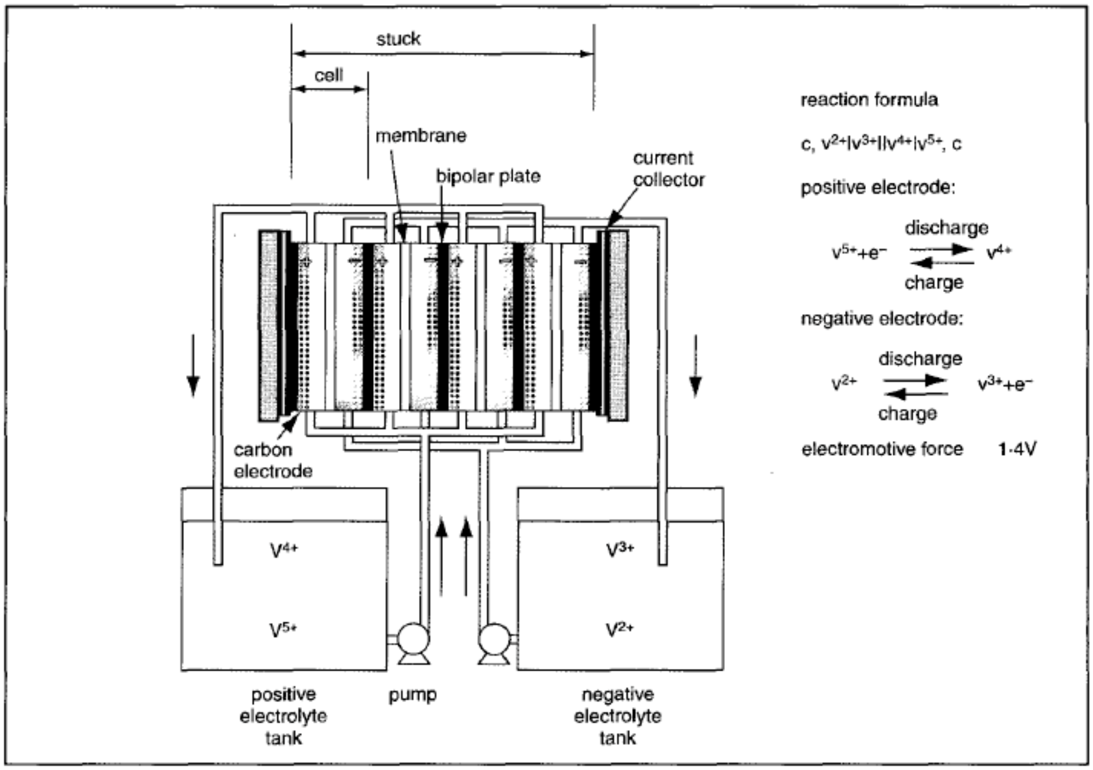

Figure 6: Typical layout of a VRB (Shibata, 1999)

Another major benefit of VRB is that under normal conditions, no hydrogen is produced. Therefore, there is no need for venting and spark prevention nearby a VRB which reduces the costs of housing the battery. VRB's have a practical efficiency ranging from 68% to 81% (Skylas-Kazacos, 1997).

They have lower energy densities per litre than lead-acid batteries (VRB is 20Wh/Litre, lead-acid is 40Wh/Litre) and the major capital investment to buy the vanadium, set up the storage tanks, the pumps and the power membrane prevents their use in small facilities (Shibata, 1999). The lifetime of the battery depends on the power membrane, which currently only lasts approximately 3000-4000 cycles (Wen, 2006).

2.4 Comparison of the Different Batteries

This section aims to make different comparisons between the different batteries in order to choose the most appropriate battery for a set of conditions. The different conditions that are looked at will include efficiency, cost, lifecycle, energy density, temperature sensitivity, recyclability and safety.

Battery Comparison					
Battery Type	**Efficiency**	**Costs per kWh of Storage**	**Lifecycle**	**Energy Density (Wh/kg)**	**Sensitivity to Temperature?**
Lead-acid	70.00%	$500.00	2500	20Wh/kg	High
Vanadium Redox	60-80%	See Table	3000-4000	20Wh/kg	Medium
Sodium Sulfur	75-83%	$650.00	up to 6500	117Wh/kg	Low

Table 3 Comparison of the different battery technologies considered

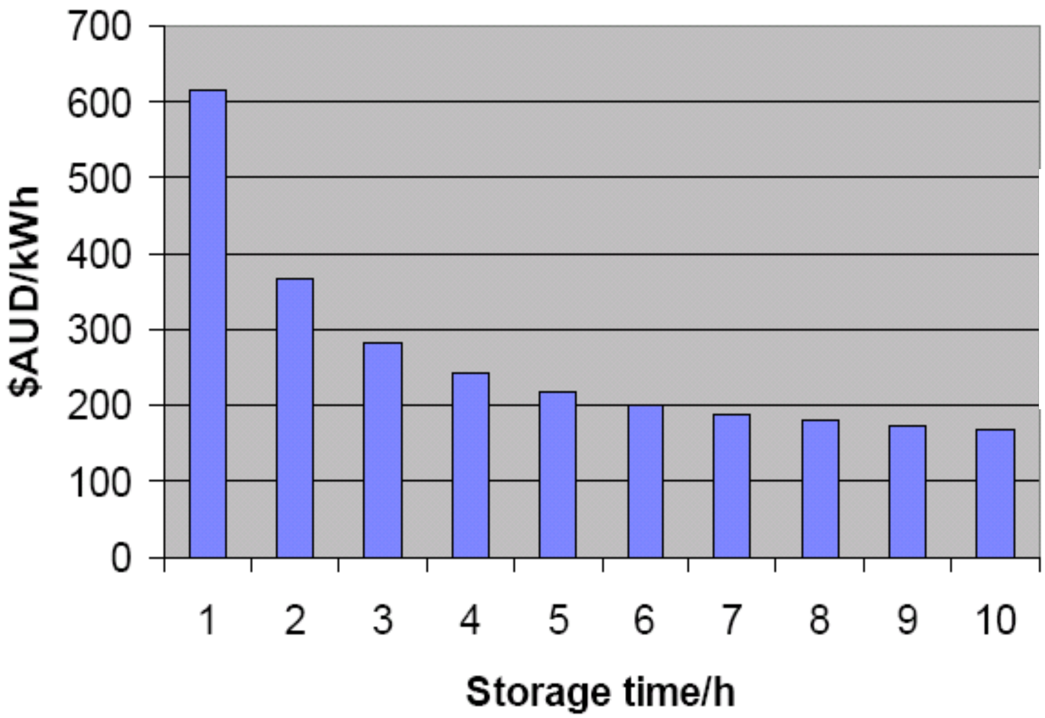

Figure 7 VRB Capital costs per kWh versus storage time

Table 2 and Figure 5 show that the cheapest battery to implement would be the VRB as the storage time is expected to be approximately 14 hours. This information is only relative to the lifecycle however and does not include the need to replace the batteries over time. The VRBs lifetime is due to the power membrane needing replacement rather than the electrolytes.

The high efficiency of the NaS battery, as well as its high energy density and insensitivity to the ambient temperature make the batter well suited for portable applications where the minimum amount of infrastructure can be present. The NaS battery is still under heavy development though, so prices are expected to fall and the efficiency and lifecycle should increase.

3. Portable Accommodation Units

Solar power is more expensive than traditional power generation methods such as coal or gas so more consideration is placed in reducing energy demand. This will lower the cost of the solar power plant by reducing the energy the plant needs to produce.

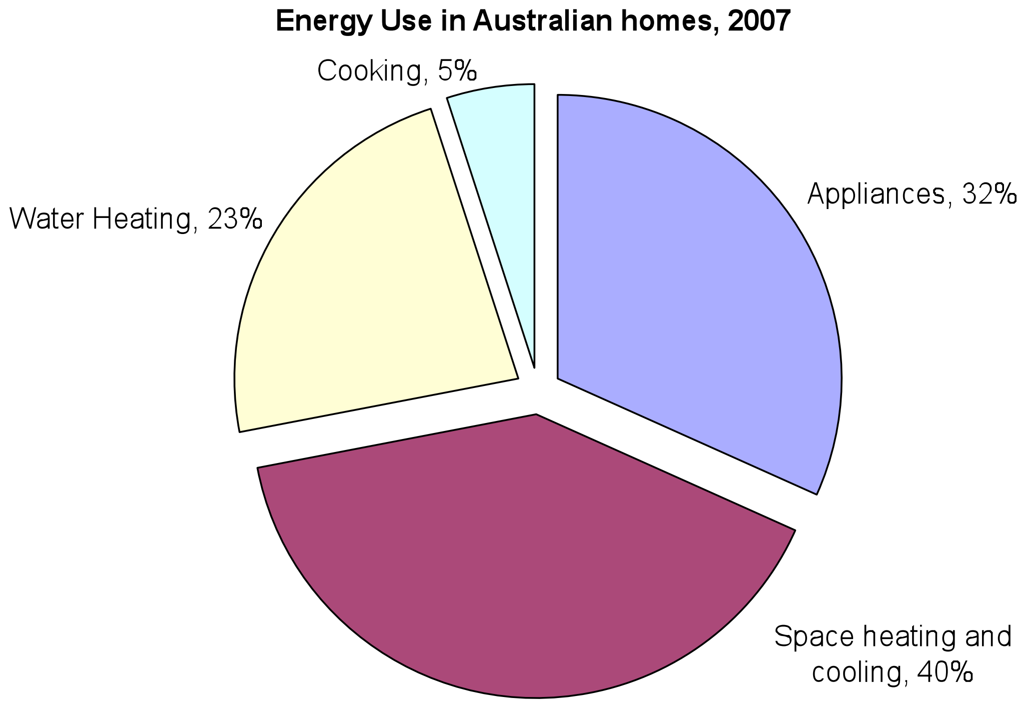

Figure 8 Average simplified energy use for an Australian home in 2007 (Holt, 2008)

Figure 8 shows the average power usage in an Australian household, and thus where the greatest energy savings are possible. Heating and cooling comprise 41% of total energy use. A well designed house will limit the heat loss from a house, which should drastically reduce the energy required for heating and cooling

Hot water usage is also a large consumer of energy at 23%. There are many cheap and effective solutions to reducing this though, such as low flow shower heads and taps, solar hot water and heat pumps.

Other main energy users are televisions, dishwashers, clothes washers, dryers and computers. The Australian government has the star rating system to choose the most energy efficient systems which can reduce energy use.

3.1 Prototype Accommodation Unit Design

The prototype accommodation unit currently under construction contains a variety of energy saving measures, including the insulation, hot water, and lighting. The insulation is a unique system comprising of 2 walls, with an air gap in-between. Air is a very good insulator, but is still heated by from the outer wall. Once the air inside the wall reaches a certain temperature, a fan blows air from the bottom of the house, which is in the shade so should be cooler, and transfers it into the walls. The air in the walls is then blown into and out of the roof. The effective R value is 4.5, where the R value is a measure of thermal insulation. Standard accommodation units have an R value of 2.

The hot water system is a passive solar heater with an electric booster. This is expected to save 70-90% of the energy needed to heat the water. The electric booster can be changed to a natural gas booster but obtaining gas supplies can be problematic on certain sites. The original donga design included an evaporative air conditioning unit to ensure low running costs and power. However, the Pilbara's high humidity during much of the year prevents evaporative units from being an effective solution, so refrigerative units will be necessary.

Photovoltaic systems will also be included in the donga. The original sizing is of the PV system is 1.25kW with total energy storage of 3kWh. For the original system, this was enough energy for 24 hours. However, the refrigerative air conditioning units use up large amounts of energy, as well as having high starting currents. It is estimated that up to 19kWh per day will be needed with a peak power of 17.5kW. Energy storage was originally lead-acid batteries. However, sodium sulfur batteries are available and will prove to be a better alternative. The total system cost is expected to be around $64,000. This cost is only for the prototype however, and lower costs are expected for large purchases.

4. Conclusions

Solar power stations are more expensive than conventional power generation sources currently but as solar and battery technologies develop the cost of producing solar energy is expected to fall to a level equal to that of current energy prices. This will be particularly beneficial to remote areas as grid connection will be much less of an issue due to the cheaper cost of portable systems and the power systems lack of reliance on liquid fuel.

The most promising technologies for a portable power station are the CIGS cell, which can achieve higher efficiencies and low costs in the future. The current concern with the CIGS cell is the high temperature coefficient as the Pilbara can reach temperatures up to 50°C. The sodium sulphur battery is the best suited for remote operations due to its high energy density making the battery easily transportable, and the high operating temperatures mean the battery is relatively unaffected by the ambient temperature, thus preventing the need for ventilation or cooling.

The prototype accommodation unit is expected to greatly reduce both the total energy use, as well as reduce the peak power usage. This will save on both liquid fuel and greenhouse gases or if a solar power plant is built with the accommodation unit, the cost of the plant will be significantly reduced.

5. References

Bito, A. 2005, "Overview of the sodium-sulfur battery for the IEEE Stationary Battery Committee", Vol. No.2, pp: 1232-1235

Frank, R.I., Goodlich, J.L., Kaplow, R. 1980 "A Novel Silicon High-Intensity Photovoltaic Cell," Conf. Rec. 14th IEEE Photovoltaic Conf., New York, p. 1350

Holt, S. 2008, "Trends in Australia's Energy Consumption", Department of the Environment, Water, Heritage and the Arts.

Largent, R., Skylas-Kazacos, M., Chieng, J. 1993, "Improved PV System Performance Using Vanadium Batteries". *Photovoltaics Specialists Conference,* IEEE**:** 1119-1124.

McChesney, P.J. 2000, "Solar Electric Power for Instruments at Remote Sites", U.S. Department of the Interior

Shibata, A., Sato, K 1999, "Development of the vanadium redox flow battery for electricity storage" Power Engineering Journal, Vol. 13 (Issue 3), pp:130-135

Solar Systems, *Victorian power tower project*, viewed 14 December 2007 <*http://www.solarsystems.com.au/154MWVictorianProject.html*>

Sze, S.M. 2002, *Semiconductor Devices: Physics and Technology*, John Wiley and Sons Inc.

The Australian Bureau of Meteorology (BOM), *Solar Radiation Chart*, 2008, viewed 1 August, 2008, <http://www.bom.gov.au/cgi-bin/climate/cgi_bin_scripts/solar-radiation.cgi>

Valera, P.; Esteban, A., de los Reyes Carrillo, M, Osuna, R., Menna, P., Gambi, R.; Helm, P., Grottke, M., Geyer, M., Dobon, F., Monedero, J,; Lugo, A., Romero, M., Chenlo, F., Alonso, M., Sanchez, M., Artigas, J., Fresneda, A., 2003, "Solar energy: comparative analysis of solar technologies for electricity production" Photovoltaic Proceedings of 3rd World Conference on Energy Conversion, Volume 3, 12-16 May 2003 Page(s):2482 - 2485 Vol.3

Wen, Z. 2006 "Study on Energy Storage Technology of Sodium Sulfur Battery and it's Application in Power System" International Conference on PowerCon, pp:1-4