To beam or not to beam down

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Abstract

Concentrating solar thermal (CST) technologies can be employed for high-temperature applications such as electricity generation, industrial process heat and solar thermochemistry. There has been on-going interest in tower reflectors or beam-down systems without any commercial systems in operation yet. This paper reviews the geometry of beam-down central receiver tower systems along with the resultant receiver flux distributions to develop an understanding of the opportunities for beam-down systems. It includes a qualitative analysis in terms of the field, tower, secondary reflector and receiver, as well other CST beam-down systems.

Although beam-down systems will have a lower optical efficiency than an equivalent tower system, there is also a trade-off between either power or energy collection and concentration, although there are design options to improve these. The application of beam-down systems may be suited to applications, such as solar thermochemistry, where the cost of the additional plant is warranted by the value of the products.

Keywords: Concentrating, solar, thermal, CST, beam-down tower, secondary, reflector, CPC, flux, power

1. Introduction

Concentrating solar thermal (CST) technologies can be employed for electricity generation, industrial process heat and solar thermochemistry (Blanco and Miller, 2016) and the choice of technology depends on a range of details required to meet the end-use specifications or overall cost envelope. One critical detail is the temperature requirements of the end-use, and point focus technologies provide the higher concentration ratios required for high-temperatures. While one limitation of dish CST technologies is the mass of the receiver in the focal point, the optical efficiency is better than central receiver systems. However central receiver tower systems are being increasing deployed for electricity generation because they are often more cost effective than other CST technologies.

While secondary reflectors can be employed in close proximity to linear receivers to improve the capture of reflected rays, they can also be used to achieve further concentration in point receivers, such as in a solar furnace, but with an overall loss in optical efficiency. There is growing interest in beam-down central receiver systems, where the rays reflected onto a tower mounted secondary reflector are further reflected down to the ground.

The beam-down concept is attributed to Rabl (1976) who proposed a tower reflector as an alternative to the tower boiler concept for a central receiver solar thermal electric conversion plant. He expected this could be accomplished without excessive optical losses and his preliminary estimates appeared favourable. He recommend that a detailed systems analysis be performed comparing the tower reflector with the power tower.

In 1991, Vant-Hull considered the beam-down concept as based on a Cassegrain reflector system. While he felt there may be obvious benefits in simplifying the tower and saving on pumping power and piping, there were also penalties and difficulties. The obvious loss of added reflection is that of the primary heliostat reflector, ~5%, although at higher flux densities on the secondary reflectors, this might more likely be 10%. If this 10% optical energy loss represents thermal energy absorbed by the secondary reflector, active cooling might be required to dissipate this heat. Vant-Hull assumed the secondary reflector area must be smaller than the primary reflector area, except “where cost is secondary to performance”, as for a solar furnace.

Vant-Hull (1991) considered 3 secondary reflectors shapes based on geometrical optics, finding:

- An elliptical (concave) reflector would need to be placed beyond the focal point of the heliostats, requiring a taller tower to reflect a more diffuse cone of rays (image) created by a longer optical path without any advantage
- A hyperboloidal (convex) reflector would need to be placed before of the focal point of the heliostats, requiring a shorter tower. The smaller the secondary reflector, the larger the reflected secondary sunshape image and lower the concentration. A further concentrator could be placed at the receiver, adding to the cost

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- A flat reflector would need to be placed anywhere up to the focal point of the heliostats, so long as the total optical path length does not change. The flat reflector system would have small, 5-10%, reflection losses but require a moderately large mirror.

In reference to beam-down system, he stated that “Although often recommended, when subjected to a comprehensive design and costing analysis, all such concepts have failed to date”.

In 2000, Segal and Epstein considered both concave (ellipsoidal) and convex (hyperboloidal) tower reflectors for electricity generation system. They identified that elliptical reflectors require both higher tower, perhaps twice as high, and also a larger secondary reflector and directed their attention to hyperboloidal reflectors. In 2011, Segal stated that appropriately placed hyperboloidal and ellipsoidal tower reflectors can provide comparable results, although the hyperboloidal surface is definitely more effective. Although a “quadratic surface mirror always magnifies the sun image” and they highlight the importance of its linear magnification, it is noted that the flux density and concentration decrease as the beam area increases by the square of the linear magnification.

There has been on-going interest in beam-down systems for both electricity generation and solar thermochemistry. The purpose of this paper is to review work since 2000 with a view to understanding the opportunities for beam-down systems. This paper will focus on simple ray geometry of beam-down systems as well as receiver flux distributions that affect the resultant black-body temperature limit.

2. Simple ray geometry

In CST technologies, determination of receiver flux distributions requires ray-tracing involving the position of the sun and the properties of any reflectors, including consideration of the conical magnification of the sun upon reflection and the imperfections of the reflector structure and tracking. An example of the initial system design using simple ray geometry is shown in Figure 1 for a hyperboloidal secondary reflector. This geometry considers the rays from the edges and centre of the heliostat that is furthest from the tower (R_{max}). The heliostat is flat, although a curved heliostat can also be considered. The sun position and annual DNI intensity for Alice Springs, Australia, shown in Figure 2 highlights the range of zenith and azimuth angles that need to be considered in the design of CST systems.

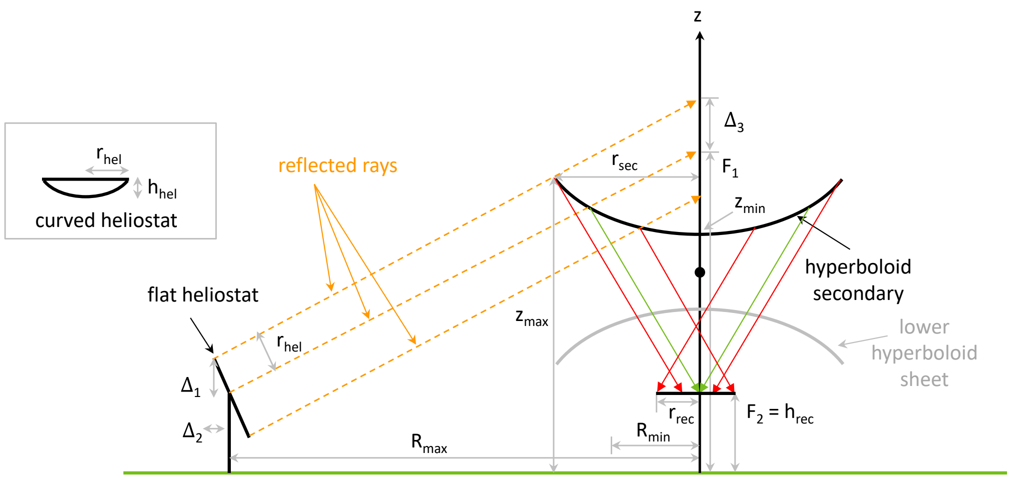

Fig 1: Geometry of beam-down tower system with hyperboloidal secondary reflector

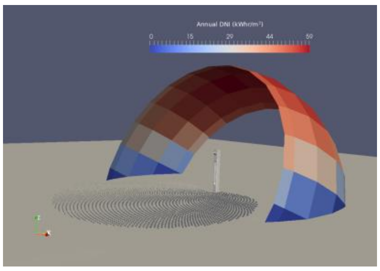

Fig. 2: Sun position diagram for Alice Springs, Australia (Potter et al., 2017)

The effect of eccentricity on the hyperbola size and shape is shown in Figure 3 for an upper focal height (F_1) of 75m for a heliostat radius of (a) 5m and (b) 1m, both at R_{max} = 150m. The vertex of the hyperbola changes with eccentricity but not heliostat radius. The radius of the hyperbola increases with increasing eccentricity and increasing heliostat radius. The linear magnification of the rays with the smaller heliostat will be less since the outer edge of the hyperbola is slightly closer to both the heliostat and the receiver.

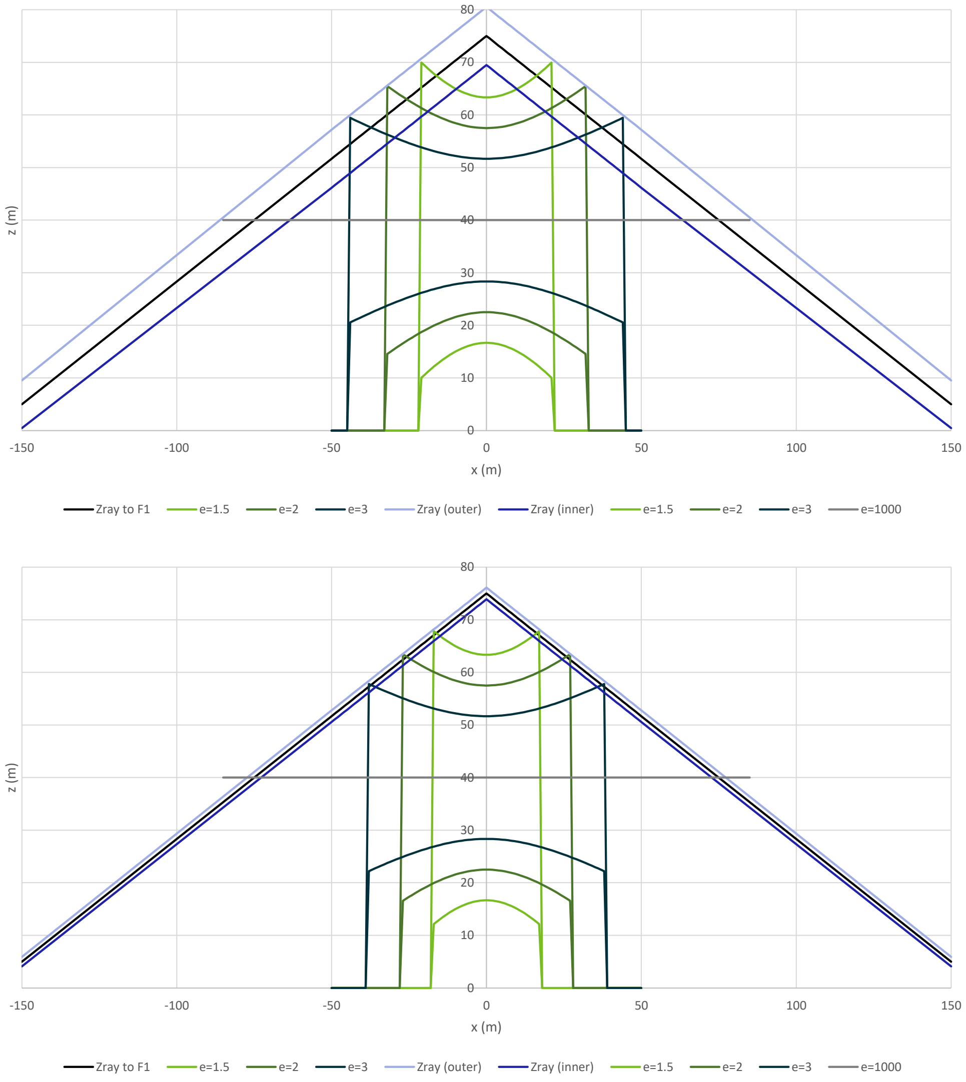

Fig. 3: Effect of eccentricity on hyperbola size and shape for heliostats of (top) 5m and (bottom) 1m (F1=75m, Rmax=150m)

3. Receiver flux distribution

In 2012, Vant-Hull stated there are 3 basic configurations for central tower concentrating solar power (CSP) systems defined essentially by the receiver; these being an external cylinder receiver, with a cavity receiver as principal alternative, and a beam-down concept as the third alternative. In 2014, he stated that “However there are substantial disadvantages which make the beam-down concept impractical except in a few very special situations”, without clearly articulating the special situations. The tabulated results for a Gemasolar type system show the beam-down system has a receiver power of 124 MW_t, which is 91% of the original 137 MW_t. More dramatically, the concentration of the beam-down system without a compound parabolic concentrator (CPC) on the receiver is only 28. Adding a CPC gives a concentration of 390, which is still much lower than the original 736. The concentration of the beam-down system can be further increased by reducing the rim angle, which reduces the field size but the power is also significantly reduced. The effect of decreasing the field radius on decreasing the receiver incident power whilst increasing the concentration, and black-body temperature are shown in Figure 4.

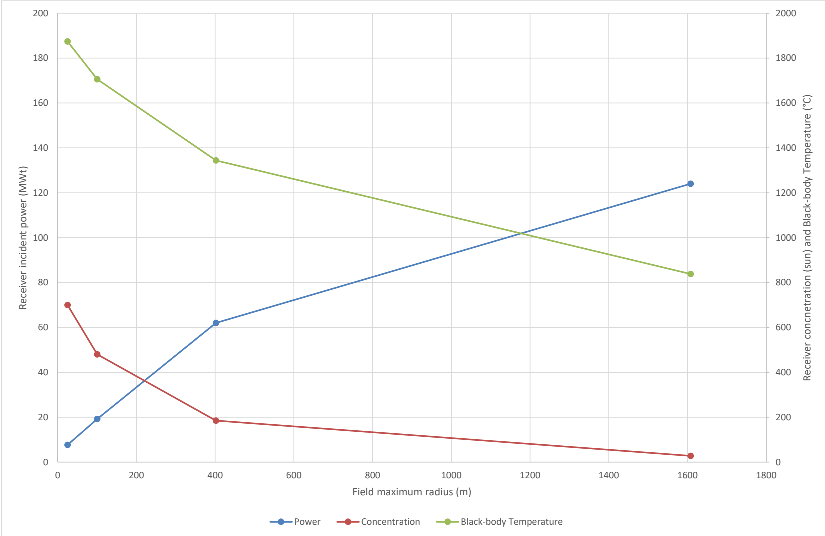

Fig. 4: Effect of field maximum radius on receiver incident power, concentration and black-body temperature (data from Vant Hull, 2014)

Circa 2000, the Weizmann Institute (Israel) built a 700kW experimental system with a secondary hyperboloidal reflector of 75m² and claims to use a CPC, with a magnification of 25, to attain average concentration of ~4000. Segal and Epstein (2003) published a concept for a 50MW ground reformer, involving an asymmetric surround field, hyperboloidal secondary reflector and a packed array of CPCs. The geometric concentration ratio of CPC aperture to heliostat mirror area is 12909. The pattern of rays arriving at the CPC aperture shows a high power density (25 MW or 3400 kW/m²) at the central CPC and low density (~4.8 MW or 653 kW/m²) in each of the outer 6 CPCs (see Figure 5).

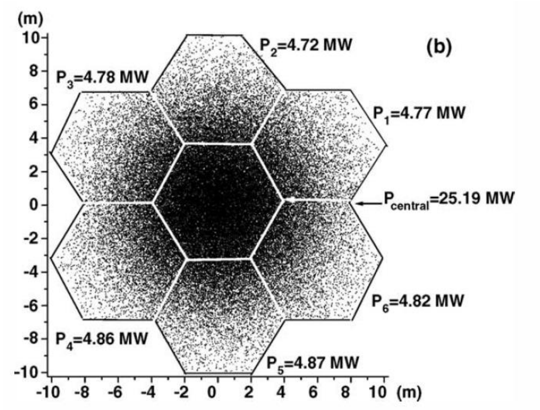

Fig. 5: Pattern of rays arriving at the CPC aperture for a 50MW ground reformer (Segal and Epstein, 2003)

Blackmon (2008) reports some details about a 10MW$_t$ "High Concentration Solar Central Receiver Demonstration Plant" for Zaafarana (Egypt) based on ideas from the Weizmann Institute. The system involves a tower-mounted reflector and CPC on the ground passing to volumetric air receivers, with quartz windows, coupled to a Brayton turbine system. This type of volumetric receiver is capable of operation at high concentrations of 2,000 to 10,000 suns. They determined that smaller heliostats were needed and selected 9.2 m² to achieve the required high concentrations at the receiver. Appendix C (Blackmon 2008) has the power from the solar field as 12.1 MW having 10.0 MW at the secondary reflector and 9.6 MW at the collector (presumably the CPC inlet). The equivalent concentration is 58.7 kW/m² at the secondary reflector and 1,013 kW/m² at the collector. Appendix E (Blackmon 2008) reported flux density at the aperture of the real CPC of 54 kW/m² (0.054 MW$_t$/m²), ranging from peak of 95 to edge of 30 kW/m². Blackmon designed and patented a number of features including the tripod-tower, the secondary reflector frame with heat recovery.

Circa 2007, Masdar Institute built 100 kW pilot plant based on a design from the Tokyo Institute of Technology (Hasuike et al., 2009). The total heliostat field aperture is 280.7 m², using small flat heliostats of 8.5 m² each, a hyperboloidal tower reflector composed of 45 flat mirrors mounted on a 19m tower. The original receiver was a

4.88mx4.88m (16'x16') near-lambertian ceramic tiled surface located 2.3m above ground to allow performance measurement (Mokhtar et al., 2014).

Mokhtar et al. (2014) report experimental analysis of the original Masdar system. They measure the optical performance in terms of flux, then compute the optical efficiency as well as both the receiver intercept factor (spillage) and thermal efficiency based on a model to determine optimum receiver aperture for a desired temperature. For a large receiver aperture of 1.71m (9.186m²), the peak optical efficiency appears ~48%, with the daily average over ~10 hours of sunshine given as 37%. The daily average mean flux density was given as 9.422 kW/m², corresponding to power of 86.55 kW, presumably at 300°C.

For a small receiver aperture of 1.06m (3.53m²), the peak optical efficiency appears circa 42%, with the daily average given as 32%. The daily average mean flux density was given as 20.9 kW/m², corresponding to power of 73.77 kW, presumably at 600°C. The higher temperature, at 2.2 times the concentration, results in a 15% loss of power.

Moktar (2011) calculated both the flux density and accumulative power with radius at the receiver plane. The peak flux density was 110 kW/m², decreasing to about 50 kW/m² at a radius ~0.75 m and decreasing to about 20 kW/m² at a radius ~1 m (Figure 6). The accumulative power is 80 kW at 0.75m and 105 kW at 1 m, reaching 130 kW at 3 m (Figure 7). However the large the receiver aperture, the greater the heat loss, so the useful radius is likely to be 1 m.

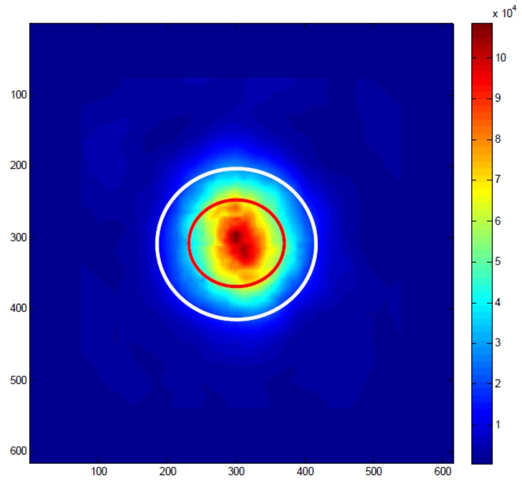

Fig. 6: Typical flux distribution [W/m²] at the receiver plane [distance in cm] (Moktar, 2011)

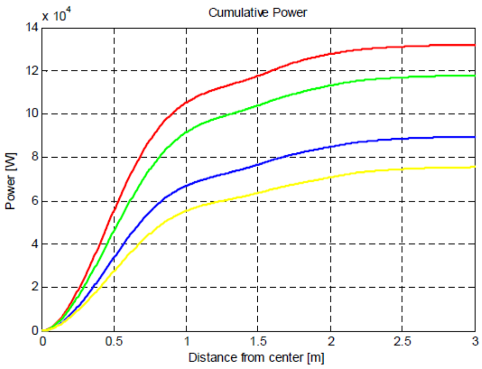

Fig. 7: Accumulative power [W] with radius at receiver plane at different times of the day (Moktar, 2011)

Grange at al. (2015) simulated the system giving an efficiency, from 77 % to 22 % depending on the solar zenith angle, appearing to be circa 68% at 40°. The simulated concentration was stated as ~150 suns at zenith angles of <40°. To improve the concentration, both a CPC and a cone were considered as a third-stage non-imaging concentrator. The power at the inlet to this final optical element was 143.2 kW at midday and 104.1 kW at 10am, being 71 and 52 kW/m² respectively. The 0.385 m² CPC led to a power loss of 5.2% at midday and 6.4% at 10am, but increased the concentration to 353 kW/m² and 253 kW/m² respectively. The 0.636 m² cone led to a power loss of 4.5% at midday and 5.5% at 10am, but increased the concentration to 215 kW/m² and 155 kW/m² respectively. Thus the CPC gave higher concentration, but also increased the power loss.

In 2012 Magaldi built a 100 kW thermal experimental system at Buccino (SA), Italy. CSP Today (2014) described the system concept being multiple 500 kWe modules. A photograph shows a hyperboloid type secondary reflector, being a 4-sided inverter pyramid on 4-legged tower system, with the receiver being directly underneath. The heliostats appear flat, but there are no optical details.

In 2016 Magaldi started operating a 2MW thermal system at S. Filippo Del Mela (ME), Italy. This is designed to produce 20.5 tons of steam daily, using 786 heliostats on a site of 2.25 hectares. The website says each module can store 8.2 MWh of thermal energy. Several modules can be combines to produce superheated steam at circa 500°. It indicates the 270 ton sand receiver-fluidised bed operates at 550-650°C.

Each module has 390 heliostats of 7m² each, or 2,730 m² (on a site of 12,000 m²), giving a thermal input of 1.05 MW, which equates to 0.384 kW_t/m^2.

Circa 2012, the University of Miyazaki (Japan) built a 100 kW experimental system (Kodama et al., 2014). The system has an elliptical secondary reflector, 4.6m diameter, mounted on a 16m tower. The heliostat field is a half circle around the tower. Each of the 88 heliostats units consists of 10 small mirrors with 50 cm diameters, giving a total area of mirrors is 176 m². The sunlight being beamed-up to the elliptical secondary reflector pass through the first focal point at 14 m height and returns to a second focal point plane 10 m above ground level (Figure 8).

Kodama et al. (2014) report using 78 of 88 heliostats, DNI was about 0.9 kW/m², 113 kW_t solar power was concentrated within an area of 1.3m × 1.3m at the second focal spot, being ~59 kW/m². Of this, 70 kW_t was concentrated within area of 0.6m × 0.6m, or 194 kW/m² (Figure 9). However, laboratory results suggest that a flux >1000 kW/m² is required to get 1400°C. Thus a CPC was proposed with a 0.75m inlet and 0.44m outlet, length of 1.525m, to achieve this. Kodama et al. (2016) reported testing this system on a fluidised bed of sand that had been pre-heated to 600°C. They achieved central bed temperatures of 1100°C, albeit with a non-uniform flux distribution (Figure 10a). They subsequently proposed that canting the CPC by an angle of 6-12 ° will provide a more even flux distribution (Figure 10b) and, with smaller particles, higher temperatures can be achieved.

Fig. 8: University of Miyazaki (Japan) tower with elliptical secondary reflector (Kodama et al., 2014)

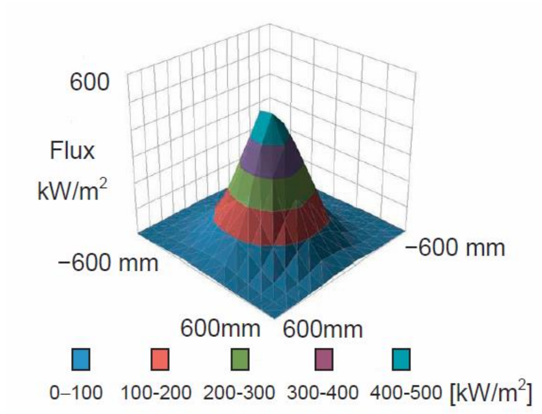

Fig. 9: Flux density from elliptical secondary reflector at CPC inlet (Kodama et al., 2014)

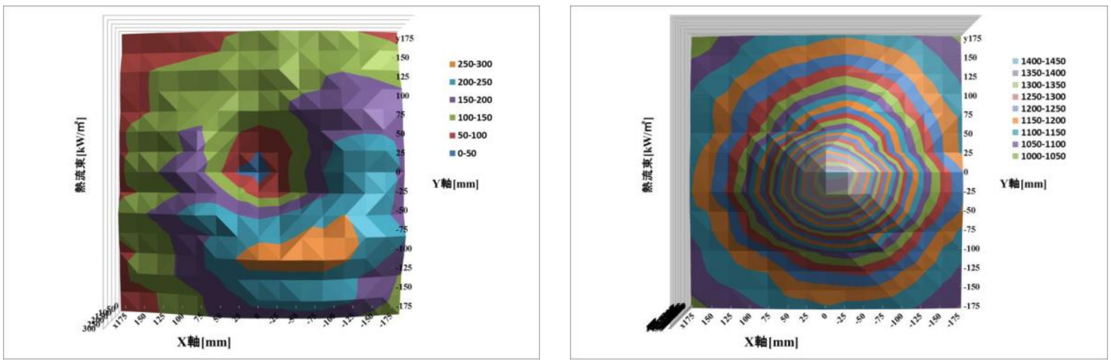

Fig. 10: Flux density 25 cm below CPC outlet (a) uncanted (b) canted (Kodama et al., 2016)

In 2013, Seigel and Ermanoski proposed a thermochemical water splitting system using a flat secondary reflector. This system places the particle-based receiver-reactor close to the flat secondary reflector to minimise image magnification and not need a terminal (CPC) concentrator for high concentration. In considering a 3MW thermal system capable of temperatures of 1500°C, they propose that the annual average collection efficiency can be 43% or more. They note the secondary reflector design will need to consider non-uniform incident flux of 20-140 kW/m². They emphasise the need for accurate, and possibly individually focused mirrors, choosing small heliostats of 1m².

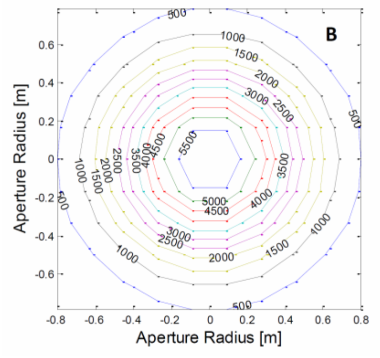

Fig. 11: Flux density from flat secondary reflector at receiver reactor inlet (Seigel and Ermanoski, 2013)

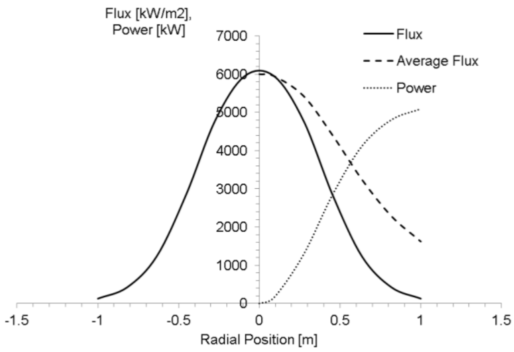

Fig. 12: Flux density, average flux and power with receiver reactor radius (Seigel and Ermanoski, 2013)

Hoffman (2011) also considered a flat secondary reflector and concave converging heliostats for a 1 MW, 1000 suns concentration, showing 2 MW and 4,000 suns concentration is achievable. He considers performance details for 4 days of the year, being solstice and equinox. The peak power output ranges from 1-2 MW, with peak concentrations of 2,000-4,000 and peak optical efficiencies of 39-50%.

In 2012, Leonardi undertook a detailed analysis of a beam-down central receiver system. The system has a symmetrical surround field, flat heliostats of either 5m or 1m radius, hyperboloidal secondary reflectors with eccentricities 1.5, 2.0 or 3.0 as well as considerations of a CPC. Ray-tracing to examine the sunshape at the upper and lower focus, she considers a conic bundle of perfectly rays reflected from the heliostat centre to the aim point (F_1). At low eccentricity, the sunshape is most spherical and the magnification is largest, resulting in the lowest concentration. At high eccentricity, as the secondary reflector becomes more flat, the sunshape is more elliptical and the magnification is unity, resulting in little concentration. Leonardi (2012) found that simplifying the optical analysis to only one conic bundle per heliostat results can lead to drastic approximations; with errors up to 35%.

Leonardi (2016) compares the use of flat and concave heliostat in beam-down systems, considering the secondary reflectors as hyperbolas with significant concavity (eccentricity, e=3), or flat (e=∞). The system has a symmetrical surround field with heliostats of 5m radius. The design point is solar noon at equinox, but also considers the annual efficiency. She finds that concave heliostats are beneficial, even when a hyperbola of small eccentricity (e=3) is considered. Concave heliostats provide a higher concentration, ~ 10 times, over a smaller receiver area, offering the possibility of avoiding a CPC. She deems that it may not be practical to have each heliostat with its own concavity in large solar fields (Figure 13).

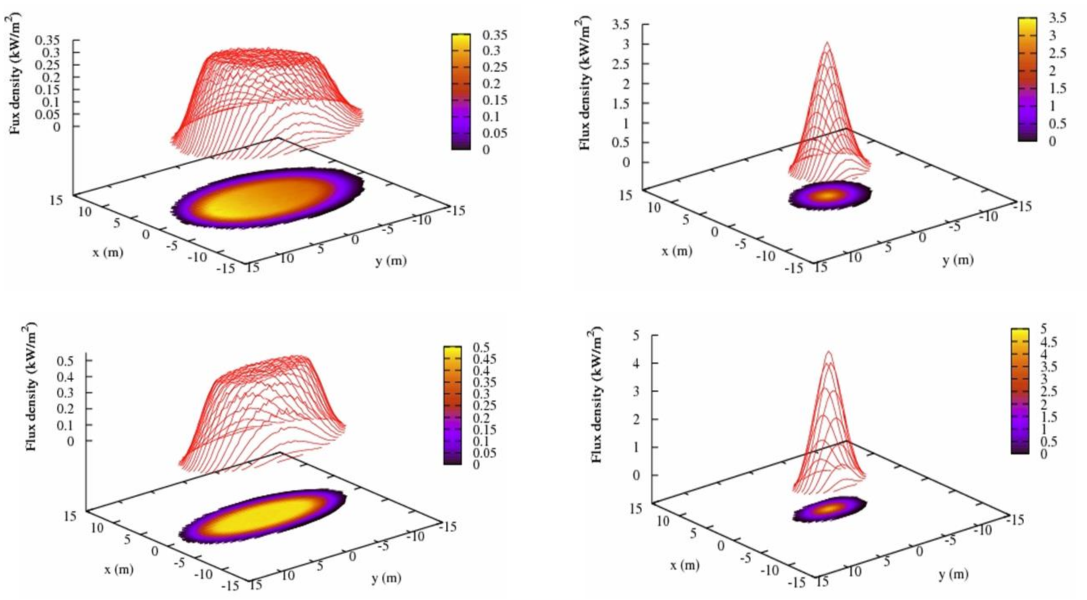

Fig. 13: Receiver flux density for (a) Flat heliostat, hyperbola eccentricity = 3 (b) Concave heliostat, hyperbola eccentricity = 3 (c) Flat heliostat, hyperbola eccentricity = ∞ (b) Concave heliostat, hyperbola eccentricity = ∞ (Leonardi, 2016)

A convex or hyperboloidal secondary receiver provides a higher annual energy collection than a flat secondary, particularly at low receiver radius (Figure 14). The relationship between concentration, black-body temperature and annual energy collection is shown in Figure 15. In this system, at the low receiver radius and high concentration, the field efficiency based on annual energy is 66.37 % in the case of concave heliostats and only 19.30 % in the case of flat heliostats. The field efficiency at the design point is 80.1 % for concave heliostats and 15.8 % for flat heliostats.

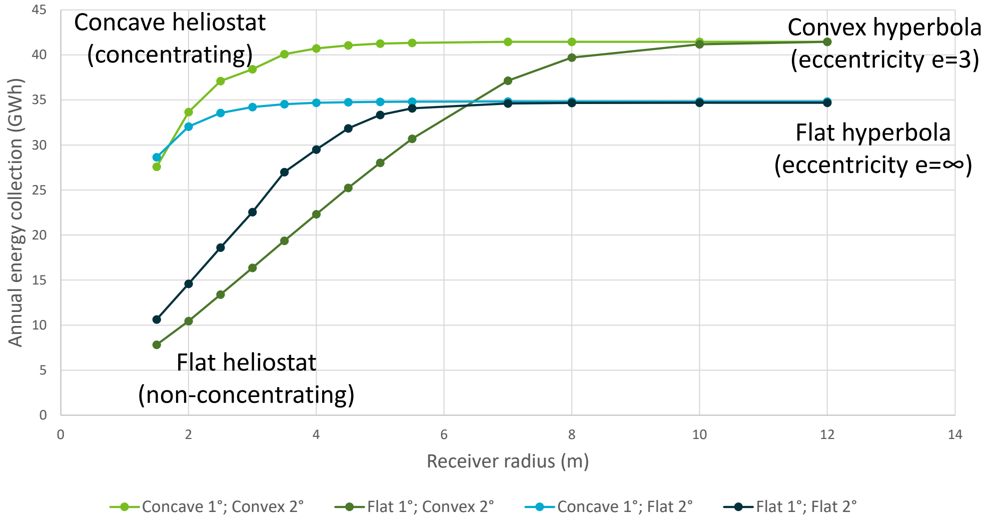

Fig. 14: Effect of receiver radius on annual energy collection (data from Leonardi, 2016)

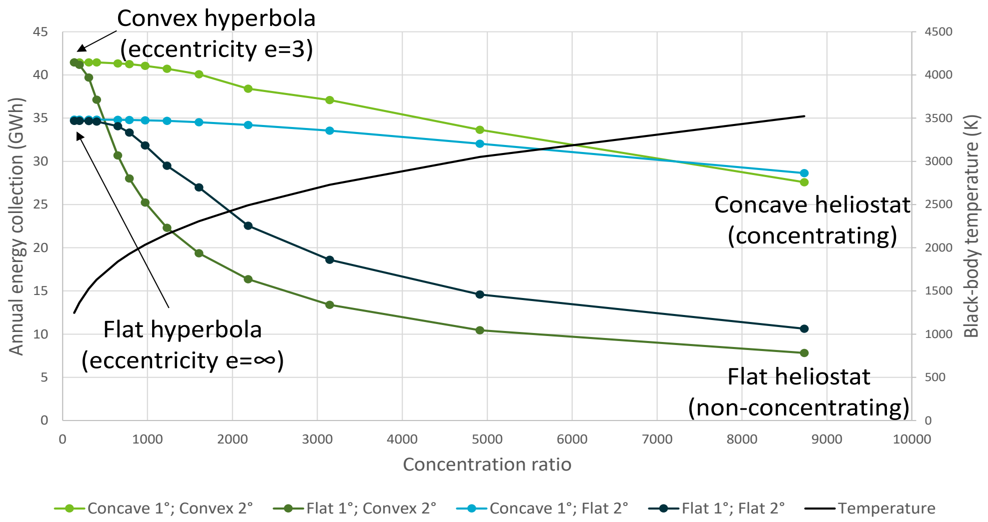

Fig. 15: Relationship between concentration, black-body temperature and annual energy collection (data from Leonardi, 2016)

4. Discussion

CST systems are often simple in concept and complex in detail, with subsystems that integrate to optimise power, energy, concentration and ultimately cost. CST beam-down systems have the added complexity of a secondary reflector. This paper has focused on central receiver tower systems and the following analysis considers the field, tower, secondary reflector and receiver, as well other CST beam-down systems.

Field

The literature reviewed in this paper suggests heliostat size plays an important role the design of CST beam-down systems with small heliostats giving less beam magnification. Reducing the size of the heliostats implies increasing the number of individually controllable heliostats in a heliostat field. While the number of heliostats may be decreased by having different sized heliostats in the field, it is noted the greatest linear magnification occurs from the most distant heliostats.

The style or concavity of heliostats has been explicitly considered by Leonardi (2016). Concave heliostats provide a higher concentration over a smaller receiver area, offering the possibility of avoiding a CPC. She deems that it may not be practical to have each heliostat with its own concavity in large solar fields. . While increasing the number and concavity of heliostats increases the total cost, this may be offset by a system cost benefit.

Heliostat pedestal height has not been considered in this paper but it is noted that it is normally the minimum height to match the heliostat size. It is further noted that the heliostat height might need to be considered in terms of the height of the receiver.

The size of the heliostat field is normally dictated by the power sizing of the system. Where an application involves heating particles to heat a heat transfer fluid, it is possible to design multi-tower systems where a number of small fields are closely packed. This packing may be to (1) keep the size of each system small, (2) have the heat transfer fluid from each system accumulate to produce a large system and/or (3) have heat from one system pass to one or more systems to increase the temperature of the system.

In addition to the outer size of the heliostat field, a zone around the tower will be void of heliostats. While this zone will house the receiver, it may also need to house ancillary equipment such as pumps, heat exchangers and turbine, although these may also be sited underground.

The literature reviewed in this paper considers a range of heliostat field styles, being asymmetric surround, symmetric surround or polar wedge. While asymmetric surround fields are common for large solar thermal electricity plants, it is likely this will remain the case for large single-tower beam-down systems, while the other options remain under consideration for small multi-tower systems.

Tower

The tower height relative to the outer size of the heliostat field gives a rim angle, with a small rim angle having a relatively tall tower to field radius. This may also be considered in terms of the optical *f*-Number, which is the focal length divided by twice the field radius. Thus decreasing the field radius, whist keeping then focal length constant, decreases the rim angle and increases the *f*-Number. As shown by Vant Hull (2014, decreasing the field radius decreases the receiver incident power whilst increasing the concentration (Figure 4).

This paper has not considered the tower design options but notes that the tower may need to be a significant structure to support the secondary reflector to prevent imparting wind loads onto the mirror, thereby increasing aberration errors. Consideration should also be given to preventing soiling of the secondary mirrors as well as potentially needing to capture and/or dissipate heat to cool the secondary reflector.

Tower Reflector

The literature reviewed in this paper covers hyperboloidal, flat and ellipsoidal secondary reflectors. It is most common for researchers to consider the hyperbola. Leonardi (2012) compared different eccentricities and found that at low eccentricity, the sunshape is most spherical and the magnification is largest, resulting in the lowest concentration. At high eccentricity, as the secondary reflector becomes more flat, the sunshape is more elliptical and the magnification is unity, resulting in little concentration. In 2016 she found a convex or hyperboloidal secondary reflector provides higher annual energy collection than a flat secondary, particularly at low receiver radius.

Thus Leonardi and Vant Hull are both clear that there is a trade-off between either power or energy collection and concentration.

Seigel and Ermanoski (2013) considered flat secondary but located the receiver close “up the tower” close to the secondary. While this avoids losses due to magnification, it negates some of the common drivers for beam-don to have the receiver close to the ground. In this case the receiver aperture is the entrance to a reactor and having a CST particle reactor facing upwards has some advantages over a particle reactor facing downwards.

Kodama et al (2014) considered an elliptical secondary reflector but did not achieve the desired flux density. They added a CPC to increase the concentration by ~4-5 and then found they needed to cant the CPC 6-12° to provide more uniform flux distribution. Since they are using a semi-circular field, further consideration is required to determine whether canting the secondary reflector, more concentrating heliostats or a surround field provide alternative solutions.

Receiver

In this paper, the receiver is taken to be the focal or aperture plane. It is noted that CPCs are often considered as part of the receiver to increase the concentration. CPC may also provide a means of minimizing heat losses from the receiver by shielding the cavity from aperture wind and/or reducing convection currents.

It is noted that Leonardi (2012) proposes that concave heliostats offer the possibility of avoiding a CPC. Seigel and Ermanoski (2013) propose to locate the receiver close "up the tower" close to the secondary to avoid needing a CPC. The height of the receiver is an important consideration to avoid introducing additional shading of the solar field.

Other CST beam-down systems

Although this paper focuses on central receiver tower beam-down systems, the general concepts can also be applied to

- linear Fresnel systems, where a longitudinal receiver might be fixed and located near the ground
- parabolic trough systems, where longitudinal receiver might be integrated into or onto a torque bar at the vertex
- parabolic dish systems, where a cavity receiver might be integrated into or onto the structure at the vertex

A brochure in 2009 describes the CNRS solar furnace in Ordellio, France. This furnace has a more horizontal beam-redirection and is intended for research purposes. The heliostat field reflective area is given as 2136 m², with the elliptical secondary reflector area as 1830 m² and the receiver area as 0.29 m². This equates to a heliostat-to-secondary geometric concentration ratio of 1.17 and heliostat-to-receiver geometric concentration ratio of 7321. The thermal output is stated as 600 kW, equating to an average flux of 2026 kW/m². This flux equates to a black-body radiation temperature of 3371 K. Assuming a peak insolation of 1 kW/m², the thermal output relative to the heliostat area is 28.1%.

The peak and annual optical efficiency of a "conventional" CST collectors in large solar thermal electricity plants are

- parabolic dish: peak 94%, annual 87%
- central receiver tower: peak 63%, annual 51%
- parabolic trough: peak 72%, annual 59%
- linear Fresnel: peak 64%, annual 41%.

It is noted that the most significant proportion of the cost for large solar thermal electricity plants is for the CST collectors (Fernandez-García et al., 2016). The beam-down system increases this cost by adding the secondary reflector whilst reducing the overall optical efficiency. The beam-down system also either (1) reduces power and concentration or (2) requires more complex concentrating heliostats and/or more complex receiver by including a CPC. Thus the potential applications for beam-down systems must be able to tolerate thermal energy costs that are higher than equivalent large solar thermal electricity plants. These applications are likely to include solar thermochemistry where the additional cost is warranted by the value of the products.

5. Conclusion

Although beam-down systems will have a lower optical efficiency than an equivalent tower system, there is also a trade-off between either power or energy collection and concentration. The power or energy collection and concentration can be improved by using small, individually controlled heliostats, and keeping the rim angle and heliostat field outer radius small, with options of asymmetric surround, symmetric surround or polar wedge fields being options for small multi-tower systems. Convex or hyperboloidal secondary reflectors provides higher annual energy collection than a flat secondary, particularly at a low receiver radius. CPCs are often considered as part of the receiver to increase the concentration.

The beam down concept may be applied to CST systems other than central receiver tower systems. . The application of beam-down systems may be suited to applications, such as solar thermochemistry, where the cost of the additional plant is warranted by the value of the products.

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7. Nomenclature

Symbol	Description	Units, range and sign convention
F_1	Upper focal height	m
F_2	Lower focal height	m
h_{hel}	Heliostat depth/height	m
h_{rec}	Receiver height	m
r_{hel}	Heliostat radius	m
R_{min}	Inner heliostat field void radius	m
R_{min}	Outer heliostat field limit radius	m
r_{sec}	Secondary reflector radius	m
r_{sec}	Receiver radius	m
z_{min}	Secondary reflector minimum height	m
z_{min}	Secondary reflector maximum height	m
Δ_1	Canted heliostat effective height	m
Δ_2	Canted heliostat effective width	m
Δ_3	Focal height of top of furthest heliostat	m