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Issues with beam-down concepts

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Abstract

Most beam-down central receiver systems replace the usual central tower, receiver, and heat transfer vertical piping and pump with a hyperbolic reflector located below the aim point of the field. This reflects the impinging light toward the ground. It is shown that this also expands the image which would have been produced at the initial aim point by several fold, to the extent that an array of CPC's is required to restore some of the concentration. It is suggested that the costs of the towers to support the secondary reflector assembly, the reflector and its strong-back, and the CPC's may well equal or exceed that of the elements eliminated. The requirement that secondary size and cost be constrained also limits the boundary of the heliostat field to the extent that, for a given aim point height, typically half or less of the optimum power to the tower top receiver can be achieved in the beam-down configuration.

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1. Introduction

So-called 'beam down' systems have been suggested for central receiver systems [1,2]. They propose to replace the elevated receiver and associated tower and heat transport system with an intermediate level reflector (a secondary) to redirect the converging energy to a receiver on or near the ground, thus saving the cost of the tower and much of the heat transport sub-system. The advantages of such a system are so obvious that it is frequently proposed, sometimes carried to a design level, and a few such systems have even been constructed at a small scale. [3,4,5]

However there are substantial disadvantages which make the beam-down concept impractical except in a few very special situations [6,7,8]. Chief of these disadvantages are the large magnification of the spot from each heliostat compared to that which would have been formed at the primary focus (Fp), the large size of the contoured and specularly-reflecting secondary mirror, and the requirement that this large mirror be supported rigidly at a height which is a large fraction of that of the receiver it would replace.

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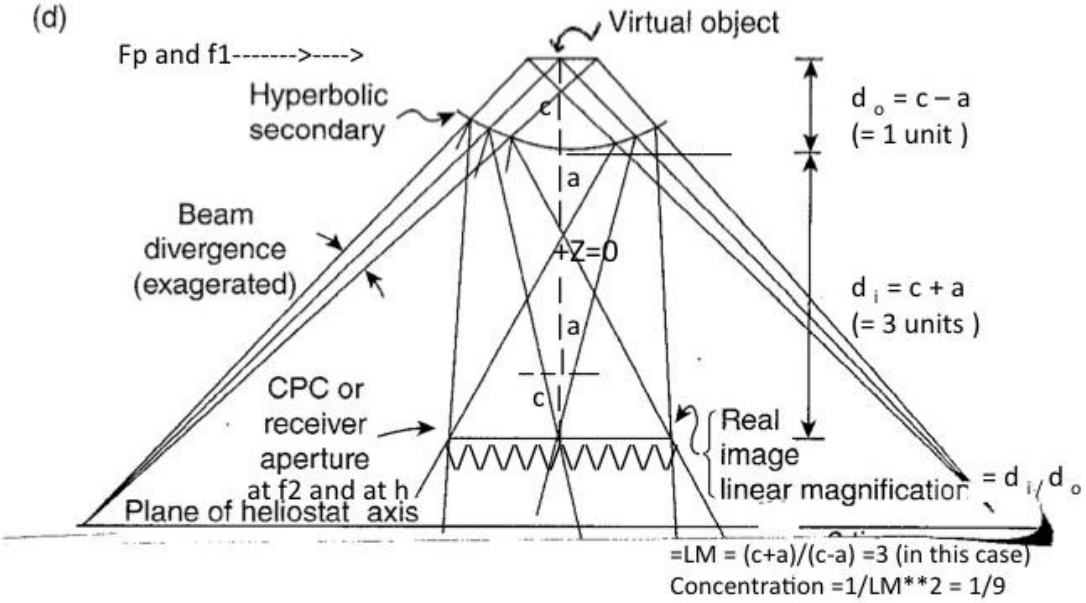

Figure 1. General optics of a hyperbolic beam down system. The virtual object is reflected to near ground and the beam divergence is magnified due to the 'off-axis-aberration' of the hyperbola. The object and image distances, d_o and d_i, are shown in terms of the hyperbolic coefficients. Fp is the focal height of the field while f1 and f2 indicate the focal points of the hyperbola relative to Z=0. (Adapted from ref 8, with permission)

The significant savings that would result from elimination of the tower and the vertical heat transport system are usually given as important reasons for adopting a beam down configuration. However, the substantial cost of the optically figured secondary, of the 'strong-back' to which it is mounted, the several towers to support the secondary at an elevation more than ~ 2/3 that of the original receiver, the array of CPC's required to restore a reasonable level of concentration, and the fact that the power collected by a given focal height system is greatly reduced: are all usually ignored, or treated as inconsequential: they are not. Thus, there must be an overriding need to provide the solar flux directly to near-ground before beam-down is seriously considered.

A secondary in a beam-down configuration is sometimes also proposed for dish concentrators or for linear systems. With slight modifications, the issues noted above also apply in these cases, and the discussion below can be readily modified for dishes or line focus systems.

2. Beam down optics

The optics of a beam-down system are pretty straightforward (Fig 1). A reflecting hyperbolic secondary is placed below the initial focal point of the primary (at Fp), with one of its two foci (F1) at that initial point and the other (F2), at the aperture of a CPC array or the receiver, near ground. This configuration will transfer the sunlight reaching the initial focal spot to that aperture with only a 5-10% added loss due to the time averaged reflection. However, the diameter of a finite spot on the initial focal plane will be magnified by the ratio: (distance from the vertex of the hyperbola to the aperture of the receiver or CPC) to (distance from the vertex to the initial [now virtual] spot at F1 = Fp).

A naïve solution is to place the vertex of the hyperbola near the midpoint (at about half the initial receiver height so the linear magnification is ~1 (LM ~ 1)). However, the required ~ flat secondary must intercept the "cone" of light reflected from the field toward the initial focal point, and so this secondary must have a reflective surface area equal to about one fourth the field area (not the area of the reflectors which can cover ½ to ¼ of the field area). So for the case above, the secondary area is over half the primary reflector area. One can reduce this to 11% of the field area (1/4 to ½ of the primary area) by making the ratio above one third, i.e., supporting the secondary at 2/3 the initial elevation of the receiver and setting h to zero. In this case, LM becomes (2/3)/(1/3) =2.

To make this more general, let us consider the geometry/properties of a hyperbola of revolution about the Z-axis. It is defined by the equation $Z^2/a^2 – R^2/(c^2- a^2) = 1$, and consists of an upper and a lower sheet, with the origin (Z=0) midway between them. Two foci, lying on the Z axis, are defined with the property that all points on the hyperbola remain a constant distance (2a) from the two foci, from which it follows the two vertices (at R=0) lie at Z = +/- a.

The asymptotes of the hyperbola intersect at Z = 0 with the angle $\sin(+/-)\alpha = c/a$. The optical properties of the hyperbola are such that any ray moving between the sheets and directed at one focal point is reflected toward the other.

In the beam down application (Fig 1) the upper focal point (F1) is set at the aim point of the heliostat field (Fp) where Fp is measured from the plane of the heliostat axis (HA). With the lower sheet of the hyperbola deleted, rays directed at Fp (i.e. F1) will be reflected from the surface of the upper sheet of the hyperbola to F2, which is taken as the plane of the receiver or the CPC array aperture. This plane may be elevated a distance h above the HA plane to allow for the CPC, receivers, and power block to be stacked below.

Thus, the height of the original aim point above HA is Fp = F1 =2c+h, of the vertex of the upper sheet = V1 = a+c+h, and the height of F2 = h. Then the linear magnification is:

$$LM = (V1-F2)/(F1-V1) = (a+c+h -h)/(2c+h - (a+c+h)) = (c+a)/(c-a) = (\varepsilon+1)/(\varepsilon-1)$$

where $\varepsilon = c/a > 1$ is defined as the eccentricity of the hyperbola, 2c is the distance between F1 and F2, and 2a is the distance between the vertices of the hyperbolae. In these terms, relative to HA, the height of the first focal point is F1 = Fp, the height of the vertex of the secondary above the plane of the heliostat axis is Hs = Fp –c + a, the receiver or CPC aperture is set to an elevation h, which is also the location of the second focus, F2.

The nominal radius of the secondary by congruent triangles is:

$$Rs = Rf *(c -a)/(2c+h) = Rf *(c -a)/(c+a+c-a+h) = Rf/[LM +1 + h/(c -a)]$$

where Rf is the radius of the field. However the effective value of ‘a’ will be increased by the upward curvature of the hyperbolic surface, which can significantly reduce the value of Rs’ required to intercept the edge rays from the field. A reasonable fit to the results of a graphical analysis gives Rs’/Rs = 1- (cone angle/90deg)**3.5. For a 16 deg rim angle (= 90 – cone angle) the reduction amounts to about 40%.

To restrict the area of the secondary to 1% of the area of the field (if h = 0) requires LM = 9, or $LM^2 = 81$, a disaster in most cases as the concentration is divided by LM^2. Thus, this reduces the high concentration available to a central receiver to that typical of a linear system. In an application where that is all that is required, such a system could make sense. However, one must still support the secondary rigidly at 90% of the height of the original receiver and it will require active cooling to survive the high flux density at that point, which will exceed 100 suns at the center of the secondary. One can add a CPC array to this system, but it will be extremely large and costly and absorb an additional 5+% of the energy.

Of course one must also account for the shading of the heliostat field by the secondary, which is not too serious for LM = 9, but is a major effect if LM < 2 (> 11% of the field area: and the shadow moves as the sun does.)

3. Effect of sun size and beam errors

A common error is to design a system using the central ray from the sun reflected from the center of the heliostat as representative of the sunlight from a heliostat. As Associate Editor of Solar Energy and an occasional reviewer of proposals to DoE etc., I have frequently seen such errors in papers or proposals submitted for review, but such papers seldom survive the review process. For well-aimed heliostats, ignoring the sunshape and beam errors results in a tiny spot at the primary focus, and nearly as tiny a spot at the ‘ground’ and all seems to be well. However, the sun is NOT a distant star, but has a limb angle of 4.65 mrad. Adding solar limb-darkening effects and atmospheric scattering allows our sun to be well represented by a Hermite series of Gaussians, and as the kurtosis is small, reasonably represented by the first term, which is a Gaussian with a standard deviation of ~2.2 mrad [6]. Adding to this in quadrature beam errors due to the reflector surface deviations and the random tracking errors gives a *degraded sun*, which may be reasonably represented by a Gaussian with typical beam errors of 3 to 5 mrad. Thus, the spot at the primary (virtual) focus from a heliostat at a slant range of 100 m from that focus will have a radius at the 2 sigma level (86% interception on a perpendicular surface) of 0.6 m to 1.0 m, while for a larger system (with a slant range up to 1000 m (or greater)) the spot radius will expand to 6-10 m. [6]

This assumes “perfectly focused” heliostats. If flat facets (canted to superimpose the solar beams at the original aim point Fp) are used, the diameter of each beam will roughly be increased by the diameter of the facet. Except at the design point, canted and/or focused facets will experience off-axis aberrations, which will contribute further to the spot radius, up to half the mirror radius at a 60-degree incidence angle [6].

All of these *off-axis rays* (due to the degraded sun or facet focusing effects) will continue on to the ‘ground’ after *off-axis reflection* at the secondary, and experience the associated magnification. Consequently, the final spot from a heliostat at a slant range of 1000 m will have a radius of LM*(6 m to 10 m plus the radius of unfocused facets or the mean effects of aberrations) rather than a few mm for the central rays: a major difference. Thus, while central rays may be used to discuss the general configuration of the system, the degraded sun must be used in all considerations of spot size, interception, flux density, receiver size, etc.

4. Re-concentration via a CPC

A CPC array can replace the aperture of the receiver, and regain much of the “lost” concentration. Each CPC must view the entire secondary within its acceptance half angle, q, or considerable energy will be rejected. The concentration of such a CPC will be limited by the usual $1/\sin^2 q$ where, for smaller rim angles, one must account for the departure d of the hyperbola above its vertex by computing the increase in the effective ‘a’: this is the source of the 0.6 below for a 16 deg rim angle. For designs using smaller cone angles this correction will approach unity. As Fp = 2c+h, the true radius of the secondary can be computed by congruent triangles to be

$$Rs = Rf\,(c - a - \delta)/(2c+h) \sim Rf*0.6*(c-a)/(c+a+c-a+h) = 0.6\,Rf/[LM + 1 + h/(c-a)]$$

Then, for the case we discuss in section 5 below,

$$\tan q = Rs'/(c+a) \sim 0.6*Rf/LM*Fp = 0.6*430/(5*120) = 0.43$$

whence sin q = 0.395 and the linear CPC concentration is 2.53. The linear concentration of the system (CPC * secondary) in this case is then 2.53/5.0 =0.51 and the overall area concentration of the beam-down/CPC is 0.26 ~ ¼, i.e., the concentration at the receiver aperture for the beam-down system is one fourth that at the tower top focus. Typically, the area of the final spot is too large to be accommodated by a single CPC, requiring a close-packed array of 7 or 19 CPC’s, each viewing the entire secondary, and presumably having separate receivers. For larger systems these CPC’s become very large, tall, and costly and will surely require active cooling near their throats.

5. Cost issues

For consistency, all costs reported here are adjusted to 2010 US dollars, using the Chemical Engineering Plant Cost Index as a reference. [CEI = 550.8 in 2010].

A primary justification for studying the beam-down concept is that it obviates the need for a receiver tower and for the vertical heat-transfer piping and pump: and their costs. However, the costs of the secondary, the secondary support structure, the tower(s) to support it rigidly in the face of operating winds and to survive in the case of windstorms, and of the CPC's required to achieve a reasonable recovery of the lost concentration are seldom mentioned.

In addition, the typical heliostat fields associated with a given beam-down system are much constrained, partially due to the limitations of the cavity receiver usually assumed, but also in order to restrict the size of the secondary reflector. Rim angles of 45 to 30 degree are typically quoted compared to the 10-15 degrees typical of a less constrained optimized tower-top system. This results in the need for a much higher principal focal length for the beam-down system, with the result that the elevation of the secondary may well exceed that which would be required for a tower-top receiver to collect equivalent energy, or multiple systems will be required for the same power.

The costs for the tower and vertical heat transfer piping of a central receiver system are relatively well known from the multiple design studies and several plants which have been built. An algorithm [10] developed during the US Utility Study of the 1980s for the tower cost provides \$3.1-3.4 million for a 100 m steel or concrete tower supporting a light load (air or sodium receiver), or heavy load (salt receiver or cavity) respectively. Such a tower could support an external receiver for a system having a focal height of about 120 m comparable to that of the Torresol Energy Gemasolar plant which has a thermal power rating of 120 MW of 465 ^{o}C salt delivered to the ground [9]. The additional cost of the vertical piping and salt pumps required by the heat transfer system (receiver to ground) for such a system (draw salt) is typically about \$3.5 million.

For a beam-down system costs are a bit more difficult to obtain, partially because there have been few design studies that have produced publically available costs, and partially because the cost of the elements will depend strongly on the added variable: the linear magnification, LM, chosen. This choice involves a trade between the elevation of the hyperbolic secondary, its size, the cost of the array of CPC's required to recover a reasonable final concentration, and the reduction in power output as a result of any required reduction in the boundary of the heliostat field imposed to achieve a reasonable design.

Choosing an arbitrary but reasonable LM of 5 for a design with a virtual focal height of 120 m (all above the plane of the heliostat axis at 6.5m) results in a 100 m height for the secondary vertex to produce an image at the ground; or 105 m if the image is taken as 30 m above ground to accommodate the stacked CPC array, the receiver, and the power block below it. Then $2c = 90$ m and $2a = 60$ m. For such a system, restricting the rim angle to 17 deg. provides about 62 MWth incident on the virtual focal plane from a field of about 402 m radius (compared to about 137 MWth for the Gemasolar plant with the same tower height and a larger field optimized for an external tower top receiver) [9]. The secondary would thus be located at $c – a = 15$ m below the virtual focal point, and a flat plate to intercept this field would have a radius of about 48.9 m. Fortunately the hyperbola is curved upward and will intercept the edge rays from this constrained field about 8 m higher than its vertex, allowing a smaller radius secondary of about $Rs' = 25.4$ m to intercept the central rays, or 30 m to intercept most of the reflected light from the far heliostats. Lesser magnification will require a much larger secondary, while choosing a larger rim angle (a smaller field) will generate less power, or require a significantly higher (and larger) secondary to achieve the same power.

The 30 m radius secondary will have an area of about 2800 m^2 and must be supported rigidly and must retain its hyperbolic shape. This will require a sturdy tower at least 100 m high, and perhaps 120 m to allow some support cables or trusses to resist wind effects. Such a tower could cost about the same as the 100 m tower required for the tower top configuration (less weight, but a lot higher wind loads). A more rigid alternative (Fig. 2) would be 3 lighter weight towers in a tripod configuration [9], each of which may cost 1/3 as much as the single tower they replace. A 30 m radius structure will surely require a boundary structure that could take the form of a tubular Ring [11], which could also serve as a support anchor and a framework for the interior truss-work required to provide a rigid base for the mirror itself. The surface can be tessellated with flat triangular mirror facets of 1/3 m^2 area (about 85000 mirrors) [11]. Assuming the mirrors require no cooling, a reasonable installed price of a highly reflective mirror with adjustable supports attached is \$100/m^2, or \$0.28 million for the reflectors. If a smaller secondary is

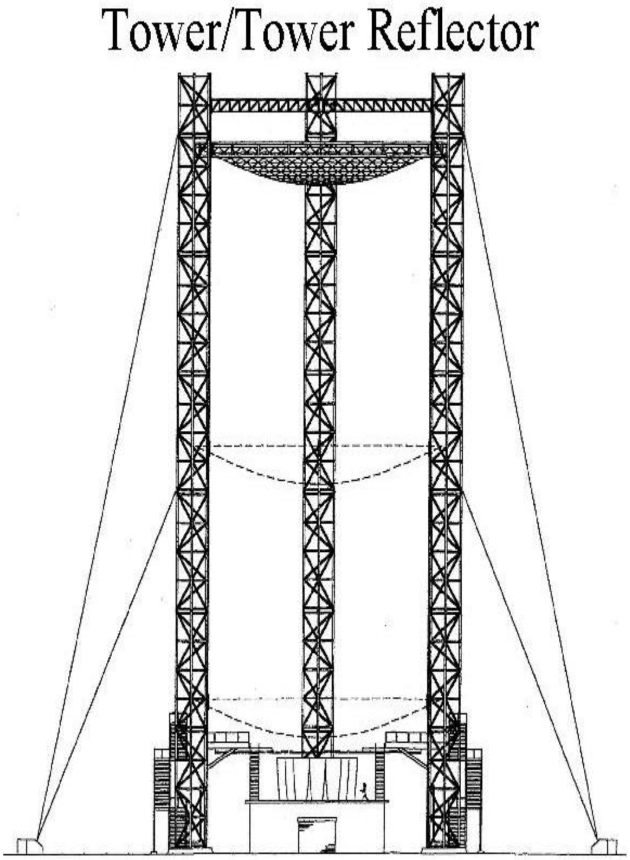

Fig. 2 A 70 m tripod tower supporting a tubular ring stabilizing a geodesic type reflector structure designed for a 10 MWth system powered by a field with an approximate 30-45 deg. rim angle (60 deg cone angle to north, 45 to south) [5]. A larger cone angle would provide more power to the secondary, but it would have to be larger to intercept the light.

selected (with higher magnification) active cooling will be required, which greatly increases the cost per square meter. Perhaps the cost can be recovered by using the heat removed to drive an ORC turbine or otherwise, but this complicates the system and adds a single point failure mode. The mirrors are mounted on a trussed framework, which is estimated to cost \$0.84 million [11].

The magnified image at the inlet to the CPC array will have a radius of about 2*sigma * SR * LM + (? -- a contribution from the secondary imperfections.) For reasonable, well focused heliostats the combination of the limb-darkened sun with several 1 mrad error sources gives a degraded sun with about 3 mrad divergence = sigma. Thus for the 430 m radius field and a LM of 5, and assuming a pseudo-Gaussian shape for the final spot, we require a CPC array aperture of 2*0.003*446*5 = 13.4 m radius (+?) = ~15m to intercept 87% (2sigma) of the light from the edge of the field (and essentially 100% from the central 2/3 of the field). The CPC array can concentrate this spot by a linear factor of ~5 or [1/sin (arctan15/75)] to produce an effective receiver size of 28 m^2, or an average receiver flux density of 2.2 MW/m^2. Assuming an array of 1 CPC surrounded by 6 surrounded by 12 (array radius ~ 5 times CPC radius) we need each CPC aperture to be 15/5 = 3 m radius; and the central 7 will certainly require active cooling, perhaps the outer 12 will not. Again, the cost of the active cooling can possibly be recovered by 'selling' the heat but another single point failure mode must be accepted. Guessing that the central 7 will cost \$200,000 each, and the outer 12 (subjected to lower flux density) will cost \$100,000 each gives a CPC array cost of ~\$2.6 million.

Table 1: Comparisons of reduced beam down fields to Gemasolar; linear magnification = 5, Focal height = 124 m, CPC aperture plane elevated 40 m, 113 m^2 high quality focused heliostats. Data from Sener web site, Google Earth, and estimates by author

	Rim angle degrees	Helios #/ <ground coverage factor>	Receiver incident power MWt	Concentration <SUNS> /1000 w/oCPC wCPC	Rs' Corrected Secondary radius: m	Secondary <flux density> kW/m^2
Sener Tower:CR	8.94	2650/0.157	137	736 NA	NA	NA
Beam Down	8.94	2650/0.157	124	28 390	29.2	46
BD:1/4 field	17.16	1330/0.308	62	185 3,340	25.4	30.6
BD:1/16 field	30.16	411/0.358	19.2	480 14,200	19.6	15.8
BD:1/64 field	43.89	129/0.460	7.70	700? 39,500?	14.1	12.4
Central Exclusion	64.55(59m)	0 / 0	0.0	0		

Adding all these costs gives an estimate of ~ 3.3 + 0.84 + 0.28 +2.6 ~ $7 million to replace the ~$7 million dollar investment in the tower and vertical piping and heat transfer fluid pump for a tower top receiver. Note that while the above beam-down design is consistent, it is completely arbitrary and is subject to a number of design trades (magnification, rim angle, active cooling), which may result in a lower cost. Also, the beam-down output is in the form of concentrated light vs. hot salt. Thus, these results only suggest that to eliminate the "high cost of the tower and salt transport system" carries costs that are also "reasonably high". Also, the requirements of the customer must play a role.

The diameter of the secondary reflector required to intercept the light from the rim of the field can be reduced by reducing the rim angle. This reduces the field area and also the area of the primary reflector, and hence the power to the receiver. A comparison to the Sener plant is shown in table 1. Reducing the rim angle (field boundary) without changing Fp or the LM results in a reasonable possibility for CPC re-concentration, but the power is reduced significantly. At the extreme shown (1/64 the field area), 18 plants would be required to produce the same power as Gemasolar, each with a nearly equivalent tower height and a large secondary. At 1/16, more than 7 plants would be required.

6. Use of 'focal zone' for non-flat receivers

Typically, beam-down studies have assumed a flat aperture, i.e., the aperture of a cavity or of a CPC. This is not necessary. The focal zone of a parabola or of a heliostat field is a three dimensional object, defined by a superposition of the focused but diverging rays from each heliostat. A three dimensional receiver can fill this zone effectively, allowing a much larger acceptance angle than the 45 deg. or so generally assumed for the flat receivers or for cavity apertures. Consequently, many more heliostats can be accommodated for a given tower height. This focal zone will be reflected to the 'ground', perhaps with some REALLY MAJOR modifications due to different reflection geometries for the transverse and sagittal rays reaching the secondary. An appropriately shaped external receiver (cylindrical, square, or multi-apertured) can be deployed in the secondary focal zone. Of course the dimensions will be increased by the linear magnification, but in many cases the flux density at the primary focus considerably exceeds that allowed by the receiver/working fluid. Hence, a linear magnification of 2 or 3 may not be a serious issue. The nearly vertical incidence angle due to the small secondary (in the case discussed above) implies that a vertical cylinder is not an appropriate shape, but a conical or hemispherical shape may work. In the unreasonable limiting case of magnification near 1, the large secondary will effectively illuminate a cylinder near the ground , but the secondary will be VERY large, and much of the field will be shaded. While this will allow the elimination of the cost of the tower and the vertical piping, of course the issues related to supporting the very large secondary, maintaining its optical accuracy, and dealing with its shadow remain; along with the cost.

7. Use of a “Non-Imaging-Secondary” (NIS)

In a recent paper, Y. T. Chen et al. (12) have proposed that a NIS can be placed beyond the primary focus of a parabolic dish to redirect the diverging rays from the concentrator to the target in a well-defined pattern. Their NIS was originally designed to overcome the dark spot produced on a CPV array by the secondary shadow. In practice, the NIS can be designed such that the transverse edge rays from heliostats forming the primary, upon leaving the NIS, do not continue to diverge, but cross over on the way to the final target. They thus form a sort of secondary focus, and so exhibit less divergence for off-axis rays, i.e., less magnification of the image observed at the primary focus. Curve fits to the required surface shape have been developed. The second degree fit is in the form of a closed, off-axis, parabolic surface, located beyond the primary focus, and facing the target. The third order curve does not deviate much from the second order fit in the region of interest. While the detailed performance of such systems is best handled by ray tracing techniques, there is promise that a somewhat smaller degree of magnification of the heliostat spot will be produced by such non-imaging systems located above the aim point.

8. Conclusion

The beam-dow**n** configuration replaces the tower and vertical heat transfer system of a regular central receiver with a Cassegrainian secondary, a large hyperbola; which must be supported well above half the elevation of the tower top receiver, requires a strong-back and support tower(s), and usually an array of CPCs to recover lost magnification. The system design must be costed and a trade study of cost vs. size and magnification by the secondary, and vs. focal height and field rim angle, must be carried out to define a system to be compared to the cost of an optimized tower top system delivering the same power. Finally, the customer must determine if the value of concentrated sunlight delivered to the ground vs. hot salt or steam at the ground is worthwhile.

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