Identifying the optimum storage capacity for a 100MW CSP plant in South Africa

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Abstract

Eskom intends building a 100MW$_e$ central receiver plant in the Upington area in South Africa. This has been identified as an ideal location for the development of central receiver power plants due to the excellent solar resource that it receives. The long term average solar resource in the area is estimated at 2816 kWh/m^2 [1]. The inclusion of thermal energy storage increases the capacity factor of the given plant which results in a decrease in the levelised electricity cost (LEC). Identifying the optimum storage capacity for a 100MW central receiver plant located in Upington to obtain the lowest LEC is the objective of this paper. The results indicate that unconstrained the optimum storage capacity is 16 hours with a solar multiple of 2.8 and LEC of R1.41/kWh. The majority of the capital costs associated with this configuration is composed of the solar field (29%) and storage (19%). Limiting the plant capacity factor to 60% provides solar multiple of 1.8 and 8 hours of storage and LEC of R1.78/kWh. The solar field cost and storage are still the major cost contributors in this scenario with 24% and 13% respectively.

Keywords: Capacity Factor, Central Receiver, CSP, LEC, Solar Multiple, Storage

1. Introduction

The semi-arid conditions in the Northern Cape region of South Africa provide the ideal conditions to exploit the potential that central receiver technology offers. The quality of the solar resource and the capital cost of the plant are highly influential to the outcome of the LEC calculation. Assuming a base of 2100kWh/m^2/yr (typical Spain), the expected LEC of a CSP plant is expected to decline by 4.5% for every 100kWh/m^2/yr that the DNI exceeds 2100 [2]. The inclusion of thermal energy storage for central receiver plants enables better utilisation of the power block which results in higher plant capacity factors as well as a reduced levelised cost of electricity. The Gemasolar power plant in Spain is the first commercial molten salt central receiver plant commissioned. It has proven that the technology is viable on a commercial scale with capacity factors in excess of 70% [3].

The increased drive for power from renewable resources and the acceptance that fossil fuels are finite drives the need to identify the ability of this technology on a larger scale.

2. Objective

The objective of this research is to identify the storage capacity that provides the minimum levelised electricity cost for the proposed plant. This research will look at both the unconstrained condition and a capacity factor constraint of 60%.

3. Methodology

To determine the levelised electricity cost, the investment expenditure, annual operation and maintenance cost, fuel cost and annual power produced by the proposed plant is required.

The investment expenditure is determined using costing data provided by NREL [4] which is broken down into the following categories:

- Structures and improvements ($/m^2 field)
- Heliostat Field ($/m^2 field)
- Receiver System ($1000/m^2 receiver)

- Tower and piping system ($\$/m^2$ field)
- Thermal Storage System ($\$/kW_t$)
- Steam Generator System ($\$/kW_t$)
- Power Block ($\$/kW_e$)
- Balance of Plant ($\$/kW_e$)
- Indirect costs ($\$/kW_e$)
- Contingency ($\$/kW_e$)
- Risk Pool($\$/kW_e$)

An hourly successive steady state plant operational model is developed using energy balances and efficiencies. The model provides the data required to calculate the investment cost using the breakdown above as well as the annual power output from the plant. The model provides the ability to ascertain the effect of changing parameters on the levelised electricity cost of the plant.

A power block model and solar field model were developed and these are coupled via the steam generator. The power block model was validated by simulating the same conditions in Steam Pro (a heat balance program specifically intended for design of steam power cycles) and comparing the results. The solar field model was validated by using site data for Gemasolar obtained from Meteonorm and the outputs were compared against published data for Gemasolar.

The model developed is composed of the following components:

- Solar Field: a sixth order polynomial that is dependent on the zenith angle is used to determine the solar field efficiency [5].
- Receiver: The convective and radiative losses for the receiver are determined and a receiver energy balance is performed to determine the energy transferred to the salt which is sent to storage.
- Storage: this is modelled as 98.5% efficient [6].
- Steam generator: Consists of preheater, evaporator, superheater and reheater. Modelled using pinch point temperature difference to determine if the exit salt temperature and feedwater temperature and pressure provide a possible powerblock setup
- Power Block: A 100MW single reheat, regenerative dry cooled Rankine cycle power block is developed using basic thermodynamics (the condenser pressure was linked to the ambient temperature with an initial temperature difference (ITD) of 20 ˚C). The power block is coupled to the storage via the steam generator.

4. Model Description

4.1 Heliostat Field

The heliostat field efficiency is determined by a sixth order polynomial which is dependent on the zenith angle and accounts for cosine, shading and blocking effects [5].

$$\eta_{\mathrm{opt}} = 0.4254\theta_z^6 - 1.148\theta_z^5 + 0.3507\theta_z^4 + 0.755\theta_z^3 - 0.5918\theta_z^2 + 0.0816\theta_z + 0.832$$

The zenith angle is calculated as demonstrated in Duffie and Beckman [11].

4.2 Receiver

To determine the optical energy that is incident on the receiver heliostat fouling, reflectivity, availability and spillage needs to be accounted for. It is assumed that 15 per cent of the reflected energy is lost to spillage and attenuation.

$$\eta_{rec\,opt} = (\text{Heliostat availability})(\text{Heliostat fouling})(\text{Heliostat Reflectivity})(\eta_{opt})(1 - \text{spill loss})$$

The model developed uses 1000m^2 surface area for the receiver [4]. The total energy incident on the receiver is determined as follows:

$$Q_{\text{receiver in}} = \text{Receiver absorbtivity } \times \text{DNI} \times \eta_{rec\ opt} \times F_A \times \text{SM}$$

The receiver heat flux is limited to be 700kW_t/m^2 [4].

$$\text{Max Energy absorbed by receiver} = (\text{Max allowable heat flux})(\text{Receiver surface area})$$

A receiver energy balance as shown in Figure 1 determines the net energy available for storage once thermal energy losses due to convection and radiation are taken into account.

$$Q_{\text{net}} = Q_{\text{receiver in}} - Q_{\text{conv}} - Q_{\text{rad}}$$

Figure 1: Receiver energy balance

4.3 Storage

The storage system is modelled as being 98.5% efficient. To determine the amount of thermal energy required for an hour of storage the design point data is examined.

$$\text{Thermal Energy}_{\text{for 1hr storage}} = \frac{\text{Gross Power Output}}{\eta_{PB}}$$

4.4 Steam Generator

The steam generator links the power block and storage system. The steam generator consists of a preheater, evaporator, superheater and reheater. The super heater and reheater allow salt flow in parallel and the salt flowrate is configured to allow the exit temperature from both components to be equal. The pressure drop across the pre-heater, evaporator and super heater is assumed to be equal. The energy requirement across each component is calculated knowing the feedwater conditions.

$$Q = \dot{m}(h_{\text{out}} - h_{\text{in}})$$

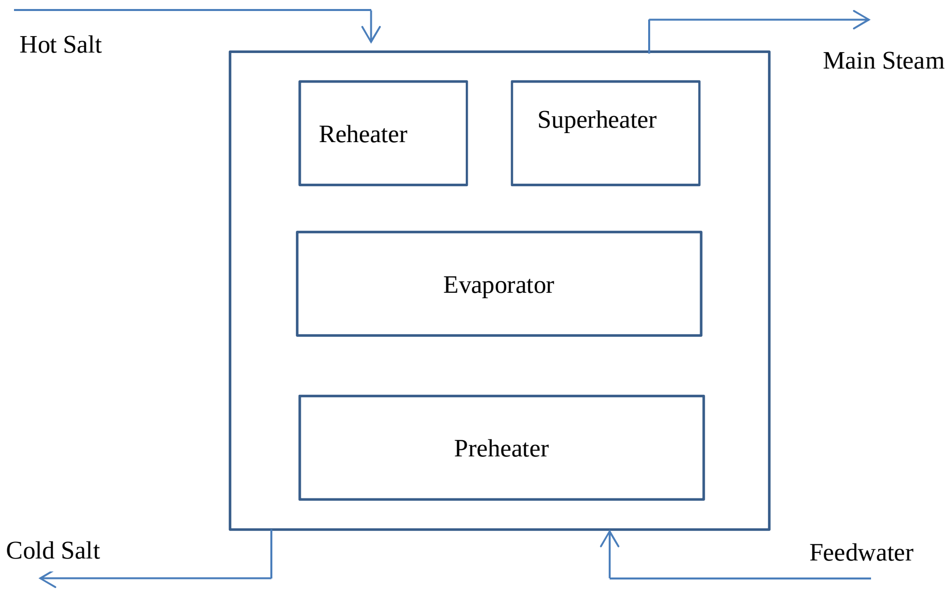

Figure 2: Schematic of Steam generator

The input and output salt temperature across the steam generator is known and the input feedwater and main steam conditions are obtained from the powerblock model. An energy balance is performed on the steam generator to determine the required salt flowrate.

$$\dot{m}_{salt} = \frac{\dot{m}_{fw}(h_{main\ steam} - h_{fw})}{C_p(T_{hot\ salt} - T_{cold\ salt})}$$

Isolating each component within the steam generator and performing an energy balance enables calculation of the exit salt temperature from each component.

4.5 Powerblock

A steady state single reheat regenerative Rankine cycle power block model was developed. The Microsoft Excel add-in X Steam was used for the thermodynamic properties of water and steam. The output of one component is taken as the input of the downstream component. The optimum reheat pressure is assumed to ¼ of the maximum cycle pressure. The isentropic efficiency of the turbine is assumed to be 85 percent. The model is an hourly steady state model with a dry cooled condenser.

$$P_{condenser} = P_{sat}(T_{db} + ITD)$$

Equal temperature rise across the feedheaters is assumed.

$$\text{Temperature rise} = \frac{\text{feedwater input temp} - \text{condenser exit temp}}{\text{number of feedwater heaters}}$$

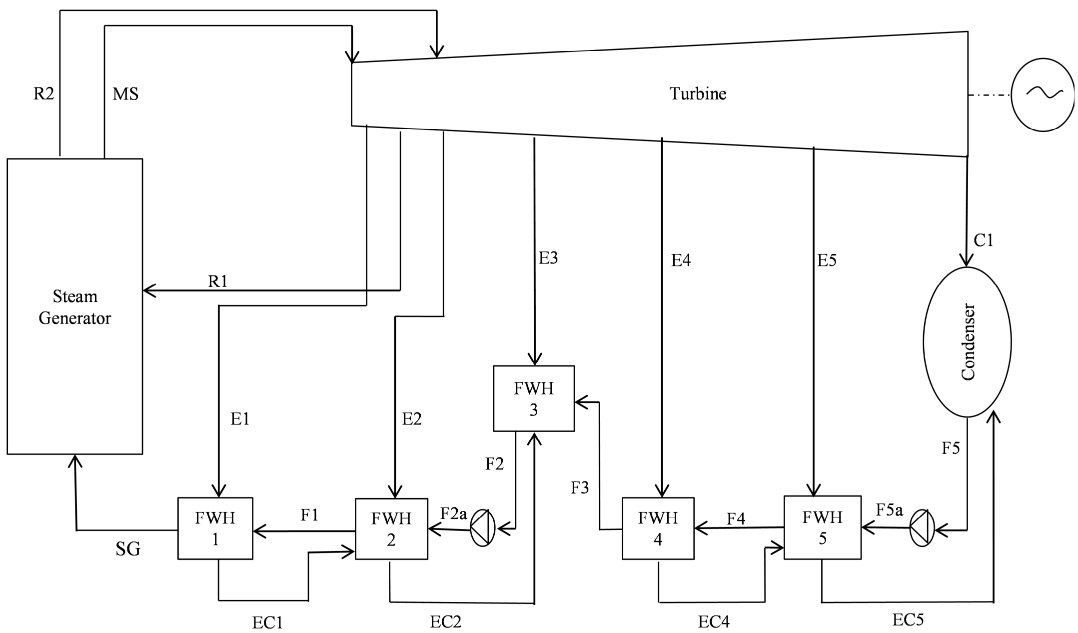

Figure 3: Power block feedheating layout

4.6 Calculation of number of heliostats for Solar Multiple of 1 at design point

To calculate the number of heliostats required for a solar multiple of one, the efficiency of the different components are used.

$$\text{Heliostat Aperture Area}_{SM1} = \frac{\frac{\text{Gross Output at Generator Terminals}}{(\eta_{PB})(\eta_{rec\ opt})(\eta_{rec\ therm})(\text{Receiver absorbtivity})}}{\text{Reference DNI}}$$

The number of heliostats required is calculated

$$\text{Number of Heliostats}_{SM1} = \frac{\text{Heliostat Aperture Area}_{SM1}}{\text{Heliostat Size}}$$

For an increase in solar multiple the values obtained at design point are multiplied by the new solar multiple.

$$\text{Number of Heliostats}_{SM2} = (2)\ (\text{Number of Heliostats}_{SM1})$$

4.7 Calculation of LEC

To determine the investment cost (I_t) the model outputs are multiplied by their respective cost category. The annual energy generated (E_t) is obtained from model. Operation and maintenance cost (M_t) are estimated from data published by NREL. It is assumed that the plant is not fuel assisted, hence $F_t = 0$. It is assumed that a 100% loan is obtained at an interest rate of 10% with loan duration of 25 years. The discount rate(r) is assumed to be equal to 5.6% and the rand dollar exchange rate used is R/$=9.

$$LEC = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

5. Parametric Analysis to determine effect on LEC

A change in the efficiency of the power block influences the thermal capacity of the storage system and the area of the solar field. A parametric analysis was performed to investigate the effect of varying parameters that affect the power block efficiency and the effect that varying the storage capacity and increasing the solar multiple has on LEC. The feedwater temperature was varied between 200 ˚C - 240˚C in intervals of 10 ˚C. The main steam pressure was varied between 100 bar and 140 bar in 10 bar intervals.

The exit salt temperature from the steam generator was varied between 260 ˚C and 300 ˚C and the storage capacity was varied between 6 and 18 hours in 2 hour intervals. The solar multiple was varied between 1.4 and 3.0 in increasing intervals of 0.2.

5.1 Results of parametric analysis

Table 1 shows that a higher exit salt temperature allows for a power block setup with greater efficiency. Figure 6 and Figure 7 show the optimum storage capacity and solar multiple and the associated capacity factor. Including a capacity factor constraint of 60% results in a solar multiple of 1.8 with storage capacity of 8 hours. This cost breakdown is shown in Figure 8

Configuration	SG exit salt temperature (˚C)	Main Steam Pressure (bar)	SG feedwater temperature (˚C)	Power Block Efficiency
1.	270	120	200	0.4120
2.	280	140	210	0.4189
3.	290	140	230	0.4206
4.	300	140	230	0.4206

Table 1: Power block configuration with highest efficiency at each exit salt temperature

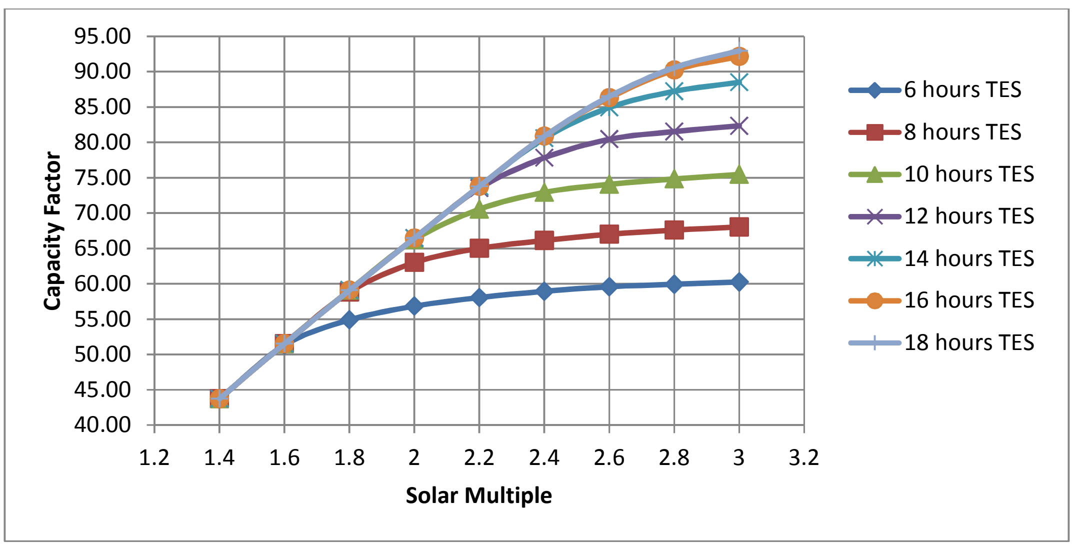

Figure 6: Capacity factor vs solar multiple

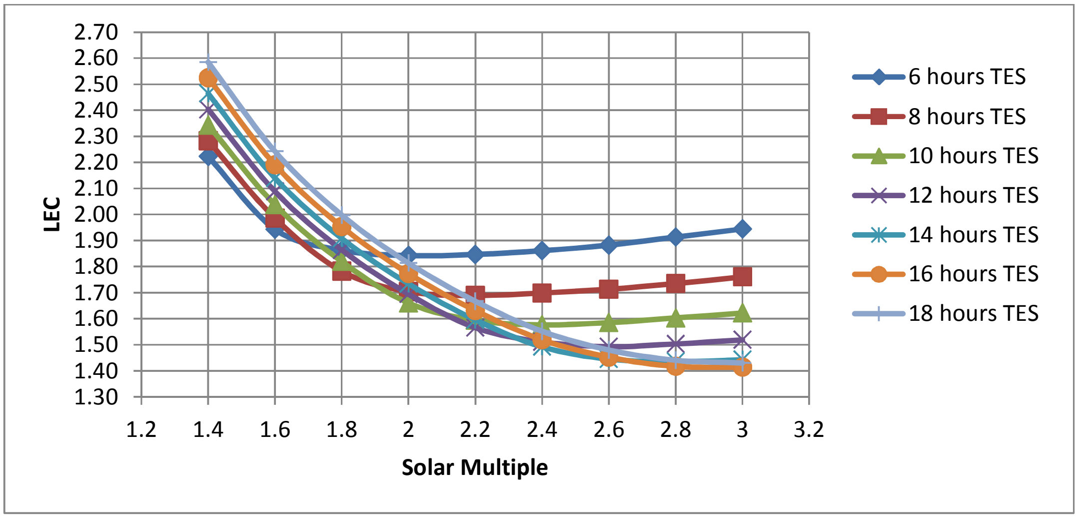

Figure 7: Levelised electricity cost vs solar multiple

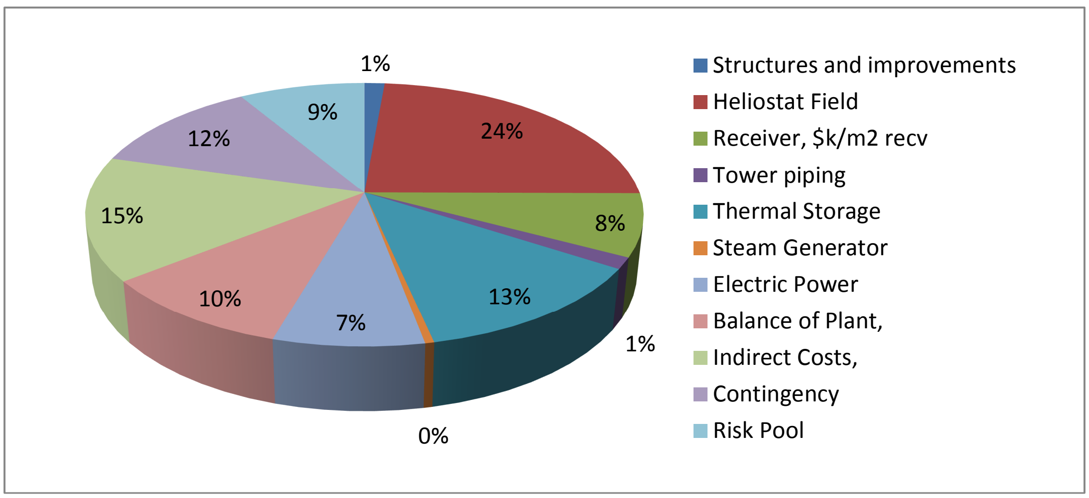

Figure 8: Cost break down for 60% capacity factor (Solar Multiple of 1.8 and 8 hours TES)

SM	Exit Salt Temperature (˚C)	Storage capacity (hours)	Capital cost (R/W)	Capacity Factor (%)	LEC (R/kWh)
1.8	270	8	67.79	59.10	1.79
1.8	280	8	67.35	58.98	1.78
1.8	290	8	67.24	58.88	1.78
1.8	300	8	67.24	58.82	1.78

Table 2: Breakdown for optimum storage capacity for different exit salt temperatures at 60% capacity factor

6. Conclusion

A solar multiple of 2.8 with a storage capacity of 16 hours results the minimum LEC of R1.41/kWh at a capacity factor of approximately 90% when there are no constraints on the system.. When applying a capacity factor constraint of 60% to the system, the storage capacity of 8 hours with a solar multiple of 1.8 provides a LEC of R1.78/kWh.

A supercritical coal plant has a LEC of R0.80/kWh [10]. Due to the age of the cost information (2003) it is expected that the LEC cost identified will be more optimistic than for current build projects. This can corrected by using better cost data as it becomes available. In the near future it is not expected that CSP will reduce to LEC values of supercritical coal power but with rolling out on a larger scale and reductions in cost from learning rates and economies of scale it is expected that it can be a key player in the longer term (10-15 years) future power generation capacity.

Definitions of symbols

C_p – specific heat capacity DNI – Direct normal irradiation F_A – heliostat field aperture ITD – initial temperature difference SM – solar multiple r – discount rate t – year E_t – electricity generated F_t – fuel cost year t I_t – Investment cost M_t – operation and maintenance cost	$h_{main\ steam}$ – main steam enthalpy $h_{feedwater}$ – feedwater enthalpy $\dot{m}_{fw}$ – feedwater mass flow rate $\dot{m}_{salt}$ – salt mass flow rate $Q_{receiver\ in}$ – receiver incident energy Q_{net} – receiver net energy absorbed Q_{conv} – Energy lost to convection Q_{rad} – Energy lost to radiation T_{db} – dry bulb temperature $T_{cold\ salt}$ – cold salt temperature	$T_{hot\ salt}$ – hot salt temperature $P_{condenser}$ – condenser pressure P_{sat} – saturation pressure η_{opt} – optical efficiency η_{PB} –power block efficiency $\eta_{rec\ opt}$ –receiver optical efficiency $\eta_{rec\ therm}$ - receiver thermal efficiency θ_z - zenith angle

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