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Rock Bed Thermal Storage: Concepts and Costs

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Abstract. Thermal storage enables concentrating solar power (CSP) plants to provide baseload or dispatchable power. Currently CSP plants use two-tank molten salt thermal storage, with estimated capital costs of about 22-30 $/kWh_{th}$. In the interests of reducing CSP costs, alternative storage concepts have been proposed. In particular, packed rock beds with air as the heat transfer fluid offer the potential of lower cost storage because of the low cost and abundance of rock. Two rock bed storage concepts which have been formulated for use at temperatures up to at least 600 °C are presented and a brief analysis and cost estimate is given. The cost estimate shows that both concepts are capable of capital costs less than 15 $/kWh_{th}$ at scales larger than 1000 MWh_{th}. Depending on the design and the costs of scaling containment, capital costs as low as 5-8 $/kWh_{th}$ may be possible. These costs are between a half and a third of current molten salt costs.

INTRODUCTION

Thermal energy storage is a key component of concentrating solar power (CSP) plants because it enables the generation of electrical power to meet demand, an increasingly necessary capability as the installed capacity of wind turbines and photovoltaics increases. Since photovoltaics are cheaper than CSP [1], thermal storage is likely to be the main reason for constructing CSP plants. At present two-tank molten sodium/potassium nitrate salt is the commercially favoured thermal storage solution. Molten salt capital costs are about 22-30 $/kWh_{th}$, and Kolb *et al.* [2] estimated that a 9 hr two-tank molten salt thermal storage system contributes 13 % of the direct costs associated with the LCOE (levelised cost of electricity) for a 100 MW_e central receiver plant. Cost reduction of the storage system will have a measurable effect on the total plant cost. Halving the storage cost would, all other costs remaining the same, reduce the direct cost by 6 % and the total LCOE (which includes interest, operational and indirect costs) by 4 %. Additionally, storage at higher temperatures than those permitted by the current molten salt mix (565 °C) would allow higher power block efficiencies, further reducing the LCOE.

Nearly 60 % of the molten salt system cost referred to by Kolb *et al.* is contributed by the salt material cost (11-12 $/kWh_{th}$), so alternatives which make use of lower-cost materials should be considered. One alternative is packed bed thermocline storage. In particular, rock beds with air as the heat transfer fluid have the potential to provide low-cost storage at temperatures up to at least 600 °C due to the extremely low cost of rock (about 0.02 $/kg for commercially crushed rock in South Africa [3]; 12 ZAR ≈ 1 US$). Rock is an abundant material, so there should be few supply limitations, although long-distance transport to regions without suitable material is undesirable, as transport can cause the cost of the rock to escalate rapidly. A rock bed thermal storage concept constructed by Zanganeh *et al.* [4] in Switzerland for use in the temperature range from 500-600 °C has proven the feasibility of this type of storage system, and a commercial system is being commissioned in Morocco.

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The use of air as a heat transfer fluid poses a number of difficulties: unlike molten salt, a high volumetric flowrate of air is required to transport thermal energy. This requires large cross-sectional areas for airflow if large pressure drops – and the consequent pumping power and cost – are to be avoided. At the same time, it is desirable to keep the containment surface area requiring thermal insulation to a minimum, due to the high cost of insulation. Additionally, ratcheting of randomly packed beds [5] may lead to containment failure.

Two concepts that were formulated to holistically address these issues are discussed in this paper. The discussion includes limited thermal modelling and cost estimates. The concept development has benefitted from research on bed flow and thermal characteristics, rock packing, duct formation, and optimum design [6-8].

ROCK BED CONCEPTS

Both concepts make use of a pile of rock with unconstrained sides, permitted to form at the natural angle of repose. This should eliminate or reduce thermal ratcheting and related containment complications. The first concept is the patent of Kröger [9], and the second is the patent of Gauché [10]. In this work, the envisioned usage of these concepts is to supply thermal energy to a steam Rankine cycle, which will require thermal storage at temperatures in the region of 600 °C. However, provided that the available rock is suitable for use at higher temperatures, there is no reason why the concepts can't be used at temperatures above 600 °C, with additional insulation as may be needed.

Concept 1

In this concept from Kröger [9], a rock bed is formed under an airtight containment structure (Figure 1). During charging, the hot air is introduced at the top of the bed (as opposed to the bottom) to reduce natural convection caused by buoyancy effects, since natural convection may destabilise the thermocline. The large plenum at the top ensures that the hot air with low density will have a large cross-sectional area through which to flow, thereby reducing the pressure drop and blower pumping costs. During discharging, the airflow direction is reversed and cold air is blown or drawn into the bottom of the bed from where it passes through the bed and into the top plenum.

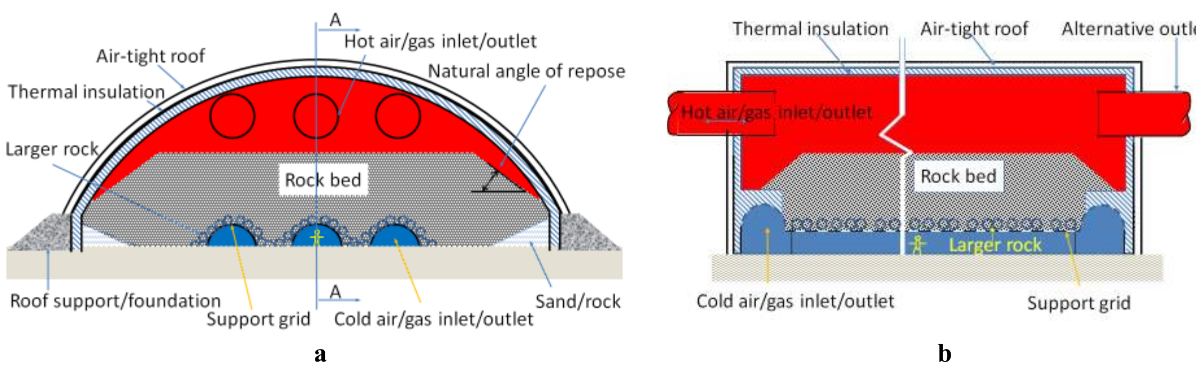


FIGURE 1. Packed bed concept of Kröger [9] showing (a) ducts, hot & cold regions; and (b) cross-sectional view on A-A

A cost disadvantage of this concept is that the entire surface area, which will typically contain air at temperatures around 600 °C, needs to be thermally insulated. Insulation costs are high, particularly at small scales where the surface area to volume ratio is large (as discussed later in this paper – see Table 3 – it can contribute a third of the direct capital cost (excluding labour) at a scale of the order of 100 MWh), which is why Concept 2, although having potential difficulties with thermocline destabilisation, is attractive economically.

Concept 2

Concept 2 from Gauché [10] is unconventional in that the hot air is introduced at the centre of the bed base and allowed to flow to the outer surfaces during charging. An illustration is shown in Figure 2. The advantage of this concept is that the containment structure – if one is used – requires no thermal insulation. The only insulation requirement is under the base of the rock bed, depending on the thermal resistance of the ground. Provided that the blower can be placed on the hot air inlet duct side of the storage, no containment is required, and the charging air that flows through the rock bed can flow freely into the surrounding atmosphere. During discharging, air is drawn (if there is no containment) or blown through the bed from the outer surface to the centre duct. The cost reduction that is possible by eliminating the insulation and, depending on the blower position, the containment structure, makes it a very attractive alternative. Technically, this concept may be higher risk than Concept 1, because thermocline destabilisation is a possibility as a consequence of natural convection caused by buoyancy effects, unless the rock is sufficiently small. According to Elder [11] natural convection and destratification should be negligible for a porous medium of depth L heated from below provided that the Rayleigh number is less than 40, a requirement which is fulfilled [12] if

$$L < 8.6 \times 10^{-4} / D^2 \tag{1}$$

It is not clear what definition of particle diameter D was used by [12], but this provides a rough estimate of particle diameter for thermocline stability. For $D = 0.02$ m, $L < 2.2$ m, and for $D = 0.01$ m, $L < 8.6$ m to ensure stability. Since rock diameters (volume-surface area ratio or volume equivalent sphere diameter) for this application of packed beds are likely to be between 0.01-0.03 m (for example [4,8]), it is possible that thermocline stability will be a problem unless measures are taken to limit natural convection.

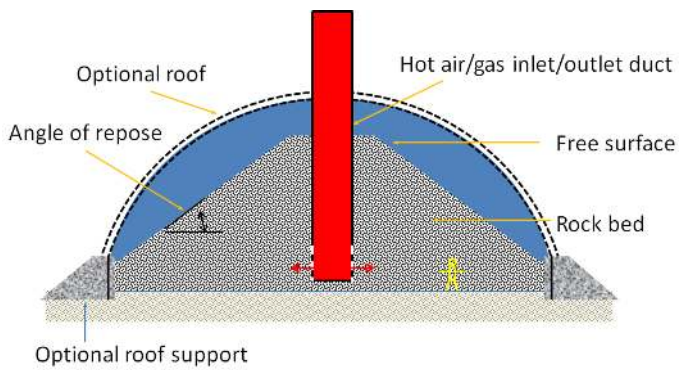


FIGURE 2. Packed bed concept of Gauché [9]

TEMPERATURE PROFILE AND COST ESTIMATE DETAILS

Temperature Profile

The thermal performance of Concept 1 was modelled by means of the E-NTU method of Hughes [13,14]. This method assumes one-dimensional fluid flow and neglects thermal radiation and interparticle thermal conduction through the bed. The thermal capacity of the sloping edge of the rock bed is neglected, essentially assuming that all flow in the bed is in the core region. Natural convection effects are neglected.

Crushed rock is irregular and non-uniform, and it is necessary to define the particle diameter. In this work, the particle diameter D_v is the average volume-equivalent sphere diameter. All E-NTU calculations in this paper made use of this definition. For n samples of volume V_{pi},

$$D_v = \left(\frac{6}{\pi} \left[\frac{1}{n} \sum_{i=1}^{n} V_{pi} \right] \right)^{1/3} \tag{2}$$

For the crushed rock tested by [8], D_v is approximately related to the total bed particle volume-to-surface area diameter D by the relation

$$D = 6\Sigma V_p / \Sigma A_p \approx 0.8 D_v \tag{3}$$

The simplified Nusselt number correlation used in the Hughes E-NTU method is only for air-rock beds [8]:

$$Nu_v = hD_v / k = \mathrm{Re}_{pv}^{0.6} \tag{4}$$

where h is the surface-area heat transfer coefficient, k the air thermal conductivity, and Re_{pv} the Reynolds number defined in terms of the fluid viscosity μ and mass flux G through the packed bed:

$$\mathrm{Re}_{pv} = GD_v / \mu \tag{5}$$

For this work, the bed is charged and discharged at a constant mass flux of 0.2 kg/m^{2}s (G_c) and 0.1 kg/m^{2}s (G_d) respectively, at inlet air temperatures of 600 °C (T_c) and 20 °C (T_d) respectively. The bed is charged for 8 hrs during the day (t_c) – as would be the case from a solar receiver – and discharged for 16 hrs (t_d), as would be the case in a CSP plant operating in such a way as to provide power during the night.

The input parameters used for calculating the temperature profile are summarised in Table 1. The air properties were based on the tabulated values in Incropera *et al.* [15]. The void fraction (ε) of 0.45 was based on the average of the measured void fractions for the rock tested previously [7]. It is possible that lower void fractions may occur, particularly if the rock compacts with packing depth [4]. For the same bed dimensions and a lower void fraction, the thermal capacity of the bed will increase, so using a void fraction of 0.45 will result in a conservative estimate of the thermal capacity.

TABLE 1. Input values for E-NTU temperature profile calculation

Parameter	***Value***	***Parameter***	**Value**
c_p (55 °C)	815 J/kgK	T_d	20 °C
D (approx.)	0.02 m	t_c	8 hrs
D_v	0.025 m	t_d	16 hrs
G_c	0.2 kg/m^{2}s	p_{amb} *(ambient pressure)*	100 000 Pa
G_d	0.1 kg/m^{2}s	***Greek alphabet***	
L	11 m	ε	0.45
T_c	600 °C	ρ_p *(rock density)*	2700 kg/m^3

The thermocline in the bed typically takes 15-30 charge-discharge cycles to reach its steady cyclic state [4], so 40 consecutive charge-discharge cycles were simulated. Bed air outlet temperatures during charging and discharging are plotted in Figure 3 for some of the cycles. Because the air flow direction is reversed between charging and discharging, the bed inlet during charging functions as the bed outlet during discharging. Similarly, the bed outlet during charging functions as the bed inlet during discharging.

The charging air outlet temperature rises by nearly 20 °C at the end of charging, which means that about 1 % of the charging energy is lost. This is a consequence of the non-ideal thermocline in the packed bed; the rock mass has a maximum theoretical energy capacity (assuming that the rock all undergoes a temperature change from 20 °C to 600 °C) nearly 2.5 times larger than the energy transported to the bed by the charging air. Lengthening of the bed would reduce the loss, but increase the pressure drop. The bed parameters used here are based on preliminary cost-optimum work [8], and there is scope for further calculations to determine the optimum bed size for the lowest LCOE.

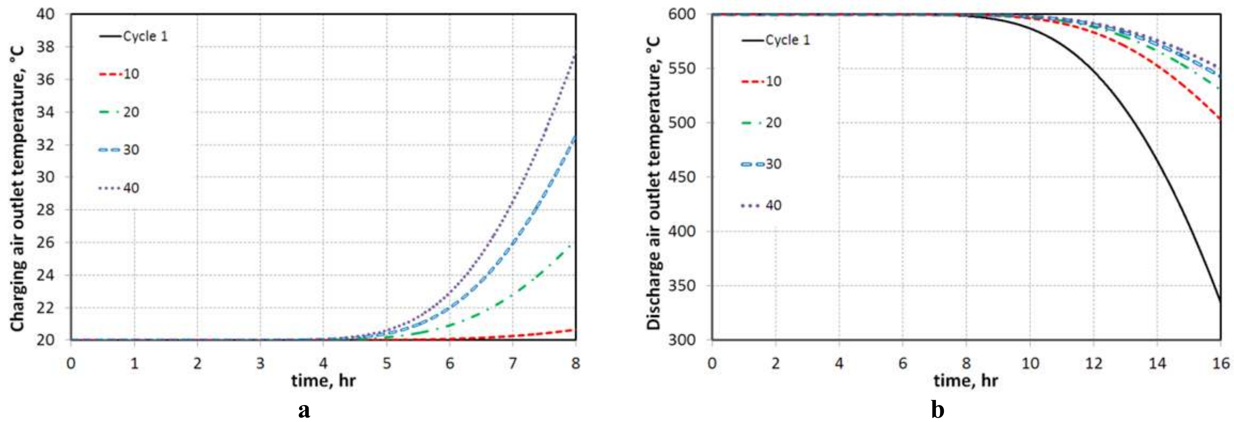


FIGURE 3. Packed bed air outlet temperature profiles during (a) charging and (b) discharging

Input Costs

The input costs used for this work are summarised in Table 2 and are generally based on South African costs. It is assumed that the rock is sourced from the area where the bed is constructed (within a distance of about 1 km) and that no long-distance transportation costs are incurred. The unit cost of the rock and insulation is based on quotations [8, 16]. The stainless steel ducting cost was based on 5 $/kg [17], the blower cost is scaled from a quotation [18] and the control, instrumentation and spares cost is directly from Kolb *et al.* [2]. The containment cost of 2500 R/m^2 floor area was based on the cost of steelwork. The labour cost (based on [19-21]) is assumed to be 30 % of the total cost for Concept 2, and 35 % for Concept 1, since this requires installation of the insulation. Given that relatively unskilled labour is required, a cost at the lower end of the spectrum of 30-60 % of total cost is reasonable.

TABLE 2. Input values for cost estimate

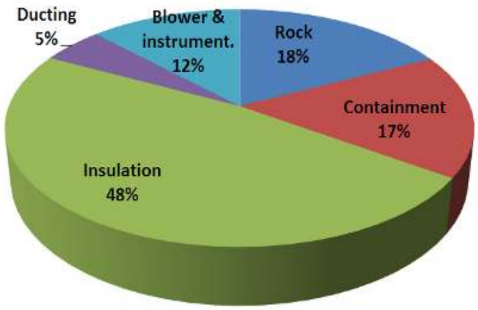
Parameter	***Value***	***Parameter***	**Value**
C_r, *(rock)*	0.25 R/kg	C_s *(instrument., spares)*	15 R/kWh$_{th}$
C_i *(insulation)*	3000 R/m^2	C_w *(containment)*	2500 R/m^2
C_d *(duct)*	60 R/kg	C_l *(labour % of total cost)*	30-35 %

The duct diameter is chosen to keep the air flow speed below 10 m/s. The internal diameter is limited to 3.5 m based on the sizes commercially available (typically < 2.5 m). It is assumed that multiple ducts are used when larger cross-sectional areas are required, which is why the relative duct cost increases from the 10 MW$_{th}$ estimate to the 100 MW$_{th}$ estimate given in Table 3.

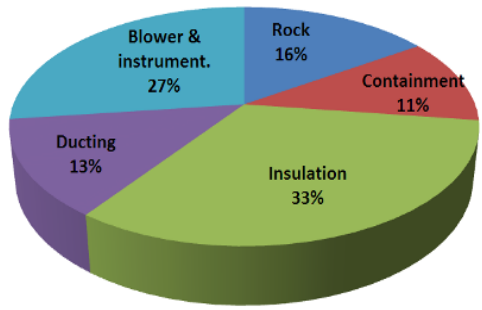
For these initial cost estimates, it is assumed that Concept 2 requires the same mass of rock as Concept 1. Louw's [6] work on Concept 2 shows that less than half of the bed's total theoretical thermal capacity can be used. His computational work was only for one charge-discharge cycle and neglected the thermocline spreading which occurs with repeated charging and discharging; this would further reduce the usable percentage of the bed capacity, which means that the assumption of similar rock mass is reasonable, since Concept 1 typically has a usable capacity of at most 30-40 % of the maximum theoretical capacity.

FINDINGS

Estimated capital costs are summarised in Table 3 for a 10 MW$_{th}$ (160 MWh$_{th}$) and 100 MW$_{th}$ (1600 MWh$_{th}$) rock bed. The total cost at the bottom of the table includes labour. The Concept 1 component costs are illustrated as a percentage of the total (excluding labour) in Figure 4. This shows the potential cost advantage in eliminating the need for thermal insulation with Concept 2.



a) 10 MW_{th}



b) 100 MW_{th}

FIGURE 4. Capital cost estimate comparison showing influence of scaling on component costs for Concept 1

TABLE 3. Component cost estimates for Concept 1 & 2 (Nominal capacity of 16 hrs. 12 ZAR = 1 US$)

Component	**Cost, Concept 1, $/kWh$_{th}$**		**Concept 2 w containment, $/kWh$_{th}$**		**Concept 2 w/o containment, $/kWh$_{th}$**	
	10 MW$_{th}$	**100 MW$_{th}$**	**10 MW$_{th}$**	**100 MW$_{th}$**	**10 MW$_{th}$**	**100 MW$_{th}$**
Containment	1.8	0.6	1.8	0.6	0	0
Insulation	5.2	1.6	0	0	0	0
Rock	1.9	0.8	1.9	0.8	1.9	0.8
Ducting	0.6	0.7	0.6	0.7	0.6	0.7
Blower & instrumentation	1.4	1.4	1.4	1.4	1.4	1.4
Total cost	**16.7**	**7.7**	**8.1**	**4.8**	**5.5**	**4.0**

The cost per unit energy is shown as a function of storage capacity in Figure 5.

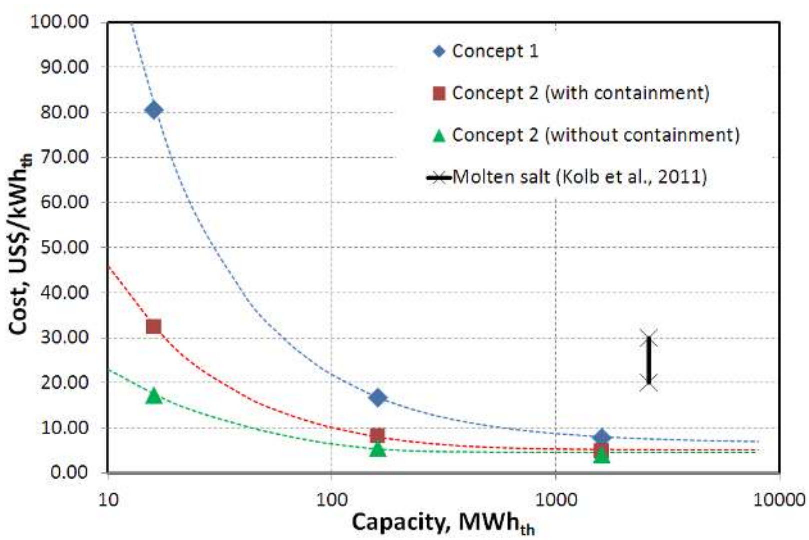


FIGURE 5. Cost summary for Concept 1 & 2

When scaled up to 100 MW_{th}, 1600 MWh_{th}, the cost of Concept 1 falls to 5-10 $\$/kWh_{th}$ because of a lower surface area to volume ratio. This compares favourably to two tank molten salt (22 – 30 $\$/kWh_{th}$ [2]). The potential cost saving for Concept 2 at scales less than 1000 MWh_{th} is 50 % (or more) of the cost of Concept 1.

It is of interest to compare costs with two previous publications on low-cost packed bed storage. Hardy *et al.* [22] give capital cost estimates between 0.03-0.12 $\$/kWh_{th}$ for a 300 MW_{th}, 180 day (1 300 000 MWh_{th}, 150 MW-year) air-rock bed storage facility for temperatures in the region of 500 °C. Adjusted for inflation to 2015, this is 0.1-0.5 $\$/kWh_{th}$ [23]. Apart from the air-distribution ducts, their design concepts make use of rock, clay and sand only for insulation and containment, so this represents the minimum achievable cost for extremely large-scale storage. The 63 MW_{th}, 5000 MWh_{th} conical slag mound concept of Curto and Stern [24], which also made use of only slag/rock, sand and clay for the bed insulation and containment, has an estimated capital cost of 0.5-0.7 $\$/kWh_{th}$, which amounts in 2015 terms to 1.4-2 $\$/kWh_{th}$, about a half to a third of the Concept 2 cost without containment at the same scale.

CONCLUSION

Two rock bed thermal storage concepts intended for high temperature (> 500 °C) storage have been presented with preliminary capital cost estimates. The predicted costs for both concepts are less than 20 $\$/kWh_{th}$ at capacities above 100 MWh_{th}. These costs are competitive with two-tank molten salt storage, and the costs may be as low as 5-8 $\$/kWh_{th}$ for capacities above 1000 MWh_{th}.

Of the two concepts, Concept 1 is perceived to be a lower risk design, since the chance of natural convection is smaller. However, it is more expensive, particularly at small scales (< 100 MWh_{th}) where the containment and insulation surface area is unfavourably large relative to the enclosed volume.

Future work on these concepts entails a detailed civil engineering study on the containment and rock bed construction, which will permit a refined cost estimate. A thermal model for Concept 2 is to be developed and tested with experimental results. It is hoped that funding will be obtained to construct a proof-of-concept facility.

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