Solar Thermal Storage Technologies for Port Augusta

u5348406 ENGN2226 Systems Engineering Analysis
Portfolio 2016

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Executive Summary

With the closure of Port Augusta's coal-fired power plants, the town is looking to install a new system for electricity production. The investigation into solar thermal power plants in this portfolio indicates that the best option is a solar thermal plant with integrated molten salt thermal storage. Solar thermal storage systems investigated include sensible heat, latent heat and thermochemical storage. This portfolio examines these three methods with a focus on cost, capacity, limitations, readiness and carbon emissions.

Introduction

The demand for renewable energy technology in Australia is increasing, as more Australians see the need to reduce emissions from coal power, and as more research emerges on the long term need to develop sustainable energy sources to replace coal use. A major hurdle in renewables has been intermittency, with weather varying the energy output. Energy from coal is also heavily integrated into current power policy, infrastructure and the nation's economy, meaning the transition from coal is likely to be complex and slow. Though renewables account for less than 15% of Australia's power supply, Government initiatives have been established to lean more towards these sources of energy, with the Clean Energy Council setting a renewable energy target of 33,000GWh from renewables in 2020 (CEC, 2014). A survey of 40 Australian communities executed by Big Solar found that 94% of people want large scale solar projects, with 95% also wanting to see more Government investment, which is indicative of the strong public interest in harnessing solar energy. The Clean Energy Council is overseeing funding of AU$10 billion towards large-scale renewable investment opportunities as part of the renewable energy target (CEC, 2014).

Solar thermal technology is being developed by researchers and engineers around the world, with particular focus on storage technologies that will solve the issue of intermittency. The three main types of storage under development, and discussed in this report are: sensible heat; latent heat and thermochemical energy. Sensible heat is the only storage system currently commercially available, while latent heat and thermochemical are still in research and development phases (Hubner *et al,* 2016).

Port Augusta Power

Port Augusta is a town north of Adelaide, South Australia that, up until May 2016, had two coal power plants, Northern and Playford B. The plants provided 31% of South Australia's power (Burgmann & Baer, 2012). The Government subsidy for renewable energy was cited as the reason for the recent closure of Playford B, and investors such as Solastor and SolarReserve are now looking at options to install a solar thermal power plant in its place (Beyond Zero Emissions, 2016). The Port Augusta community is highly supportive of the solar thermal plant proposal, their enthusiasm fuelled by the need for jobs and economic support after closure of the power plant. They also see potential for an energy source that won't pollute the town's air.

On average, Port Augusta receives 26MJ/m^2 solar irradiance per day (Bureau of Meteorology, 2016). It has strong potential as an energy hub, as it has sea access, is near the city of Adelaide (300km) and has a solar irradiance value close to Alice Springs, which has the highest in the country. Current infrastructure exists from the closed coal plants both for electricity generation (steam turbines) and transmission (power lines). This ability to use existing infrastructure in an ideal climate with a ready market makes it a perfect location for harnessing solar energy, both in immediate commercial use and as a base to research future solar methods. This portfolio provides a recommendation for the approach Port Augusta should adopt for solar thermal power, with focus on the selection of storage technologies. It will focus on cost, storage capacity, and efficiency comparisons, with a goal to present the most viable plan for Port Augusta's solar thermal plant.

Interview with Repower Port Augusta Campaign Member

An interview was conducted with Mr Dan Spencer, a member of the Repower Port Augusta campaign. The results of this interview are the main motivation for the development of the research question for this portfolio.
According to Mr Spencer, in Port Augusta, support for renewable energy to replace the recently closed coal-fired power plant is almost unanimous. 98% of responses in a survey of 4000 residents in 2012 were in favour of renewable technology, specifically solar thermal. The population of Port Augusta was approximately 13,000 in 2011, though this figure may have decreased since the closure of the coal plant in May 2016 (Australian Census, 2011). The survey therefore accounts for 30% of the population, and can be considered reliable.

From the interview, it appears the general view in the town is that solar thermal will directly benefit the community through job opportunities and tourism, with local economic benefits from the supply chain for construction and manufacturing. In the interview it was explained that the removal of the coal plant and accompanying particulate pollution will bring health benefits to the community.
The interview revealed some goals for the investigated solar thermal systems, including:

- Prioritising local employment
- Funding currently is estimated to be $100 million
- Closed loop system to ensure safety
- SA government commitment to purchasing power from the system
- Technological readiness

Permissions

It is noted that the interview was conducted with full permission from Mr Spencer, who consented to have his name attributed to the contents of the interview, with the knowledge that it would be used only for the purposes of the ENGN2226 Portfolio and not distributed elsewhere. The bias of the interviewee is also acknowledged as he is a campaigner for Repower Port Augusta, a group that is rallying to introduce solar thermal. The choice of interview candidates introduces possible error into the acquired data due to the potential for bias. Error types include: sampling error, as the interviewee is not representative of the entire population; and response error, as the interviewee did not fully answer the questions asked and may have a real or perceived conflict of interest as an advocate for a commercial venture. Efforts were made to eliminate error by: 1) making the interview written to ensure the interviewee had more time for responses, time to fact check, and to eliminate processing errors, and 2) construction of interview questions that were open-ended, to gather as much information as possible and to ensure the interviewee was unpressured in his responses.

Solar Thermal Power Plants

Due to the Port Augusta public interest in solar thermal power, an investigation into the power source has been conducted.

Operation

Large-scale solar thermal power plants for industrial use currently rely on Concentrating Solar Power (CSP) systems, where the sun's rays are concentrated using mirrors onto a receiver. The heat is then used to produce electricity in a cycle.
The basic operation of a solar thermal plant involves the following stages:

- Collection of direct solar irradiance using reflectors and a receiver
- Heat transfer fluid (HTF) absorbs heat and is circulated through pipes
- Without storage
    - HTF is used to directly produce steam

- With storage
    - HTF is used to heat a storage medium or initiate a chemical reaction
    - Heat from storage medium can later be used to produce steam
- Steam is used to produce electricity in conventional steam turbine
- Cooled HTF circulates back to receiver for reheating

An energy flow diagram is displayed in Figure 1 in order to present a simplified flow of energy in a solar thermal power plant. The reason for the lack of numerical values in the diagram is that it provides a general illustration for different plant types, all of which have variable components with varying efficiencies.

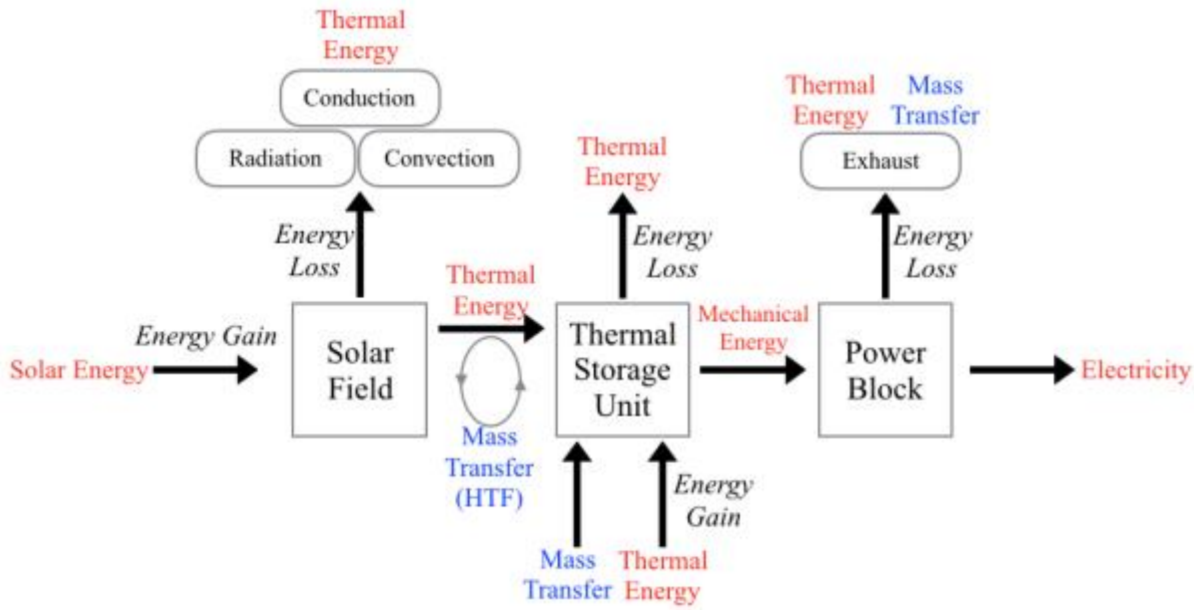

FIGURE 1 - Energy Flow Of A Solar Thermal Plant

Figure 1 depicts energy flowing out of the system as losses, as well as current energy requirements that must be sourced externally. In particular, there is an energy requirement for the storage system that, prior to the influx of heat from solar radiation, heats the storage medium up to the required temperature. A balance must be optimized between minimizing external energy requirements while still having enough heat in the storage system to create steam in the power block. An ideal situation would see the storage medium heated entirely by the sun, with no external power from other sources required (Ma *et al*, 2015).

Comparison to Photovoltaic

Photovoltaic systems take solar energy and convert it directly to electricity. They are an example of a solar system without any thermal storage. The key advantage of solar thermal plants with storage over photovoltaic power plants is the ability to shift the power output to times of peak demand. Figure 2 shows the variation in power output for a simple 196kW solar generator, adapted from a publication by CSIRO in 2012. It can be seen that the power output directly corresponds to the irradiance from the sun, meaning that during cloudy periods, the power output will decrease. Furthermore, solar cells cannot produce any power overnight without storage.

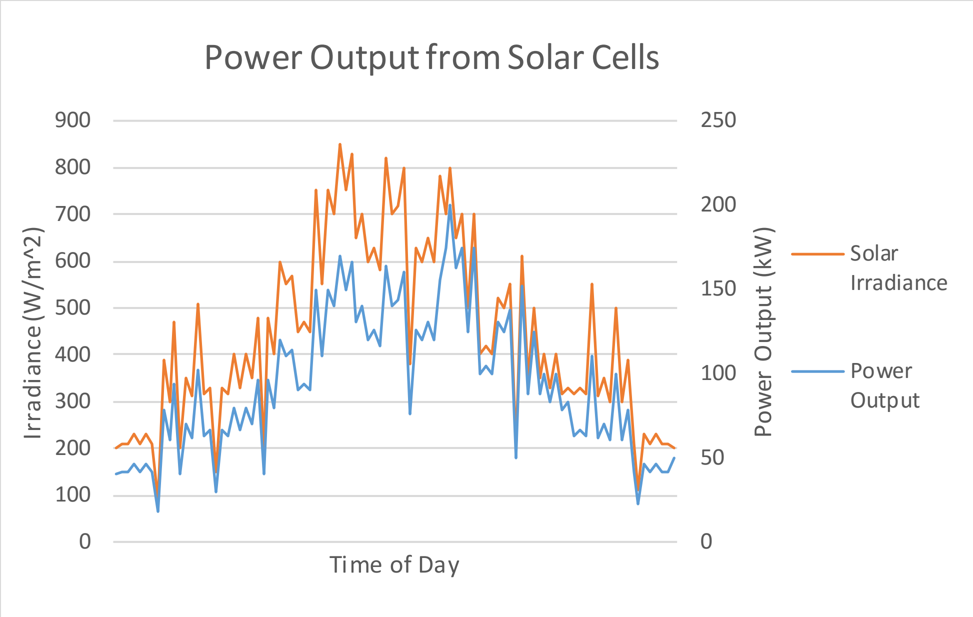

FIGURE 2 - Power Output From Photovoltaics

In order to minimize or prevent these power losses, and to enable power generation 24 hours a day, integration of a thermal storage technology is necessary. The maintenance of a constant power output is made possible by utilizing a control system that regulates the temperature and mass flow rate of heat transfer fluid. Figure 3 displays how integration of a thermal storage unit would affect the power output of a 200MW system, adapted from a publication by Powell & Edgar, 2011, incorporating the solar irradiance data from CSIRO. The data acquired for time represents a full 24-hour cycle.

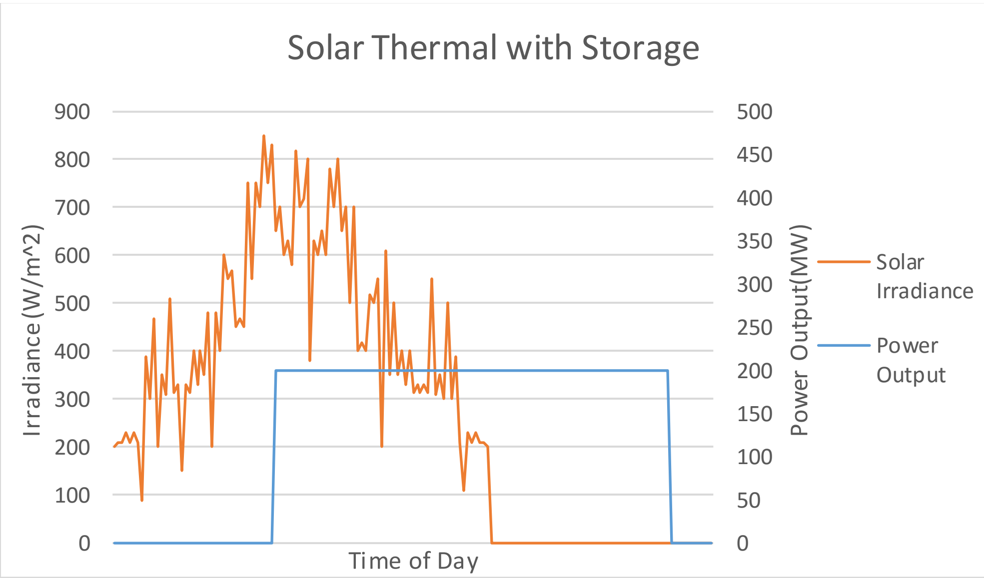

FIGURE 3 - Power Output From Solar Thermal Plant With Storage

The storage unit starts producing power once enough heat is circulating through the heat transfer system, then continues to produce power constantly until long after the sun has gone down. This figure also highlights the current limitations on the storage capacity, as thermal energy has not been stored for a full 24 hours, but in the range of 10-15 hours.

Managing Intermittency Using Storage

Intermittency in renewable sources such as wind or solar results from variable disturbances such as ambient temperature changes, wind speed and cloud cover.
The control system necessary to reduce power fluctuations from intermittent sun exposure is displayed in Figure 4. Control of output power occurs by managing mass flow rates of the heat transfer fluids (HTF) delivering heat to and from the storage medium.

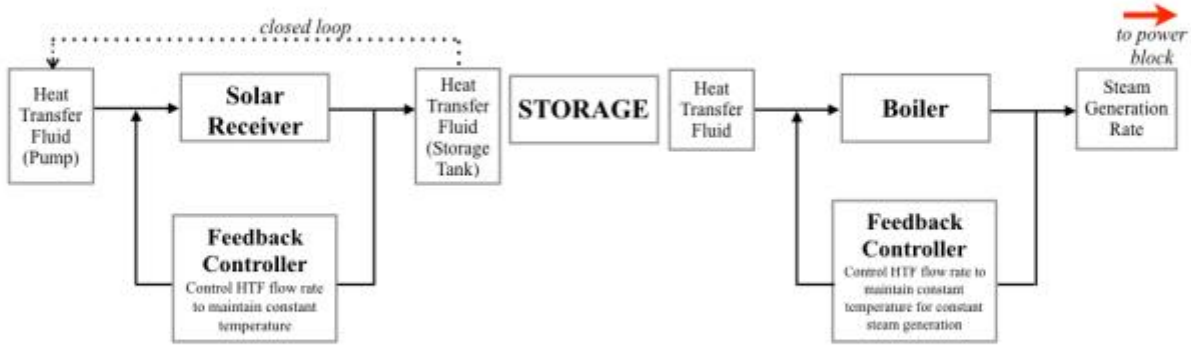

FIGURE 4 - Control Feedback Loop For Heat Transfer Fluids

As the HTF circulates from the solar receiver to the heat exchangers (connected to the storage tank), its flow rate is controlled using a proportional-integral-derivative (PID) controller to regulate the outlet temperature to the heat exchangers (Powell & Edgar, 2011). When the collector temperature is too low, such as during periods of cloud cover, the mass flow rate is decreased to give the fluid time to heat up. When too high, the mass flow rate is increased in order to regulate the outlet temperature to prevent it from overheating (overload) (Casati, 2015). The right hand side of figure 4 displays a secondary, independent control system that regulates the HTF flow rate between the storage tank heat exchangers and the boiler. The boiler needs to constantly generate steam to send to the power block in order to maintain power output. The PID controller is used here so that the mass flow rate can be adjusted if the storage tank drops in temperature.

Figure 5 below is a control chart showing the margins imposed on the temperature of the hot and cold storage tanks in order to reduce intermittency. The storage tanks modelled in this diagram are in control, as no data points lie outside the upper and lower bounds – if they did, the system would be considered out of control (Blanchard, 2006). Without the upper and lower control limits, imposed by the controlled mass flow rate of the HTF, the temperature of the storage tank would fluctuate too much to maintain system balance. The hot storage tank is regulated to 540-575°C, while the cold storage tank is regulated to 275-305°C. Low storage temperatures can cause solidification of the storage medium and significantly affect the output power, while high temperatures can overload the power block system or cause decomposition of the thermal storage medium.

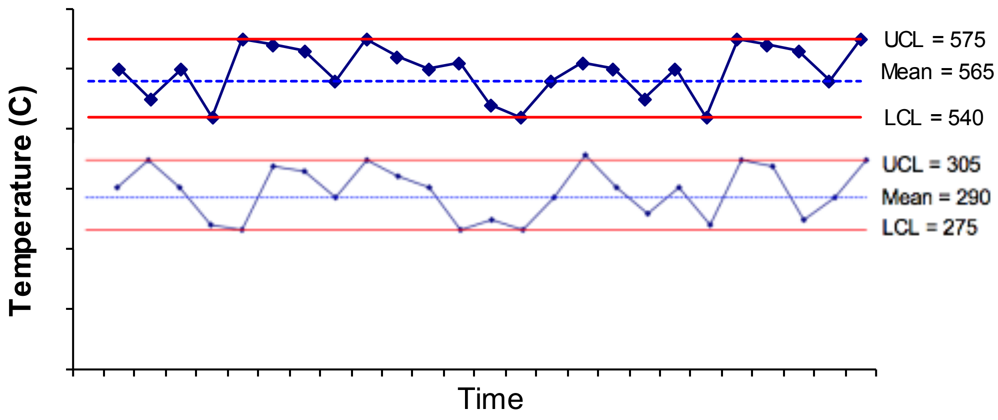

FIGURE 5 - Control Chart For Temperature Regulation In Hot (Top) And Cold (Bottom) Storage Tanks. Ucl: Upper Control Limit, Lcl: Lower Control Limit

Insights

Addressing the issue of intermittency is crucial to the development of any renewable energy resource technology. The control systems associated with regulating storage temperature for constant power output for solar thermal are well established but storage medium options remain an evolving research field. Thus, this portfolio endeavours to assess potential storage technology options to help inform the Port Augusta solar thermal decision. The remainder of the portfolio uses the following research question to guide an investigation into solar thermal storage options:

What is the most viable thermal storage technology for a solar thermal power plant at Port Augusta?

Solar Thermal Storage Technologies

Thermal energy storage systems require three main steps: charging, storage and discharging (Morisson, 2008). Sensible heat systems use solar energy to raise the temperature of a solid or liquid medium. The heat is stored in the bulk material and then during discharging is released to an electricity cycle (Price *et al,* 2002). Latent heat systems use solar energy to initiate a phase change of a material. Heat can be stored in the phase change while temperature remains constant (Hubner, 2016). In thermochemical heat storage systems, reversible reactions occur that are endothermic in one direction and exothermic in the other. Heat is stored in the former and released in the latter (Wu & Long, 2014).

Areas of assessment are based on efficiency, storage capacity, costs and major issues associated with the storage medium/technology. Research has revealed that not all of these factors have been established for all the technologies, as latent heat and thermochemical designs are not yet commercially available. Thus, this portfolio showcases those parameters that are available and draws comparisons based on them.

Sensible Heat Storage

Sensible heat systems use bulk solids, particles, or molten salts to store thermal energy. This heat storage method utilises the heat that is released from a substance as its temperature falls. The basic principle behind these systems is to pump a storage medium from a storage tank to the solar receiver, heat it using the sun, and pump it back to a second, hot storage tank. Slowly the heat from the hot storage tank passes to a heat exchanger, in order to create steam that then powers an ordinary steam turbine for electricity (Montes, 2009).

The amount of sensible heat stored (Q) is found using the mass (m), specific heat (C_p) and temperature range (ΔT):

$$Q = mC_p\Delta T$$

This storage method is time restricted as heat losses will always occur, their rate determining the time of storage. Typical molten salt storage systems store useful heat for electricity for up to 12 hours. Adequate insulation can reduce thermal losses.

Latent Heat Storage

Latent heat refers to heat released during phase changes of a material, such as liquid-solid or solid-solid. At the point of phase change, the temperature remains constant, while energy can still be absorbed or released (Allred, 2014). A typical measure for a material's ability to absorb/release heat is the latent heat of fusion. The heat stored in PCMs (Q) is found using the mass (m) and latent heat of fusion (L):

$$Q = mL$$

Phase-change materials (PCMs) are currently being developed for latent heat storage due to their high latent heat of fusion, which allows for high storage capacities. PCMs are able to store sensible and latent heat. The bulk material absorbs and releases heat as temperature changes, but in addition has the capability of heat storage in the phase change (Romero & Gonzalez-Aguila, 2013). Thermal losses occur in these systems due to conduction through the storage vessel, and radiation to the outside environment.

Thermochemical Heat Storage

Thermochemical energy storage (TCS) utilises reversible endothermic reactions to store energy by absorbing heat while the sun is shining and releasing energy via an exothermic process overnight. The types of reactions used can be carbonation, redox, decomposition and hydration (Sakellariou *et al*, 2015). They are based on reversible chemical reactions that heat a reactant to separate its components, then later recombine the components to release that heat. The heat stored in the material (Q) is found using the moles of reactant (n) and the reaction enthalpy (ΔH) (Pardo *et al*, 2014):

$$Q = n\Delta H$$

Theoretically, provided the storage system is closed, the storage period is unlimited (Masruroh, 2006). This is the greatest benefit of chemical storage, as long periods of time can elapse between heat collection from the sun, and heat transfer for steam generation (Zhang *et al,* 2016). Examples of thermochemical reactions are displayed in Table 1.

TABLE 1 - Types Of Thermochemical Reactions

Storage System	***Reaction***	***Energy Density (kWh/m3)***	***Reaction Temperature (°C)***
Ammonia	$2NH_3 \leftrightarrow N_2 + 3H_2$	745	400-700
Carbonate	$CaCO_3 \leftrightarrow CaO + CO_2$	692	700-1000
Hydroxides	$Ca(OH)_2 \leftrightarrow CaO + H_2O$	437	350-900

(Wu & Long, 2014)

Comparisons

Efficiency

The efficiency of a storage unit can be displayed using a Sankey diagram, showing the flow of energy or matter in a system. The Sankey diagram data in Figure 6 has been obtained from generalised efficiency values for each component of a sensible heat storage solar thermal plant, created using an online Sankey diagram generator (Sankey MATIC). It can be seen that heat losses accumulate from each section of the plant and contribute to the overall efficiency of ~17%. This is an average value from a number of different styles of plants, including saturated steam storage (17.5% efficient), thermocline storage (16% efficient), and molten salt storage (19.5% efficient) (Kalogirou, 2004). The 'sunny day' data is taking into account the best case scenario for sunny days, which is 70% of the year (Montes, 2009).

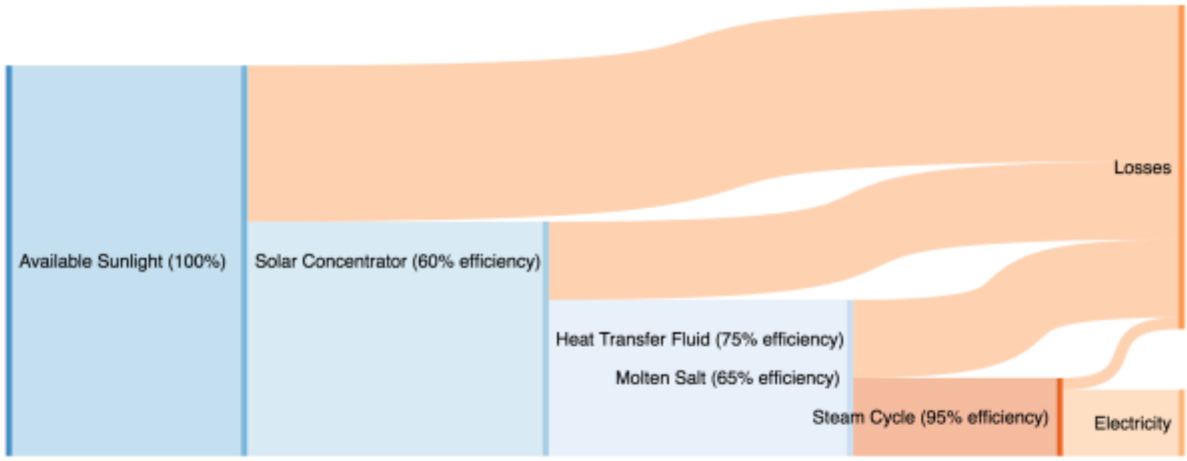

FIGURE 6 - Molten Salt Storage Efficiency

The diagram in Figure 7 below shows the losses encountered in the thermochemical system, the largest being when the electricity itself is generated after storage. The net heat capacity of the system was 925MWh, and the storage enabled 8 hours of storage during the day at 80% efficiency, then a subsequent 4 hours of full 80MW electricity generated. This corresponds to a total solar-electricity efficiency of 35% (Wu & Long, 2014). Typical efficiency values are established based on the degree of reversibility of the reaction, and can vary between 30 and 80%, depending on the reaction chosen (Zhang *et al*, 2016).

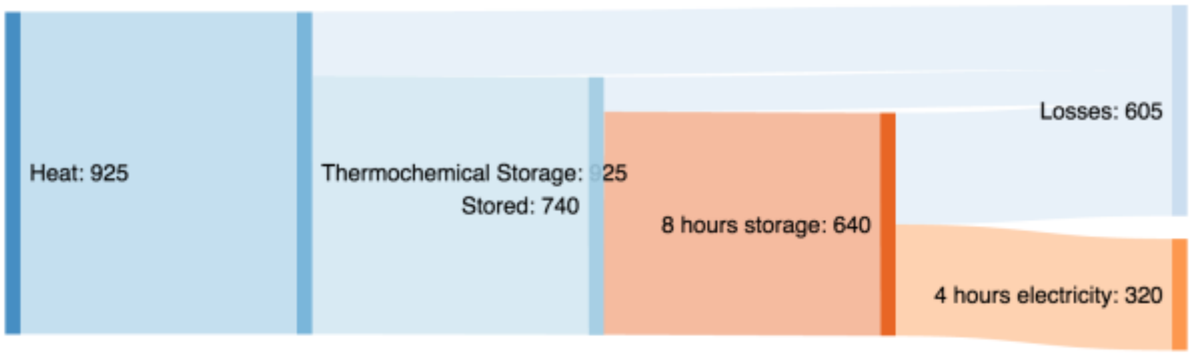

FIGURE 7 - Thermochemical Storage Efficiency

Efficiency of the systems is strongly affected by the plant setup and scale, and there is insufficient data to create a direct comparison of heat transfer efficiencies. For example, the efficiency analysis of thermochemical storage was conducted on a parabolic trough plant with output 80MW, finding an efficiency of 35%, while the analysis of molten salt considered a concentrating solar power tower plant of output 20MW.

Summary

TABLE 2 – Efficiency And Capacity Summary

System	*Molten Salt*	*PCM*	*Thermochemical*
Efficiency	17%	-	35%
Specific Thermal Storage Capacity	500kJ/kg	700-1000kJ/kg	1000kJ/kg +

(Zhang, 2016)

Carbon Footprint

An analysis of four PCMs to assess their storage capacity and carbon footprint is contained in Table 3. The CO_2 reduction compared to equivalent coal-fired power plant is a value found in the Lopez-Sabiron 2014 report. The results of the analysis show the potassium nitrate (KNO_3) had a considerable carbon impact during manufacture, but during operation presented considerable reductions in CO_2 emissions compared to a coal-powered plant.

TABLE 3 - PCM Carbon Footprint

PCM	***Storage Capacity *(GJ)***	***Carbon Footprint from Manufacturing (kg CO_2)***	***CO_2 reduction compared to equivalent coal-fired power plant (kg CO_2)***
KNO_3	128	15,176	-17300
NaOH	82	2,905	-13600
K_2CO_3, Na_2CO_3, Li_2CO_3	133	3,770	-8000
LiOH, KOH	164	3,742	-1300

* Based on 825kg of material, with equal numbers of phase change cycles

(Lopez-Sabiron, 2014)

Research has shown that implementation of a 1MW solar thermal plant with molten salt technology will produce 1360 tons less CO_2 than an equivalent coal-fired power plant. This type of plant will see an energy payback period of less than one year (Romero & Marcos, 2000). Another source has suggested that concentrating solar power plants emit 30 times less CO_2 (in g/kWh) than coal-fired plants (Zhang *et al*, 2011).

There is potential for thermochemical storage to act as a carbon capture mechanism, via the process of methane reforming, which is a reaction involving methane and carbon dioxide to produce carbon monoxide and hydrogen (Wu & Long, 2014). However, there is insufficient data to determine if this would offset carbon emissions from manufacture.

Cost

SENER, an engineering company in Spain, have successfully implemented a number of solar thermal plants using molten salt storage. The Gemasolar plant, with capacity 19.9MW, has 17 hours of storage in sodium and potassium nitrates to be used when there is no sun, allowing operation at full capacity for 74% of the year. The setup cost for the plant was approximately US$319M. The molten salt technology utilizes a hot and cold storage tank, with cold temperature 290°C and hot temperature 565°C (NREL, 2012). At optimal summer settings, the daily irradiance to the plant (taken from local irradiance data from Seville) is ~7kWh/m^2/day, about 20% larger than the irradiance of ~5.7 kWh/m^2/day for Port Augusta (calculated using hourly data, standard deviation 1.02 kWh/m^2/day).

A life cycle costing assessment of the Gemasolar Plant is provided in Table 5, allowing the total costs of the system to be established (Noel *et al,* 2014). This is a particularly advantageous tool for the molten salt storage type, as the latent heat and thermochemical storage technologies have cost estimates established but no concrete data regarding the true cost of their implementation.

TABLE 4 - Cost Analysis Of Molten Salt Storage

Component	***Material Costing (USD)***	***Labor Costing (USD)***
Tower/Receiver Components	$46,000,000	$25,500,000
Thermal Energy Storage System	$50,000,000	$6,000,000
Steam Generation System	$31,000,000	$11,000,000

Fossil Backup	-	-
Electric Power Generation System	$87,000,000	$28,000,000
Engineering Design Costs	-	$29,000,000
Site Improvements	$7,000,000	
Total	**$320 million**	

(NREL Molten Salt Power Tower Cost Model, 2013)

A number of economic analyses comparing storage types have been conducted, in particular one performed by Fleischer *et al* in 2015 that investigated PCM and molten salt storage systems. Both solar thermal systems were required to store heat for 9 hours for a 50MW capacity plant. The sensible heat storage using molten salt had volume 23856m^3 containing 45000 tonnes molten salt. The PCM heat storage had volume 17464m^3 containing 30000 tonnes PCM. It can be seen that the PCM storage reduces the tank volume by 65% and the mass of medium by 30% while still producing the same level of heat output. The reduction in volume was estimated to see a 15% reduction in cost (Fleischer *et al,* 2015).

A 10MW ammonia-based thermochemical storage system concept has been examined thoroughly in a 1999 paper by Luzzi *et al* at the Australian National University. The simulation achieved a net energy conversion efficiency of 30%, with a net power output of 10.2MW. The costing breakdown is outlined in Table 6.

TABLE 5 - Cost Analysis Of Ammonia Thermochemical Storage

Component	***Cost (AUD $M)***
Infrastructure	3.3
Collector Field (receivers and tower)	54.4
Ammonia Reactor and associated heat exchangers (endothermic)	17
Ammonia Reactor and associated heat exchangers (exothermic)	13.3
Steam Cycle	7.3
Energy Storage/Transport	46.8
Control System	12.3
Contingencies	15.4
Construction Management	10.7
Total	**$180 Million**

This system was calculated to have a levelised electricity cost of AUD 0.25/kWh (Luzzi *et al,* 1999). This figure takes into account all the costs of the system over its lifetime to determine what price to put on the energy source to break even over the projects lifetime. While this appears to be a breakthrough in low cost thermal storage, it appears that the research group has not published a follow up investigation since 2001.

Summary

TABLE 6 - Cost Summary

System	***Molten Salt***	***PCM***	***Thermochemical***	***Coal***
Capital Expenditure				
Manufacturing ($/MWh)	120-300	80-110	25-75	-
Investment ($/kW)	6000-15000	3400-4500	1000-3000	1000-1500
Operational Expenditure				

Operation ($/kW/annum)	250	120	20-60	-
Electricity Price				
Levelised Cost of Electricity (LCOE) ($/kWh)	0.11-0.17*	0.82	0.25	0.41-0.85*

*The LCOE for molten salt and coal is the 95% confidence interval range, as calculated in Appendix 1
(Smith *et al,* 2010. Parrado *et al,* 2016. Schneider *et al*, 2015. Wagner *et al* 2014. Ruegamer *et al*, 2014)
Note:
Coal power station costing breakdown was unavailable. Total cost of construction was approximately $100 million in 1954, which with inflation correlates to $1 billion in 2016 AUD.

Availability/Development

A number of solar thermal power stations are in operation around the world that utilize molten salt thermal storage. These include:

- Solana Generating station in Arizona with 280MW capacity, 6 hours thermal storage
- Noor I in Morocco with 180MW capacity, 3 hours thermal storage
- Crescent Dunes in Nevada with 110MW capacity, 10 hours thermal storage
- Gemasolar in Seville, Spain, with 20MW capacity, 15 hours thermal storage

(Romero & Gonzalez-Aguilar, 2013).

There are a number of commercially available PCMs, as well as materials that have the potential to be used as PCMs for latent heat storage. However, there are no large-scale implementations of PCM technology for solar thermal power plants. These materials have been used in domestic thermal storage but are in research and development stages for larger applications. Examples are provided of PCMs that have been identified as having potential for large scale use:

- $MgCl_2 \, 6H_2O$ - hydrated magnesium chloride salt
- KNO_3-$NaNO_2$-$NaNO_3$ – potassium/sodium nitrates
- Dodecanoic acid

(Fleischer *et al,* 2015. Allred, 2014)

Thermochemical storage systems are also not available commercially and are said to require significantly more research to assess their feasibility (Abedin & Rosen, 2012). Examples under consideration include:

- NaOH and water (Weber & Dorer, 2008)
- Ammonia (Luzzi *et al*, 1999)
- Calcium hydroxide (Azpiazu *et al*)

Summary

TABLE 7 - Availability Summary

System	***Molten Salt***	***PCM***	***Thermochemical***
Availability	Commercially available	In research and development	In research and development

Limitations

Molten salts can be chosen based on high heat capacity, which lowers the volume requirement for the tank. Low melting temperatures and high boiling points increase the range of temperatures the salt remains in molten state. Below the melting temperature, solid salt can lead to corrosion in the storage vessel, or cause blockages in piping. This currently requires the use of an additional heat source powered by fossil fuels (Morisson *et al*, 2008).

PCM storage design has a number of factors that must be considered before choosing an appropriate medium. Many latent heat materials have low thermal conductivities, despite their large latent heats of fusion. This can prevent rapid system transients (Fleischer *et al*, 2015). Research into synthesis of composites containing graphite have shown promise, with considerable increases in conductivity without sacrificing latent heat (Morisson *et al,* 2008). In order to minimise the risk of salt build-up in the storage tank during the discharging process, PCMs also require tubes or fins within the tank for heat exchange in order to increase surface area (Adinberg, 2010). This increases both the complexity and cost of the tank (Seitz *et al,* 2014). Some PCMs are toxic or flammable and this poses restrictions and risks for transport, containment, maintenance and handling (Hauer, 2011).

Thermochemical storage at present remains in the research and development phase. The high energy density of thermochemical reactions is the key benefit, but to take advantage of this characteristic, operating temperatures must also be high which poses a potential problem for extended periods of cloud cover.

Risk Analysis

Due to the lack of direct human interaction with these solar thermal systems, risks analyses can largely be focussed on technical, financial, social and policy risks (Gaurav, 2011). Technical risks include technology integration (ie solar receivers, storage and steam turbine systems and the power grid are correctly designed to work together), operation and maintenance risks, material availability and transportation, and land compatibility. Financial risks are considerable with solar thermal projects due to the large capital costs associated, but these risks are necessary as small-scale, laboratory sized developments do not directly scale upwards to the larger scales for required power output. Cost-effectiveness is also only achieved with long-term funding options. Social risks include worker health and safety, as well as local environmental protection. Policy risks relate to licensing and legislation, which may be at a state or federal government level.

Solar thermal storage media are typically chosen for their energy densities, but of particular consideration is their toxicity, corrosiveness and reactivity with their storage containers. Table 9 is a risk matrix, assessing the various hazards associated with storage media.

TABLE 8 - Risk Matrix For Solar Thermal

	Negligible	Minor	Moderate	Significant	Severe
Very Likely					
Likely		Increased heat of storage tank			
Possible		Loss of material due to gradual reaction with container	Air pollution	Corroded storage piping	
Unlikely			Emissions from material fabrication	Transportation accident	Leak of high temperature salt/fluid
Very Unlikely				Fire from flammable PCM/explosion from flammable PCM	Human ingestion/contact with storage medium. Disease over time.

As indicated by the interview with Dan Spencer, there is a requirement that the solar thermal plant be a closed system to ensure safety of workers and people in the surrounding areas. The significant and severe consequence categories in the risk matrix refer to hazards relating to escaping material. By placing emphasis on a closed system, these hazards will become more and more unlikely. Backup measures that ensure containment of materials will reduce the likelihood further.

Data Collection Methodology

The data collected in this portfolio has been sourced from peer-reviewed journals (see bibliography). Data more than 15 years old has not been included, as only the most up to date information is useful in this analysis. The issue of incomparable data was addressed using unit conversions where appropriate (such as choosing kW/MW, or m^3/t). Qualitative information has led to quantitative data collection, with unnecessary comparative information excluded. The acquired numerical data has been organized into tables and figures created by the author. As a survey was not conducted, positive and negative responses could not be coded, but many figures were cross-checked and eliminated if differing significantly from other sources. This was particularly appropriate for the costing analyses. Dynamic data, such as the direct sunlight at Port Augusta and Spain, was collected and averages taken when appropriate. LCOE values were differing so significantly that a confidence interval was taken to attain the range of possible values.

Recommendations for Port Augusta

Present

The only commercial energy storage technology currently available is molten salts (sensible heat storage). Thus, if the Port Augusta council is to apply for Government funding for the installation of a solar thermal power plant this year, molten salt is the only feasible option. Molten salt has proven to be an effective storage medium that is low cost, has a long lifetime, is reliable, and is available to be implemented in the immediate future (Abedin *et al,* 2012). Capital costing of molten salt is higher than latent and thermochemical heat systems, but the cost of storage material is considerably lower, making for a lower LCOE overall.

To implement this recommendation, the Gantt chart in Figure 8 outlines the critical path. The chart is adapted from a solar power plant Gantt chart, with the inclusion of the storage technology design and construction. Provided rapid attainment of government approval for the project along with funding approval, the time for development of the plant from design idea through to operation is expected to be between five and six years (Romero & Marcos, 2000). It is expected that the construction process will provide between 500 and 1000 jobs, with up to 200 ongoing workers needed depending on the scale of the project (Gemasolar Plant, Ivanpah Plant, Solana Generating Station).

Dan Spencer stated that Port Augusta was bidding to receive $100 million in government funding for a solar thermal project. The Gemasolar plant case study showed a power output of 20MW and total cost of $320 million, assuming public private partnership. The old coal fired plant at Port Augusta produced twelve times this output - 240MW of electricity, and was found to have cost AUD$1 billion in 1954 (Alinta Energy, 2016). The largest solar thermal plant with storage in the world (Solana Generating Station, Arizona) produces 280MW of power with 6 hours of storage, and cost US$2 billion (Ma *et al*, 2015). Thus for a small plant of approximate 20MW, the government funding of $100 million would contribute significantly, but for a plant that could produce a similar output to what the coal plant produced previously (240-280MW), considerably larger investments are required involving more Government subsidy and big private enterprise investment.

Port Augusta should also consider the future of solar thermal technology development, as there is potential to utilize molten salt storage now and fit an alternative storage system in at a later date. Designs for the solar collector and power block may be able to include infrastructure that will accommodate thermochemical or latent heat storage, however the technical feasibility of this suggestion is not yet determined.

FIGURE 8 - Gantt Chart For Solar Thermal Plant Planning

Future

Based on current research, the future of thermal storage systems lies with thermochemical processes. It has been found that the energy density of thermochemical storage systems is 5 to 10 times higher than for sensible or latent heat (Pardo *et al,* 2014). The study conducted at the ANU in 1999 revealed the potential for thermochemical storage, with a 10MW plant set to cost $180 million, however the lack of recent published documents rules this out as an option. These low cost, low risk, high efficiency and high capacity systems are currently only developed at the laboratory scale, meaning the feasibility at larger scales is yet to be proven. Additionally, the ability to dispatch thermochemical storage is a major benefit of this technology as there are negligible losses after the endothermic reaction step and the products can be held for a long time before being passed to the exothermic reaction chamber. This has significant potential for offsetting storage to times of peak electricity demand.
Latent heat storage lies between molten salt and thermochemical storage on a number of factors, including energy density and lifetime, but currently has a cost nearly three times that of thermochemical. The potential for storage is clear, but the present analysis deems it less suitable than either thermochemical or molten salt.

Conclusion

This portfolio investigated implementing a solar thermal power plant in Port Augusta, South Australia. The suitability of a solar thermal power plant for Port Augusta is clear, with community support, proposals from Solastor and SolarReserve and an appropriate climate. With 30 times less CO_2 than coal emitted per kilowatt hour, solar thermal sustainably harnesses energy from the sun, and presents a feasible electricity option for Port Augusta. It was found that a plant utilizing molten salt as a storage method was the preferred solution in the short term, as the cost of electricity was comparable to coal, but with 30 times less carbon emissions. In the future, both thermochemical and latent heat storage are likely to present even more benefits than molten salt, with high energy densities, re-locatable storage and low costs.

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