SMALL HELIOSTATS CSP SYSTEMS ON LONG-SPAN HANGING ROOFS

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ABSTRACT
Building Integrated Concentrating Solar Power (BI-CSP) schematic studies with small scale exterior two-axis tracking heliostats anchored on and semi-shading long span hanging roofs with elevated receiver(s) are presented for populated urban and rural locations. Hanging roofs (inverted shallow dome shape) with two-way structural cables and mostly square infill prefabricated slabs/panels supported from a perimeter horizontal circular donut shape rim-girder-platform without a center tension ring studies are for comparing to radial cable structural configurations with a center tension ring. Cable gap grouting between slabs/panels form a pre-tensioned inverted shell structure after temporary weights are removed. Securing vertical heliostat posts studies include: three vertical bolts cast in grout gap two-way cables intersections for three point adjustment of horizontal post base plates; and one-axis adjustable manufactured post brackets bolted to sloped roof surfaces at holes cast in the gaps/slabs. A main case study schematic is around a 30m/100ft diameter hanging roof with a 0.07 sag/diameter ratio with around 271 1m2 heliostats for 230kWt solar thermal steam or air to around 300degC/572degF building integrated thermal energy storage (molten salt, firebricks, etc.) and applications (water purification, cooling, industrial process heat, etc.). A BI-CSP hanging roofs R&D project proposal is outlined: with a circular roof study diameter range of around 25m/82ft-200m/656ft diameter for comparing two-way and radial cable structural configurations for distributed steam stations and a wide range of application temperatures.

KEYWORDS
Building-integrated CSP, long-span hanging roof, small heliostats, solar urban design

1. INTRODUCTION
Why building integrated CSP small two-axis tracking heliostats systems that only work with clear beam solar energy? There are large numbers of people and substantial mid-high temperature (above 250 deg C/482degF) heat demands for many applications (water purification, cooking, cooling and refrigeration, process heat, thermal storage, etc.) in regions with sufficient solar beam resource. Most of the people and mid-high temperature heat applications are in urban area buildings where available land is expensive thus building integrated CSP is of interest. Other CSP collector technologies include: linear Fresnel reflectors; one-axis tracking parabolic

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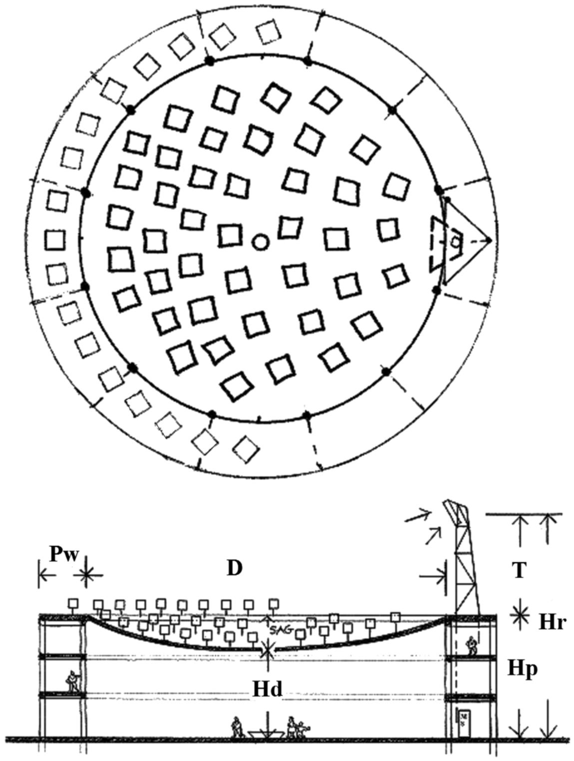
FIGURE 1. Small heliostats on a long span hanging circular roof schematic plan and section drawings.



troughs exterior and interior (e.g. GlassPoint Solar); two-axis tracking parabolic dishes; tracking Scheffers; and solar bowls. Most of these have been demonstrated on flat roof structures. It is beyond the scope of this article to comprehensively compare all the CSP collector technologies for integration with various building types and structural configurations. However, a few characteristics of small heliostats-receiver(s) systems for building integration are presented for consideration. Heliostats-receiver(s) systems have: a higher temperature range than one-axis tracking parabolic troughs and linear Fresnel reflector systems both with long glass evacuated tube receivers; and fixed continuous fluid loops without tracking fluid loop joints for mid-high temperature heat transfer fluids. Small heliostats have flexibility in layout according to where they can be anchored to building structure and have solar access to reflect to a receiver(s), and they can be retargeted. Small heliostats can be arrayed on inverted-dome-shape 'curved' roofs such as long-span hanging shell structures for aesthetic ceiling spaces without interior columns for flexible industrial and commercial planning. The roof mounted linear CSP collectors require flat or one-axis curved roof structures that can withstand the extreme storm wind loads of the collector moments. Building integrated small heliostats can be programmed to aim at multiple receiver locations to meet variable demands at different solar collection times, e.g. charging multiple applications and storages during a today according to variable consumption rates and solar beam resource.

It will be interesting to see how all this plays out with the low cost of PV electric solar panels. The BI-CSP studies in this article are intended to be complementary with BIPV, passive and efficiency design. Concentrator PV (CPV) at heliostats receivers can produce electricity and thermal energy used to cool the CPV. But could BIPV and surplus grid renewable electricity replace the fossil fuels used for mid-high temperature applications heat demands is a question.

Small heliostats systems can fit with many building types and structural configurations and several studies have been documented [1]. BI-CSP with small heliostats systems could deliver mid-high temperature heat in beam regions for industrial, commercial, and multiunit residential buildings; and industrial buildings may be most interesting for development because of the very large heat loads during the whole year. There are a few constructions of building integrated exterior small heliostats for redirecting daylight. Small heliostats systems anchored on long-span circular hanging shell roofs for mid-high temperature receiver(s) applications and storage are the focus for this article.

2. DEVELOPING BI-CSP STUDIES: SMALL HELIOSTATS SYSTEMS ON LONG-SPAN HANGING ROOFS

The small heliostats on hanging roof studies presented are one of the BI-CSP configurations previously outlined [1,2,3]. A thesis for this research is: the substantial and significant Concentrating Solar Power (CSP) research and development and commercialization of large scale concentrating solar collectors and storage systems technologies can be refined and miniaturized for building integration applications. And the CSP technologies and the building structures should be evaluated together as an integrated collector–building structure for reasonable comparative economic analysis for mid-high temperature process heat facilities with storage (molten salt, firebricks, etc.). Small scale heliostats on long-span hanging roofs are solar energy urban design building elements for regions with sufficient solar beam resource, suitable for triple effect cooling and other mid-high temperature process heat applications in populated urban and rural locations where land costs are high or not available for ground mounted collector systems. A building integrated small heliostats-receiver thermal energy storage (molten salt, firebricks, etc.) demonstration may be as significant to architecture and urban design in sunny enough regions as the 2008 Andasol plant in southern Spain was to the development of large remote CSP solar-storage plants.

The linear-zone between beam and diffuse solar collector type regions for cost-effective collector-storage systems may shift more into diffuse regions with more efficient higher temperature storage (molten salt, firebricks, etc.) and beam concentrating collectors compared to lower temperature storage (water, etc.) with reflector augmented single-end evacuated tube collectors, e.g. the BIETR [4,5]. The determination of a reference linear-zone, for example in the US between the beam collector regions of the SW and the diffuse collector regions of the NE is a research issue. An annual shorter molten salt storage 300deg C/592degF charging time with beam heliostats may be more cost-effective than a longer water-steam storage charging time with 150degC/302degF augmented single-end evacuated tube collectors. A reference is: "five times as much energy can be stored in a given volume at 340 deg. C as at 100 deg. C" [6]. Heliostats-receiver systems (steam and air) can deliver a wide range of temperatures perhaps most easily for the higher application and thermal storage (molten salt, firebricks, etc.) temperatures (above 250 deg.C/482deg.F).

Long-span hanging roofs may have economic advantage without interior columns and flexible floor plan space for several building types, for example, industrial process heat (IPH) applications (water purification, food preparation, refrigeration, textiles, steam-curing, kilns, etc.). Building integrated CSP small heliostats systems are another type of distributed steam station for populated urban inner city and rural applications to reduce demand for natural gas and fuel oil. Heliostats-receiver systems have direct insulated fluid loops suitable for the higher temperatures and molten salt storage without insulated heat transfer fluid passing through complicated articulating joints of one and two-axis tracking systems with flex hoses and swivels. The rooftop small two-axis tracking heliostat robots would collect and reflect concentrated solar thermal energy to an elevated fixed receiver-exchanger and a robot pump would deliver the energy down to storage/applications. Small heliostats manufactured in advanced robot factories may eventually reduce heliostat cost if there is a sufficient market.

Hanging roof structure substrates resemble somewhat hillsides and hollows. There is a correspondence between the upward solar-facing concaveness of hanging inverted dome roof structures with shapes similar to sloped terrains [7]. However the optical layout of small heliostats-receiver(s) systems on inverted dome shapes and roof structural analysis to determine stresses from extreme wind loads are complicated research issues. Small heliostats systems on hanging roofs may be complemented with small heliostats on: adjacent flat roofs, pergolas, Vierendeel structures, and beams [1]. Long-span hanging roof new construction studies with two-way cables for roof mounted small heliostats are presented in this article for comparison to radial cable roof structures. Small heliostats-receiver(s) systems on existing rooftops, e.g., on Madison Square Garden NYC (404ft/123m diameter) and on the Oakland Arena (420ft/128m diameter) are included for consideration in the R&D proposed project outline.

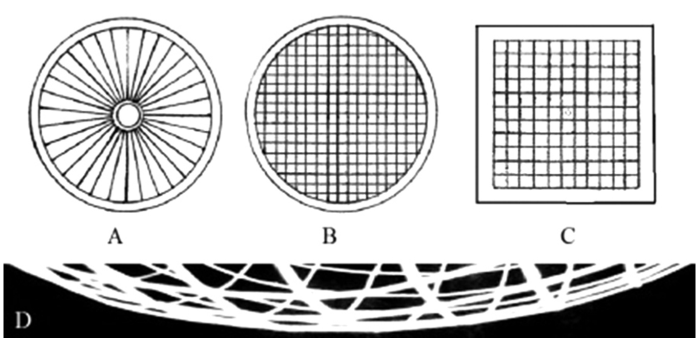
The main hanging roof structural configuration in this study is composed of: a circular horizontal rim-girder donut-shape platform supporting two-way hanging cables that are filled in with precast concrete slabs or prefabricated panels. Added temporary weight pre-tensions the cables, and cement grouting the cable gaps forms a hanging shallow dish-shape shell roof. The construction begins as a cable-net and becomes a rigid 'curved' shell with capacity for tension, compression and moment loads. This was the method for construction with radial cables and a center tension ring for the Montevideo Stadium c1958 [17]. Frei Otto indicated that he worked on a similar type of construction process in 1951 [22] Vol. 2, p30). After reviewing in the US the Raleigh Arena 1950 design by Nowicki at Severud's engineering office Otto returned to Germany and worked on cable nets covered with roofing of thin concrete layers, e.g. 15cm/6inch thick aerated concrete slabs for a 1951 Berlin concert hall project [34,35,36]. A shell with two-way cables and small sag hanging from a horizontal circular rim-girder-platform is the main structural configuration in this article, and this configuration has not been found in any literature thus far, and so perhaps it is novel. The idea of a long-span hanging shell roof with two-way cables to avoid a center tension ring requires structural engineering feasibility studies. Large diameter two-way cables circular hanging shell roofs may be constructed with an overhead crane and without an overhead crane. A main case study proposed is: small heliostats on a hanging roof with steam or air [37] receiver fluid loop systems and building integrated storage (molten salt, firebricks, etc.) for co-generation mid-high temperature applications.

3. BACKGROUND

Prof. G. Francia c1965 developed and tested small exterior two-axis tracking heliostat systems in operating solar plants at Genoa, Italy [8]; and Francia designed the 1970s Georgia Tech 400kWth solar thermal test facility [9]. Variable sloped arrays of polar-axis rotation heliostats and heliostats packing density were reported in 1992 [10]. Multi-tower receivers for rooftop heliostats studies were reported in 2003 [11]. Small scale heliostats on hanging roof schematic studies were presented in 2007 [2]. Hillside heliostats systems were studied for Cyprus by MIT [7]. Arrays of vertical small heliostats semi-shading building facades in populated urban areas for high temperature applications have been studied [12]. The "Sun and Shade" c2015–17 ongoing project has roof arrays of small two axis tracking heliostats each in a small transparent dome with daylighting on a cable roof structure [13]. A building integrated distributed demonstration includes CSP Fresnel reflector collectors and molten salt storage [14]; and molten salt storage for residential heating with tracking parabolic troughs was investigated [15]. Thermally charged firebrick storage with steam is considered feasible by Forsberg [16].

Long span hanging circular roofs constructed with radial cables and a center tension ring structure include: Montevideo Stadium c1958 (demolished in 2014)[17]; Madison Square Garden NYC [18]; The Garden State Art Center, New Jersey (now the PNC Bank Arts center) [19]; and the Oakland Arena [21,19]. Long span circular hanging roof structures with a two-way cable structural system would avoid a center tension ring which can be a substantial structural cost element. The 50 ton center tension ring for the 310ft diameter Montevideo stadium c1958 had a 5.48m/18ft diameter that was fabricated in the US and shipped in one piece to Uruguay [17].The tension ring for the 404ft/123m diameter Madison Square Garden roof, NYC, was a massive high-strength steel 9.75m/32ft outside diameter four quadrant assemble [18]. A two-way cables system hung from a horizontal compression circular ring-beam without a center tension ring is a structural feasibility engineering design research issue [22,23].The c1958 Montevideo Stadium had trapezoidal shape 2 inch/50.8mm thick concrete slab infill panels 3ft-3inches/1m long with variable widths that were manually placed on radial cables. Square infill slabs/panels for a two-way cables configuration may be larger. The Montevideo radial cables were seven-wire galvanized strands, 15.24mm/0.6 inch diameter, swedged Roebling threaded anchorages at both ends. Cables were uncovered for 2.74m/9ft adjacent to the rim beam to allow for thermal movements, and glazed above for daylighting [17]. The 15m/50ft diameter Litchfield roof project had radial cables with a center tension ring and small sag [24,25]. Inverted spherical dome hanging roofs up to 120 degrees rim angles with large sags were considered feasible up to 150ft/45m horizontal diameters for imaging spherical segment solar bowls [26]. Liudkovsky presented a 200m/656ft diameter hanging roof design with radial cables in 1962 [27]. The Arizona Coliseum saddle-shape two-way cables roof has a circular plan (112m/368ft diameter) with square (2.92m/9.58ft) precast concrete infill panels and a non-horizontal rim beam that

FIGURE 2. Hanging roof structural cable configurations: A) radial circular rim; B) two-way circular rim; C) two-way square rim; D) two-way hanging cables model photo.



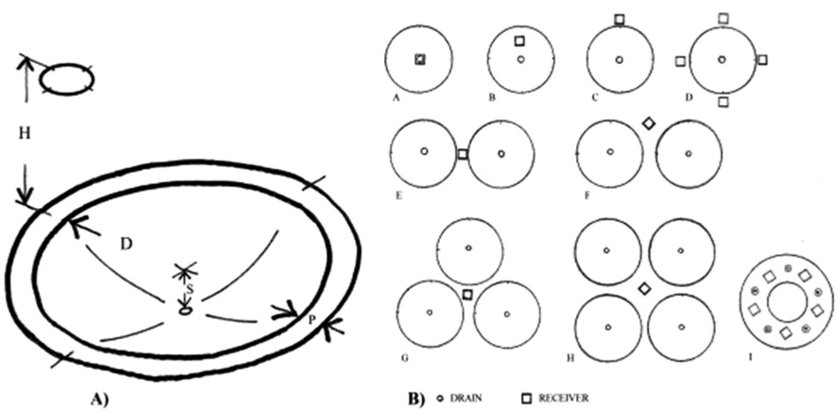
forms a hyperbolic paraboloid, and all the precast panels were held in place with full scaffolding [28]. Development of cable suspended roofs have been reported [22,29].

4. LONG-SPAN CIRCULAR HANGING ROOFS WITH TWO-WAY CABLES SUPPORTING SMALL HELIOSTATS

A long-span hanging circular roof with small heliostats research study diameter range is around 15m/50ft to 200m/656ft diameter for comparing two-way and radial cable configurations with: sag options, and construction without and with an overhead crane. The main circular two-way hanging roof structural elements are: circular compression horizontal rim-girder-platform; two way cables hanging from the compression ring-beam; and infill roof prefabricated slabs/panels mostly square with shape variations adjacent to the rim. A reinforced concrete slab donut-shape horizontal compression rim-girder-platform may be supported by reinforced concrete columns and/or walls, masonry arches, or a combination of reinforced concrete and masonry. An architectural dimensional framework reference includes: sag/diameter (S/D) ratio of hanging roof; floor to ceiling height (Hd) under drain; and circular rim platform (Pw) above ground floor level (Hp) (Figure 1).The receiver tower may be supported on a donut-shape platform structure that the circular roof is hung from, or it may be ground supported under an opening in the donut-shape rim-girder-platform, or independently structured outside the rim-girder-platform (Figure 3). The height of the lowest roof area drain (around 6m/20ft) should not be too low to have a comfortable feeling when under the roof at the lower areas, and related to the diameter and sag would have an influence to the rim-girder-platform height and the levels of construction to support the platform. A circular horizontal rim-girder-platform structure would be a significant amount of construction that may have two levels or more above ground level related to site-specific existing buildings and trees and urban design and architectural planning. A multi-story circular platform wide enough for heliostats may have stairs within or outside of the platform plan. Circular hanging roofs multiple plan patterns are diagramed in Figure 3B.

Suggested approximations for beginning layout studies of heliostats and receiver(s) for selected locations include: hanging roof around 30m/98ft diameter; a sag/diameter ratio of around 0.070 (S/D); a catenary hanging contour; and the elevated receiver on a tower on

FIGURE 3. Hanging circular roof diagrams: A) rim-girder-platform and receiver diagram; B) receiver and drain location plan options—receivers (squares) and rain drains (circles).

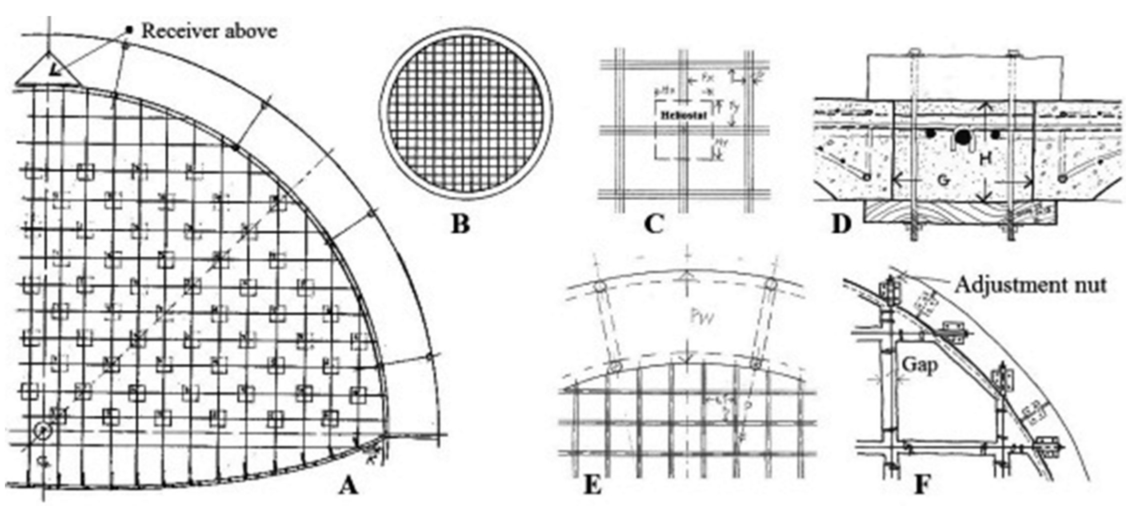


the platform, or outside of and adjacent to the platform (Hp) (Figure 1). Vertical heliostat same length posts can be compared to variable height vertical posts. A reference may be with heliostats layouts on equivalent area flat roof structures. All dimensional parameters would be refined with structural engineering participation. A case study aim is for an equivalent system to compare with the 230kWt thermal 300C degrees STS-MED EU demonstration project at Palermo, Italy [14].

If short segments of structural cables adjacent to the rim-girder compression ring, are uncovered to permit thermal movements of the hanging roof, these movements are a consideration for the optical accuracy of the two-axis tracking small heliostats and receiver target (Figure 6). There may be small roof movements to account for small optical-thermal efficiency solar collection losses; therefor small heliostats each around 1m2 reflector area and a larger receiver inlet aperture (with a secondary reflector possibility) may be favored. Additional hanging roof thermal movement factors include: partial roof shading by the heliostats, and the reflective quality over time of the roof surface coating.

There are dimensional relationships between: typical heliostat size, typical square infill prefabricated slab/panel size, and gap width (Figures 4 and 5). Each heliostat on a post anchored perpendicular to a shallow dish-shape hanging roof surface would be dependent on the capacity of the heliostat gear box and control programs. And for this study the heliostat posts are all vertical with bolted base plates at some of the intersections of the two-way roof structure cables. Larger precast square infill slabs/panels could have larger area heliostats, and the size of typical precast slabs/panels is influenced by the construction handling capacity, for example if without a crane. Several different custom prefabricated peripheral 'square' infill slabs/panels formed to conform to a standard size daylighting glazing-frame over structurally uncovered segments of the structural two-way cables are shaped to avoid dirt catching and nesting ledges (Figure 6). Structural engineering questions are: feasibility of variable length intersecting two-way structurally uncovered cables, and cable lengths. The structurally uncovered cables near the rim-girder are inside reflective thin metal triangular tubes that: reduce solar radiation on the steel cables, deters perching, and adds an aesthetic quality.

FIGURE 4. Small 2-axis tracking heliostats on a circular two-way cables hanging roof: A) diagrammatic quadrant plan; B) schematic circular plan; C-F) construction detail studies.



4.1 Circular Hanging Roof Sag

A horizontal (with no sag) two-way cables mesh would be perfectly square, and as the sag increases there would be more variations in the cable gaps between square infill slabs/panels. The hanging roof sag-contour is: a variable for the small heliostats layout-spacing and receiver location(s); structural loading factor for the rim-girder-platform; and a ceiling aesthetic consideration. Assuming a heliostats layout on a hanging roof with one elevated receiver will be most efficient with a shallow dish roof a sag/diameter (S/D) ratio, for beginning studies a ratio may be about 0.07, for example a 100ft/30m diameter hanging roof with a 0.07 ratio has about 7ft/2.13m sag. The reasoning for this assumption is the larger sags ratios referenced were for structures supporting mechanical rooms, for example a ratio of 0.095 for Madison Square Garden, and smaller sag of 0.065 for the open-air PNC Bank Arts Center. A smaller sag ratio (S/D) with two-way cables closer to a horizontal plane will have less gap dimensional variations with mostly standard square infill slabs/panels. A structural engineering consideration is a circular hanging roof shell may require ribs at the compression rim–beam. The hanging roof shape may be formed to a selected contour by placements of added weights at selected locations before mortar-grouting the gaps.

References for the sag/diameter ratio of radial cable hanging roof constructed structures include:

- 27.4'/308.3' = 0.088 for Montevideo stadium c1958 demolished in 2014 [17].
- 40.4'/425' = 0.095 for Madison Square Garden NYC [18].
- 13'/200' = 0.065 for The Garden State Art Center, NJ (now the PNC Bank Arts Center) [19].
- 33'/420' = 0.078 for Oakland Arena [21,19] (Hallenbeck jr and Johnston 1967).

4.2 Hanging Roof Cable Patterns

The radial cables with center tension ring configuration has all the same length cables and same loading on all the cables. One quarter of the two-way cables configuration has different loadings on different length cables and there would be four identical cables for each cable length. Both radial and two-way cable/rod configurations are pre-tensioned inverted shells after the gaps are grouted and temporary weights are removed. An inverted shell hanging roof with two-way cables would not have the added weight of a radial cables tension ring. Only 51mm/2 inches thick concrete slabs manually placed were on the radial cables 94m/308.3ft diameter Montevideo stadium [17], and a two-way system may have larger infill mostly square prefabricated slabs/panels. Hanging long span circular rim roofs have been constructed with radial cables, and an emphasis of this article is with two-way cables avoiding a center tension ring. Mostly square roof infill slabs/panels for a two-way cables configuration can be larger than for slabs/panels for radial cable systems related to the spacing of the parallel two-way cables and heliostats layout spacing and anchorage to the hanging roof slopes. The center lowest square panel with drain opening of a two-way system generally would not be large enough for a tower crane. Two-way parallel cable/rod spacing is related to the infill roof slab/panel size and weight.

An aesthetic consideration is: the precast panels for a radial cable pattern are likely to be different size wedge-shaped flat panels with flush gap grouting forming a continuous surface ceiling; and for the two-way cables pattern the mostly square infill slabs/panels (except for some edge-rim panels) can have an inverted dish form in each square panel with a small lighting opening in the center of the panel (Figure 5). Large flat infill slabs/panels may have a polygon ceiling expression according to the hanging roof curvature. Another hanging roof 'radial' cables idea with a center tension ring may be with precast diamond-shaped infill panels and conforming cable patterns similar to the dome (but inverted) of the 1955 small sports palace in Rome by P.L. Nervi.

A shallower hanging roof dish catenary shape with shorter sag would have less angular differences between adjacent flat precast infill slabs, and more direct pull closer to the plane of the rim-girder-platform donut-shape compression ring. This may ease the construction tolerances for the sequence of infill slab loads to maintain safe eccentric loads on the rim-girder-platform. A study has pipe-sleeves for the cables/rods cast into the rim-platform with adjustability of the cable/rod lengths for positioning to designed drapes (Figure 4). The sag ratio is also a factor for the aesthetic quality of the interior space that the dish-shape hanging roof forms, and the floor to ceiling height at the low rain drain region should not feel too low.

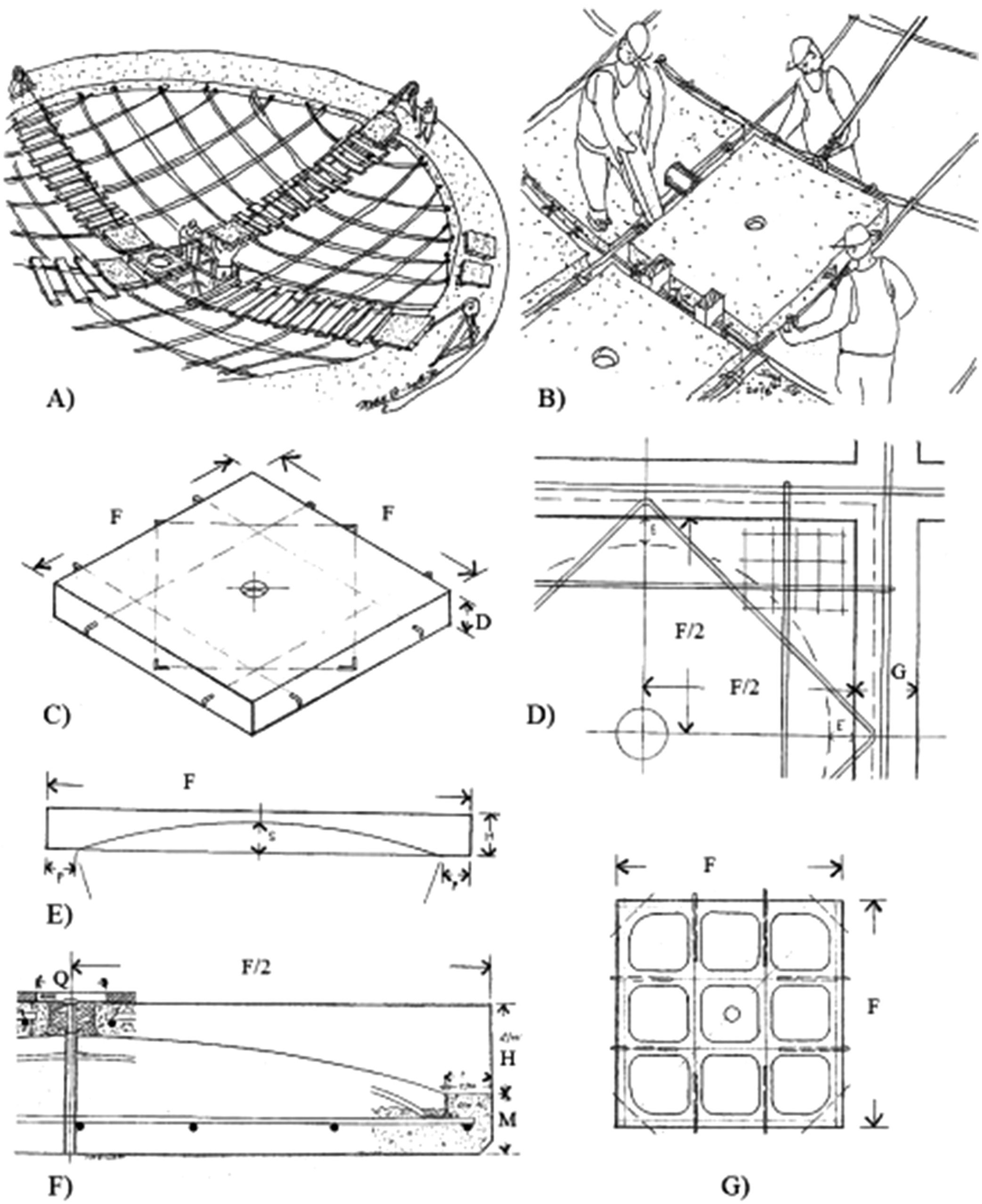
When a short part of the hanging cables adjacent to the rim-girder are uncovered for thermal movements, radial cables have all the same length and positional drape, for example, the Montevideo Stadium design. A hanging roof with two-way cables at a circular rim-girder would have different lengths of uncovered cables and different positional drapes with 90 degree two-way cable intersections (Figure 5 and 6). A square plan rim-girder may have a better integration with a two-way hanging roof cables configuration, however a building structure 'square' rim beam would be more complicated and expensive compared to a horizontal circular rim beam (Figure 2C). Reflector material (bent thin metal reflector, etc.) on uncovered cables under daylight glazing would reduce heating of the cables and have an aesthetic quality, and an acute top edge ridge could detract critter perching.

4.3 Prefabricated Infill Slabs/Panels For Two-Way Cables Hanging Roof Structures

Mostly square prefabricated infill panels would be positioned on the two-way hanging cables/rods. Temporary weights on the infill slabs/panels would pretension the cables before grouting the gaps. After the gap grouting is set the temporary weights would be removed. The weight of the mostly square infill slabs/panels is a limiting factor for construction without an overhead crane with manually positioned slabs/panels. And a two-way hanging cables configuration may be limited to construction methods without an overhead crane as the center low drainage panel opening may be too small to fit a tower crane. Spacing of two-way parallel hanging cables/rods may be determined by the handling capacity for a square precast concrete standard infill slab size, and around 225Kg/500 pounds per concrete slab may be a limit, or less, dependent on site specific construction capabilities. For example, if a concrete precast square slab/panel side is 1m/3ft-3" x 78mm/3inches average thickness, at 68kg/0.028m3 (150 pounds per ft3) for reinforced concrete, the slab/panel would weigh about 180kg/396 pounds.

A form-mould idea for precast concrete roof slab/panels has two layers of concrete separately applied. The first lower part concreting establishes the perimeter area for a rotating mason's guide. The second concreting forms the shallow dome form for the inverted shallow dish shape. A steel-flat (1"/25mm) ring welded to the reinforcement bars forms a coherent circular edge (Figure 5 C-G). Larger lightweight prefabricated infill square panels would have wider cables/rods spacing, considered at less than 3.65m/12ft wide for economical truck transport. A research idea is injection molded panels with glued extension rod-hook inserts. Infill panel research issues include: thermal expansion compatibility with gap grout and hanging cable/rods, and roof surface durability in solar beam regions. Another area for research is with 3d printing (Figure 5).

FIGURE 5. Hanging two-way cables roof construction: A-B) Infill slabs/panels placement without a crane; C-G) prefabricated infill roof slabs/panels.

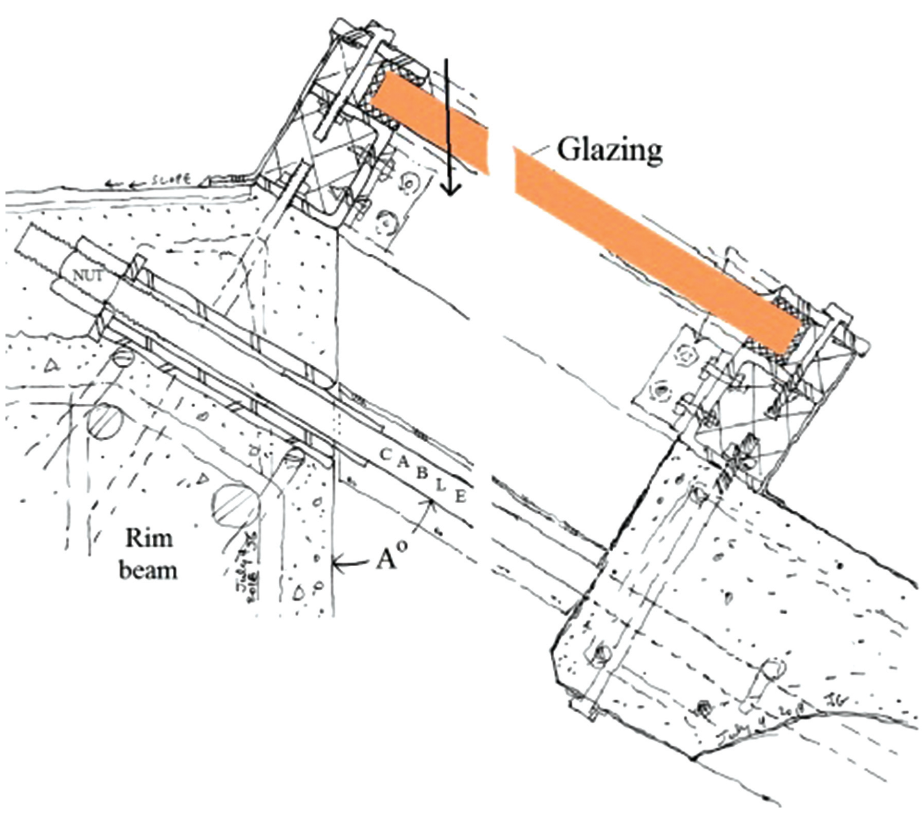


The perimeter (adjacent to the cement uncovered cables) variable-shaped slab/panels have holes for bolting edge concreting forms. There are holes in the edge wood forms for bolts to form holes in the edge concrete for bolting the metal (aluminum) channel glazing frames. The perimeter edges concreting would be at the same time as the cable-gaps grouting. Added reinforcement bars are in the edges that may also be tied to the cables. The stresses on the reinforced concrete perimeter edges when the temporary weights are removed are an engineering consideration. The straight edge lengths of the variable-shaped slabs/panels are also the straight lengths of the metal glazing frame, determining the sizes of the glazing. The radial daylight glazing mullion frames are above the two-way uncovered (with cement) cables that can have thin metal reflector ridged sleeves to deter perching. The circular curved concrete rim-girder has a vertical inner surface below the sloped cable pipe sleeves, and a top concreting (after the cables are adjusted) covers the cable pipe sleeves and transitions to a straight-line polygon in accord with the upper perimeter glazing frame support. The top straight-line glazing frame channels bolt onto the top sloped concrete of the rim beam (Figure 6).

4.4 Hanging Roof Construction Methods

A circular rim pre-tensioned hanging roof with two-way cables construction can be considered without and with an overhead crane in developing and developed global regions. A radial cables configuration with a large enough center tension ring can have a tower crane at the center. A two-way hanging cables configuration with infill standard size square prefabricated slabs/panels (with variations in the grouted gap) does not have space at the center drain opening for a standard size tower crane. A tower crane's jib radius at the perimeter of the rim-girder-platform may limit a hanging roof diameter, and a crane could lift larger heavier prefabricated slabs/ panels. Placing prefabricated slabs/ panels without a crane limits the size/weight of the panels. For example, if square precast concrete panels weigh around 68kg/.028m3-150 pounds/ft3, a slab/panel would be limited to around 1.2x1.2m/4x4ft for handling without a crane. Lighter weight prefabricated slabs/ panels are a research issue, e.g. with 3d printing. A 'square' prefabricated slab/panel size influences eccentric loading on the rim-girder-platform by the spacing

FIGURE 6. Section drawing at: rim beam, adjustable cable, infill slab and daylight glazing.



of the two-way cables. Closer spaced cable connections to the rim beam-platform will have less eccentric loading. Larger square slabs/panels with wider structural cable spacing would have a more eccentric loading on the rim-girder-platform.

A prospect for a feasibility engineering study is: construction of a long-span hanging roof with two-way cables to support small heliostats without an overhead crane. A construction sequence idea to avoid a large crane has temporary boards secured on four (compass quadrants) cable-sets forming four sloped platforms to slide down in a balanced distributed way the precast concrete panels held by adjustable cable winches (four) secured up on the circular donut rim-girder-platform, with some access scaffolding under the hanging roof (Figure 5). The ninety degree intersections of two-way cables at the sloped upper most regions of the hanging roof should not be too close to the compression rim-girder-platform to have suitable space for each individual adjustable cable connection. Two-way cables distortion during infill slabs/panels placement is a consideration. Wood gap forms and brackets are considered because they could dent-conform to slight variations without damaging the prefabricated slabs/panels. Hanging cables cross clamps would be embedded in the mortar-grouted gaps (Figure 4). Bolting the grout gaps with ceiling underside wood form boards may be sufficient to align the infill concrete precast panels for an aesthetic ceiling expression.

Frequent small movements may not damage the structural cables if the low end of the cable pipe sleeve is bell-shaped curved and the cable has a protective wrap at the outlet of the pipe sleeve. These kinds of details were in the c1958 Montevideo Stadium [17].The heliostats can be retargeted after: infrequent roof movements (differential foundation settlement, roof structure cracks, etc.) or wind damage. Roof thermal movements would be part of the optical design. This would be exacting structural engineering and optical design work to quantify.

4.5 Construction Sequence Outline

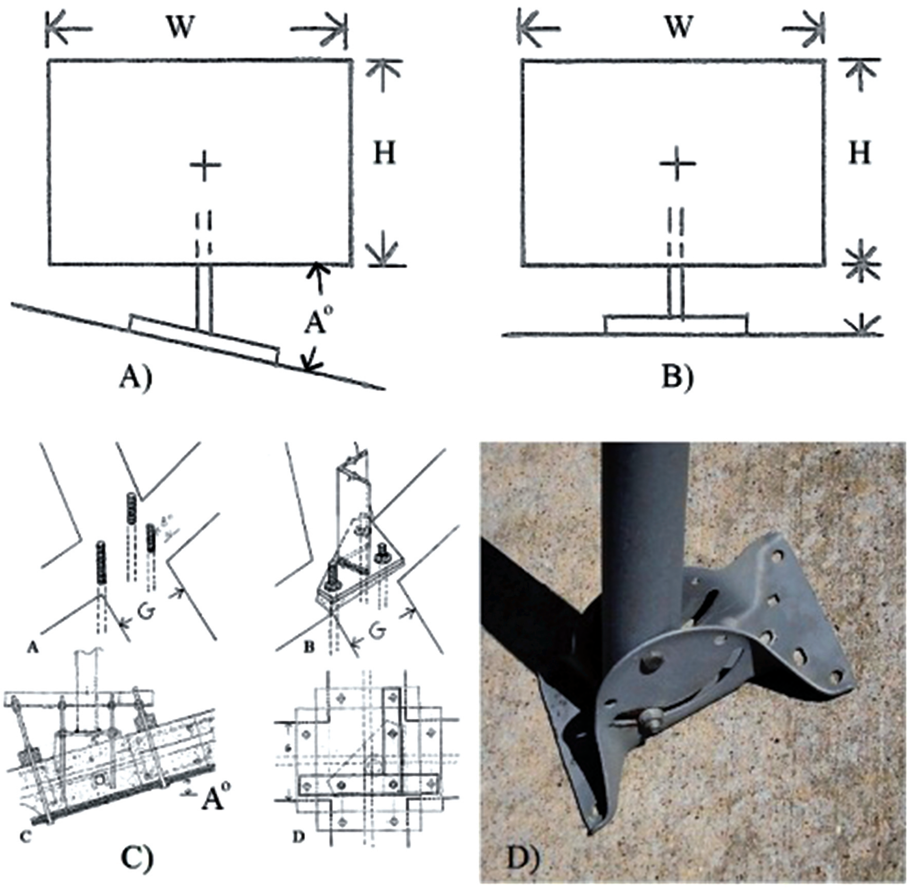
A construction sequence outline study for a long-span circular hanging roof construction with two-way cables for supporting small heliostats includes:

- Construction of circular rim-girder-platform on columns/bearing walls
- Two-way cables hung from circular rim-girder-platform
- Adjustment with adjusting nuts at the threaded ends of each cable
- Hanging cables cross clamped at the intersections
- Prefabricated infill slabs/panels hung on cables and positioned
- Temporary pre-tension weights put on panels
- Cables adjusted to design position.
- Gap wood forms and 3 bolt holders bolted in position
- Gap mortar grouting
- Remove temporary weights
- Install heliostats on vertical posts
- Wire connections for power and control to each heliostat to a controller and power source

5. SMALL TWO-AXIS TRACKING HELIOSTATS AND POST ANCHORAGE

Heliostat posts in this study are mainly all vertical for standard gearbox/driver and positioning software control products. Feasibility of heliostat tracking mechanisms and software for heliostat posts all secured at different angles to the various slopes of a hanging roof surface is a

FIGURE 7. Small Two-axis Tracking Heliostats hanging rooftop mounting options: A) vertical post on hanging roof slopes; B) vertical post on horizontal roof; C) three vertical bolts cast into two-way cables gap intersections for adjustable anchorage of vertical heliostat posts; D) vertical post anchorage with one-axis adjustable bracket bolted to sloped roof structure.



research question. Small two-axis tracking heliostats mainly considered for this study have each around 1–2m2 reflector area on a vertical post anchored to the various slopes of a hanging roof or secured on an adjacent horizontal ring-beam-platform. Mounting anchorage of the vertical post base to hanging roof structures has a variable angle (A degrees in Figure 7A). Extreme wind loads on the heliostat reflector area will be transferred down the post to the anchorage on the hanging roof structure and the moment forces, sometimes impact forces due to extreme wind gusts, are an important hanging shell roof structural engineering consideration. Heliostat size and capacity to adjust focal length for a smaller receiver target area related to extreme wind loads on an elevated receiver target size is another structural consideration. Small heliostat vertical posts on ballasted bases would have a secure connection requirement to a variable sloped roof structure likely to need some kind of bolt connections, and there would also be the concern of added ballast weight to a hanging roof structure. Therefor ballasted small heliostats do not appear feasible for the sloped areas of hanging roof structures. Maintenance workers may frequently be on the roof to clean the reflectors. Tracking heliostats with irregular movements during non-operational times as part of the controller program may deter: perching and nesting on the frame, insects in the gearbox, and critter droppings on rain collecting roofs. Remotely controlled heliostats and a small PV-battery at each heliostat could avoid wiring on the roof. Rooftop wires may need to be in conduit to avoid being damaged.

The heliostats/posts layout pattern on a hanging roof may have advantage to not be limited to the two-way cables spacing and gap intersection locations influenced by a square infill slab/panel size. Reference heliostats/posts layouts anywhere on a hanging roof surface with associated anchorage construction detail considerations could be compared to the post anchorage at some of the two-way gap intersection locations idea. Site specific annual solar collection performance and heliostats shading and blocking would be part of complicated engineering system integration evaluations.

Small heliostats with a single reflector facet or multiple reflector facets with each facet individually adjusted could have a smaller focal zone at an elevated receiver inlet target with less extreme wind loading structural survival concerns. Small heliostats with multiple flat glass reflector facets (2–16 'square' facets with each facet at about .3m x .3m/12 x 12 inches) with each facet independently aligned to reduce receiver inlet aperture area have been considered. A small heliostat (1.12m2/12SF with twelve square 305mm/12inch flat adjustable contour reflector facets) and controller products in the market reference is Practical Solar, Inc. (Boston).

5.1 Heliostat Post Anchorage to Hanging Roofs

Three vertical bolts cast in cement mortar at some of the two-way cables gap intersections have been studied. The three vertical bolts provide three-point adjustability for anchoring the vertical heliostat post base plates. A steel angle weldment 'T' temporary bracket holding the three inverted bolts is held in place with extended bolts that also holds the gap form boards in place. Wood form boards and small wood bolting spacer pieces can slightly deform to the various angular differences of the flat square infill slabs forming a curved roof without damaging the edges of the concrete slabs, influenced by the sag/diameter ratio. After the vertical post base plate is bolted in position to the three vertical bolts above the sloping roof the space between the base plate and sloping roof is filled with cement mortar (Figure 7C). A one-axis adjustable heliostat post bracket manufactured product may be bolted to the sloped hanging roof surface in radial alignment at holes cast in the: mortared gaps, infill slabs/panels, or both (Figure 7D).

Shallow sag would ease closer to horizontal gap grouting. A small sag for hanging roofs has less angular difference between the roof slope near the horizontal circular rim-girder-platform, for example if 0.07 is the sag/rim diameter ratio the angle between horizontal and the sloping roof at the rim-girder is about 15 degrees (Figure 7C-c).

Each heliostat gear-box on a post anchors to the hanging roof. Each post may be vertical or at different angles perpendicular to the slope at the hanging roof location related to gear-box and control-program capacity. An all vertical heliostat posts configuration was mainly studied. A temporary horizontal angle 'T' weldment holds the bolts in vertical position during the grout-concreting of the gaps. After the gaps concreting, cement fills the space under the horizontal bolt plate and sloped gaps. All heliostat posts would be vertical for gear-boxes and control systems that require vertical heliostat posts. Heliostat post anchorage for a radial cables pattern or anywhere on a hanging roof surface was considered with holes cast into flat infill slabs and a steel angles 'T' weldment bracket for adjustable three-point bolting thru the roof. The bracket would be horizontal for vertical posts, and unused holes would later be filled in with waterproof sealant/mortar or used for lighting. Structural anchorage may be in radial grouted gaps and/or in the radial infill precast slabs with bolt holes cast in or drilled. Small diameter holes drilled in

TABLE 1. Heliostats (1kWt,1m2) coverage at 20% and 25% of circular hanging roof horizontal area.

Roof dia.	20% reflector area	25% reflector area
30m/98ft	141 1m2 heliostats	176 1m2 heliostats
50m/164ft	392 1m2 heliostats	490 1m2 heliostats
100m/328ft	1,570 1m2 heliostats	1,962 1m2 heliostats
200m/656ft	6,280 1m2 heliostats	7,850 1m2 heliostats

precast slabs may avoid damaging reinforcement mesh/rods during drilling. Bolt holes cast in grouted gaps where gap-joint form boards were bolted may be bolt holes for the small heliostat post bases. The heliostat post may be welded to the 'T' bracket for variable slanted posts bolted flush to a hanging roof related to gearbox/drivers and controller orientation capability.

5.2 Heliostats Coverage

Heliostats coverage, called fill-factor, is considered at 20% and 25% of circular horizontal plane areas (not including heliostats on rim-girder-platforms) of hanging roofs with 1kW thermal 1m2 reflector area per each heliostat (Table 1).

6. RAIN WATER COLLECTION

Collected rain water would flow down to an outlet drain opening at the lowest area of a hanging roof with a floor to ceiling height of around 6m/20ft. The roof drain diameter would fit within the lowest square slab/panel of a two-way cables structural system. The roof drain should have a removable grid with a devise to deter perching to avoid fouling the water. Possibilities include: rain water would fall thru the roof drain to a floor level drain and a sloped drain pipe under the floor would direct water to storages; and a concentric small gutter collecting water at a higher hanging roof level could direct it with sloped pipes to tanks at or beyond the rim-girder-platform structure. Stored rain water could then be treated (FO-forward osmosis, etc.) with the small heliostats solar thermal heating system.

7. CASE STUDIES WITH BUILDING INTEGRATED SMALL HELIOSTATS-RECEIVER(S) SYSTEMS

This section outlines possible case study schematic building configurations for research and development. The main case study is a hanging roof supporting small heliostats for delivering 230 kWt to molten salt storage and applications to compare with the STS-MED EU demonstration project [14]. Some of the schematic studies are intended to be urban design planning elements with adjacent buildings for a variety of applications with thermal storage options. Small rooftop heliostats with direct absorption to a hanging small molten salt tank receiver at the top of an adjacent multi-story building appears feasible, however it would be limited to small molten salt storage volumes with added design complications and added costs with a tracking tank bottom receiver insulation cover. The higher temperatures that can be delivered with small heliostats systems coupled with building integrated ground level molten salt storage tanks may be a reliable solar thermal energy system for critical applications. In the case of solar thermal water desalination a wide range of temperature requirements for the different technologies (forward osmosis, etc.) can be delivered with small heliostats-receiver systems, perhaps most easily for the higher application temperatures. Therefore the temperature range being considered for the US DoE Solar Thermal Water Desalination Research Program is of interest.

7.1 CASE STUDY: 230kWt for distributed molten salt storage/applications

A circular hanging roof with small heliostats and one elevated receiver to deliver around 230kW thermal power is considered for comparing to the linear Fresnel collector with molten salt storage STS-MED EU demonstration project [14]. The three linear Fresnel reflector units at Palermo have around a 739.5m2 plan area (8.5mx29m x3 = 739.5m2). The diameter of a 739.5m2 area is around 30.68m/100ft. If the small heliostats reflector area is around 20% of the circular roof area there would be around 148 one m2 heliostats. Assuming a heliostats elevated receiver and distribution to storage/applications is around 85% efficient, and each small heliostat has a thermal output power of 1kWt, the heliostats would need to deliver around 271kWt (0.85x271kWt=230kWt); and there would be around 271 small heliostats. Preliminary schematic layout studies indicate that around 271 small heliostats (1–1.5m2 mirror area) can fit on a circular hanging dish-shape hanging roof (with around 0.07 sag/diameter ratio) and circular rim-platform with a 100–120ft/30–37m rim diameter. A plan study of a hanging roof around 120ft/36.5m diameter has around 234 small heliostats, and with 34 additional heliostats on the donut shape rim-girder-platform there would be a total of 271 heliostats (Figure 4A).

7.2 Additional Case Study Schematics

Schematics of hanging roofs supporting small heliostats over atriums with receivers supported by adjacent multistory buildings are in Figure 8. Insulated cylindrical thermal storage tanks with aesthetic covers may be in the atriums. Building integrated small heliostats on multiple circular hanging roofs are illustrated in Figure 9. Small heliostats on a long-span circular hanging roof over an urban open-air plaza or enclosed commercial space have multiple receivers (5–6) on

FIGURE 8. Rooftop small heliostats-receiver studies: A) circular hanging roof with small heliostats adjacent to a rooftop receiver on adjacent multi-story building; B) atrium rooftop heliostats with adjacent rooftop receivers; C) small heliostats on an oval hanging roof over an atrium.

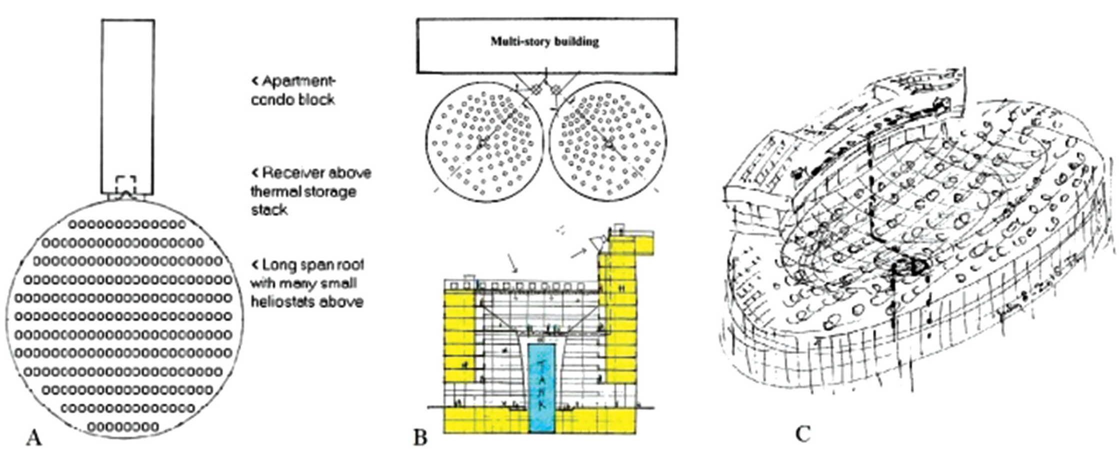


FIGURE 9. Small heliostats on multiple circular hanging roofs.

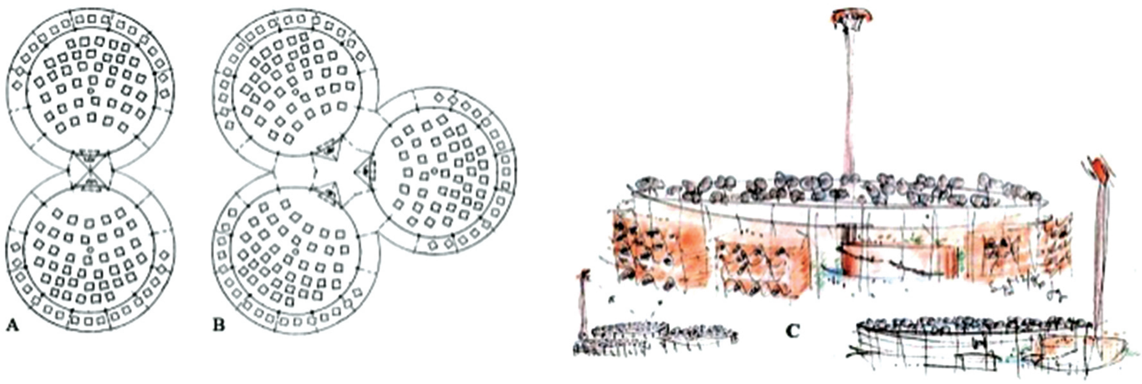
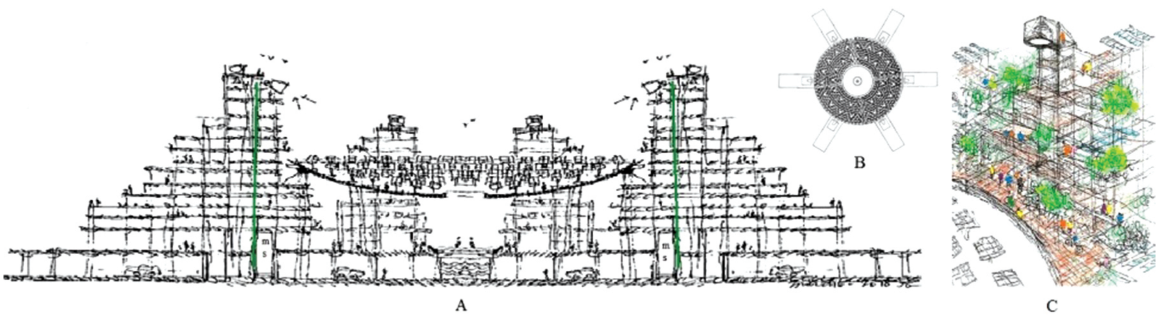


FIGURE 10. Small heliostats on long-span circular hanging roof over urban open-air plaza with multiple receivers on adjacent buildings.



multi-story adjacent mixed use buildings. Each receiver may be above a molten salt storage tank at ground level which can be charged by programming the heliostats field accordingly for the hours, solar angles, and insolation levels that are most efficient. The programming objective of the heliostats during the day is to aim at the receivers to meet the variable application demands and storage capacities at each receiver location with the variable solar beam radiation supply (Figure 10). A multi-story circular donut-shape rim-girder-platform would be a substantial construction cost, and more useful as part of a larger complex with additional adjacent buildings. A schematic sketch plan in Figure 11 has small heliostats on a circular long-span hanging roof over an open-air plaza urban design element as part of an arterial near ground level pedestrian circulation that is also a dining area for an adjacent kitchen. Several interrelated design factors include: site specific solar angles; the receiver-heliostats layout; building massing; and location of molten salt storage to cooking and refrigeration equipment. Donut-shape hanging roofs with small heliostats-receiver(s) schematics are in Figures 12 and 13. Large airplanes indicate a plan size diameter of about 160m/525ft which is applicable for several industrial process heat (mid-high temperature) building integrated applications with molten salt storage (Figure 13). A 'square' plan two-way cables hanging roof structure with curved rim beams is illustrated in Figure 14. Supplemental case studies with different heliostats support structures are: small heliostats at peaks of skylight pyramid frames over atriums; and a large diameter hospital ship with small heliostats trusses on reused long off-shore wind blade beams and a receiver tower above storage (molten salt, firebricks, etc.) tank ballast (Figure 15)[30].

FIGURE 11. Schematic plan of small heliostats on a circular long-span hanging roof open-air plaza urban design element as part of a pedestrian circulation pattern.

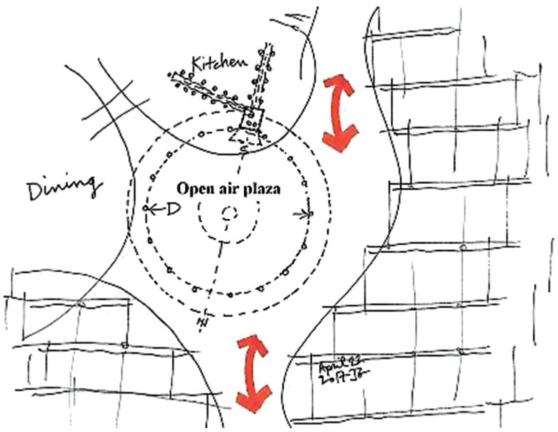


FIGURE 12. Small heliostats on long-span and donut-shape hanging roofs model photos.

FIGURE 13. Donut-shape hanging roofs with small heliostats-receiver(s): A) long-span airplanes hanger; B) donut-shape hanging roofs with multiple receiver towers; C) donut-shape hanging roofs with central receiver tower in a piazza.

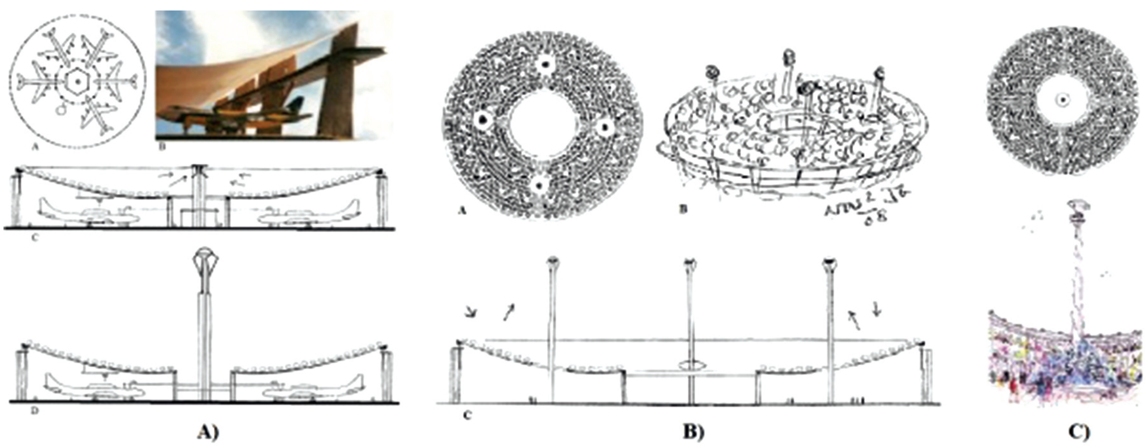


FIGURE 14. 'Square' plan hanging roof with curved rim beams

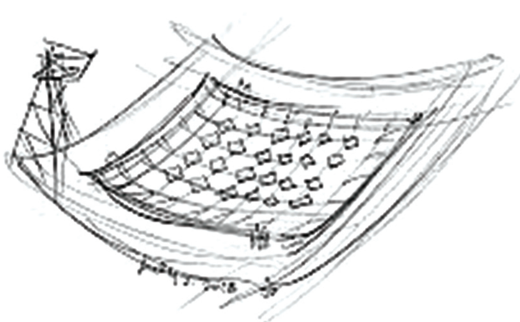
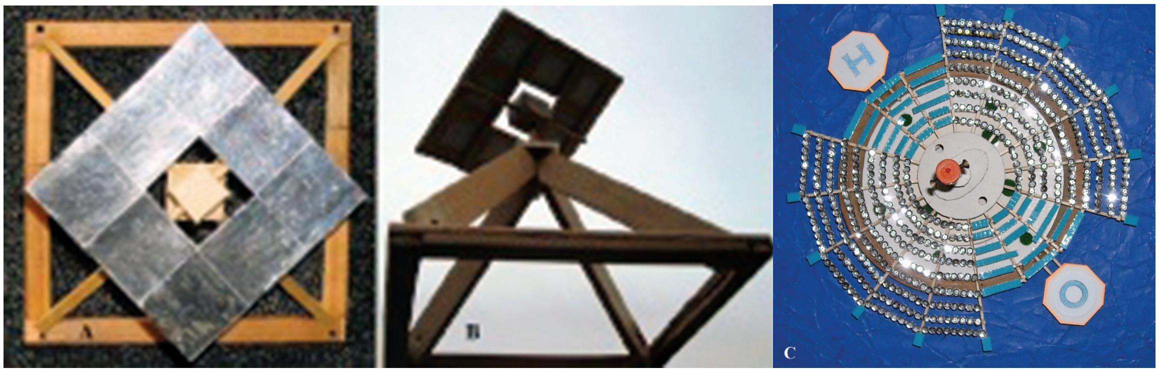


FIGURE 15. Supplemental case studies: A-B) small heliostats at peaks of skylight pyramid frames; C) hospital ship with small heliostats trusses on reused off-shore long wind blade beams and receiver tower above a storage (molten salt, firebricks) tank ballast model photo.



8. SMALL HELIOSTATS SYSTEMS ON LONG-SPAN HANGING ROOFS RESEARCH PROJECT OUTLINE PROPOSAL

The proposed small heliostats on hanging roofs and receiver(s) multi-year research project initiative is part of a Building Integrated (BI) CSP research program idea [31,5] to comparatively evaluate the CSP technologies and the building structures together as an integrated collector–building structure with economic analysis for mid-temperature and higher, process heat facilities, to include studies of building forms and structures with CSP collector technologies combined with building integrated molten salt storage tank distributed steam station systems in various planning and urban design environments. Initial studies are suggested to be: two-axis tracking heliostats receiver systems compared to other CSP collector systems, and transportable prefabricated cylindrical (up to around 3.65m/12ft diameter) molten salt storage tanks for one tank(s) systems up to around 300degC/572degF [14]; and preparation for engineering evaluations of building integrated heliostats-receiver(s) systems with selected roof structures, mainly circular long-span inverted-dome hanging concrete shells. A long-span hanging circular roof with small heliostats research study diameter range is around 15m/50ft to 200m/656ft diameter [27] comparing: two-way cable and radial cable configurations, sag options, and construction without and with an overhead crane. A proposed multiyear research project outline includes: initial independent studies of heliostats-receiver layouts and hanging roof structures; surveys for case studies; economic estimates; design of a testing and demonstration facility; and development of a simple front-end computer program tool for building integrated small heliostats-receiver(s) layouts for architects. A July 13, 2018 reply from the European Commission Directorate General for Energy stated: "The Commission is not in a position to determine if there is a simple front-end program tool for heliostats-receiver layouts for architects" [33].

Both the layout of heliostats and receiver sizes, and the two-way long-span hanging roof structures of cable spacing, sag and prefabricated infill slab/panel sizes have reciprocal influence to each other. Beginning study iterations for selected regions are independent works of: preliminary structural engineering design of long-span hanging roof structures; and layout of small heliostats and receivers. After review and comparing results, proposed in a second set of iterations, is to create integrated configurations combining the hanging roof structures and the heliostats-receiver layout. An object is first to gain understanding of: the relationship between the solar collector heliostats-receiver(s) layout optical efficiency for circular hanging roofs sag options; and hanging roof structural engineering of two-way cables spacing and infill slabs/panels sizing, for continuing systems integration design iterations for selected configurations and locations.

PHASE-1 Proposed R&D Project Outline

- **PHASE-1 TASK: Layout of small heliostats and receiver**
  Preliminary layout studies for small heliostats and receiver(s) systems for selected TMY data locations on selected hanging roof diameters and sag configurations. Factors include: heliostats shading; blocking; receiver target size; and fluid loop length. A beginning study is for a 320 kWt for 300C degrees storage (molten salt, firebricks, etc.) building integrated case study for comparison to the STS-MED demonstration EU project [14].
- **PHASE-1 TASK: Hanging roof structural engineering**
  Preliminary structural engineering studies of selected hanging roof, two-way and radial cable configurations compared, for selected locations and construction methods without and with an overhead crane. Consider a hanging roof inverted dome: with uncovered cables adjacent to a rim beam for thermal movements; and rigidly constructed with ribs extending from the rim-girder.
- **PHASE-1 TASK: Heliostats and roof anchorage**
  Survey of marketed heliostats with price lists; and vertical posts anchorage details to hanging roof structures.
- **PHASE-1 TASK: Economic studies**
  Preliminary economic studies to include: heliostats, receiver and distribution to application-storage systems; and long-span hanging roof structural configurations and construction methods. Cost estimates of small heliostats manufacturing of selected quantities, and large quantities in a robotic factory [32].
- **PHASE-1 TASK: Frontend small heliostats-receiver(s) computer layout tool for architects**

PHASE-2 Proposed R&D Project Outline

- **PHASE-2 TASK: Integrated layout and structural engineering**
  Heliostats-receiver(s) layout and hanging roof structural engineering systems integration design iterations. Evaluate hanging roof sag-shape structural and construction options together with heliostats-receiver layout and storage options. Consider the sag influenced by extreme wind loading on the heliostats; and this may include wind tunnel testing.
- **PHASE-2 TASK: Receiver types, sizes and location(s)**
  Compare receiver types, sizes and location options. A lower elevated building integrated receiver may avoid some extreme storm wind loads, and fit with regulated height levels of some city planning codes.
- **PHASE-2 TASK: Prefabricated infill slabs/panel testing**
  Design prefabrication infill slabs/panels and cost estimate production methods; and fabricate and test selected slabs/panels with a two-way cables test stand for handling and installation of test panels.

- **PHASE-2 TASK: Test facility design and cost estimate**
  Design and cost estimate a small testing and demonstration facility at a selected site.
- **PHASE-2 TASK: Economic studies (continuing)**
  Economic comparative studies include: performance; heliostats-receiver(s) and distribution to application-storage systems; and long-span hanging roof structural configurations; construction methods; land costs and availability; and operations and maintenance costs.
- **PHASE-2 TASK: Survey for case studies**
  Survey for site specific case studies (USA and globally) Considerations include: TMY regions for study; soil and foundation types and other site-specific geotechnical factors; regional construction methods.
- **PHASE-2 TASK: Preliminary study of building types**
  Preliminary studies include: building types (IPH, commercial, etc.) and urban design configurations.
- **PHASE-2 TASK Selected application studies**
  Building integrated small heliostats systems with building integrated molten salt storage for co-generation applications, e.g. estimate hanging roof diameters with 1–2 m2 reflector area two-axis tracking small heliostats for driving a 350–3500 kWt chiller with inlet of 190–225 C deg. at sunny 800–1000kW/m2 regions and compare costs to local conventional fuels.
- **PHASE-2 TASK: Small heliostats systems on existing buildings**
  Preliminary feasibility and layout studies on selected existing buildings (rooftops, facades, additions, and environs), for example, Madison Square Garden NYC (404ft/123m diameter) and Oakland Arena (420'/128m diameter). Considerations include: structural capacity of existing roofs, shading by adjacent buildings, and, receivers on taller adjacent buildings.
- **PHASE-2 TASK Comparative studies of CSP collectors on similar roof areas**
  Compare BI-CSP schematics with approximately the same floor plan area and column spacing: a circular column-free plan long-span hanging roof with 16 columns with small heliostats anchored to the rooftop; compared to a rectangular column-beam plan with 30 columns with rooftop linear Fresnel, small heliostats, Schefflers, etc. collectors. Roof terrace options with CSP collectors structured above the roof terrace may be included.
- **PHASE 2 TASK: Selected engineering studies**
  Select for engineering study: site/region TMY data; rim shape (horizontal circular, etc.); diameter and sag ranges; heliostat specification and size range; heliostats layout; receiver specification and location options. Calculate solar concentration at receiver inlet, and solar energy at receiver outlet.
- **PHASE-2 TASK: Selected detail studies advanced**
  Selected detail studies include: anchoring heliostat vertical pole bases to roof structure at various inclines and extreme wind forces; and structures supporting PV panels at the outer perimeter of the rim-girder-platform that may also be a wind fence which is a site specific research consideration regarding extreme wind gusts and vertical wind forces, perhaps including wind tunnel testing.
- **PHASE-2 TASK: Frontend small heliostats-receiver(s) computer layout tool for architects (continued)**

9. COMMENTS

The substantial and significant Concentrating Solar Power (CSP) research and development and commercialization of large scale concentrating solar collectors and storage systems technologies can be refined and miniaturized for building integration applications. The linear-zone between beam and diffuse solar collector-storage type regions may shift according to economics with more efficient higher temperature storage (molten salt, firebricks, etc.) and beam concentrating heliostats collectors compared to lower temperature storage (water, etc.) with reflector augmented single-end evacuated tube collectors. Building Integrated small scale heliostats-receiver systems studies presented are mainly circular hanging roof shapes with two-way cables and small sag ratios for rooftop small two-axis tracking heliostats (1–2m2 reflector area) systems. A proposed case study is small heliostats on a hanging roof and elevated receiver for delivering 230 kWt (steam or air) to storage (molten salt, firebricks, etc.) and applications to compare with the STS-MED demonstration EU project. Evaluation studies that only compare solar collector systems independent of building integration factors are insufficient to indicate fair comparative economic estimates of building integrated schematics. A main point of preliminary studies thus far indicate that economic comparisons must include the building schematic configuration together with the solar collector and storage systems. A proposed systems integration architectural R&D multi-year project outline includes complicated components (heliostats-receiver(s) technologies and layouts; long span hanging roof structures; comparative cost estimates; etc.) however the architectural systems integration work appears to be straightforward and feasible architectural research activities, dependent on the expertise of the component engineers. A step towards realization could be a feasibility design and evaluation study by an architectural-engineering team, which usually requires funding. The proposed R&D project includes development of a simple front-end computer program tool for building integrated small heliostats-receiver(s) layouts for architects.

10. IMPLICATIONS AND INFLUENCES

This work is intended to encourage: development of layout computer tools of BI-CSP small heliostats systems for architectural and urban design configurations; structural engineering feasibility studies for long-span circular hanging CSP roofs with two-way cable horizontal rim-girder systems (apparently novel); and R&D funding for mid-high temperature building integrated CSP solar heating in populated urban and rural areas.

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