BUILDING INTEGRATED CSP SELECTED STUDIES II

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ABSTRACT

Building Integrated (BI) CSP (Concentrating Solar Power) R&D program parts for developed and developing regions are: exterior and interior fixed nonimaging (NI) CPC large augmenting troughs; fixed spherical bowl with tracking linear volumetric air receiver; interior and exterior linear Fresnel, heliostats-tower; and thermal storage. Schematics include: thru-wall oven kitchens and walk-in basin still; terrace overhead linear Fresnel building systems; heliostats-tower with radial roof beams; and fabric screened storage tank. Building Interior Evacuated Tubes and Reflectors (BI-ET&R) studies for snow accumulation regions include: fitness facility (gym, pool, climbing wall tank, 80,500 sqft-24,535 m2 monolithic glass roof, 224 bays, 85,568 sqft-26,079 m2 interior CPC reflector area); atrium hotel (inclined 8 NS roof bays, 90 ET-NS CPC per 36ft/10.9 m EW bay); saw-tooth roof with daylighting; and 2-car garage size wood frame demonstration test facility. CSP collector, distribution and storage technologies are schematically integrated with building structures (masonry, etc.) and architectural spatial forms combined with passive aspects.

1. INTRODUCTION-BACKGROUND

About 20% emitted CO2 warms for 10,000+ years (5). Shale gas hydro toxic-chemical fracturing has pollution problems, delaying transition to renewable energy development with a future. BI-CSP studies to reduce fuels imported to buildings are based on refinement and miniaturization of CSP components (collectors, distribution, storage) in early stages of commercialization for large standalone power plants, and CSP is wider defined to include building size fixed NI-CPC type reflector troughs for low-mid concentrations. An aim is to present feasible BI-CSP schematics to stimulate supported advance of a

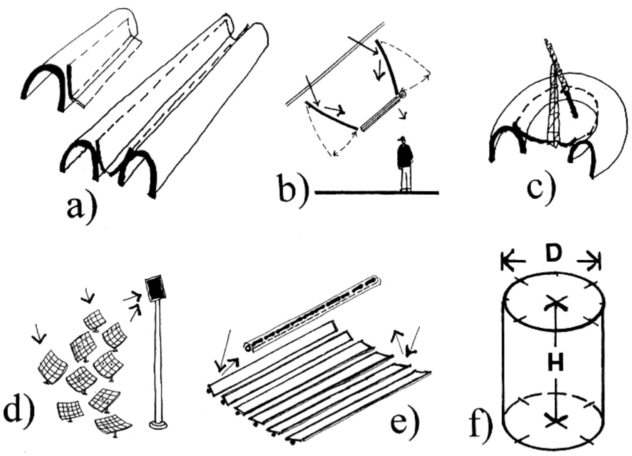

Fig. 1: Building Integrated CSP- a) exterior 1&2-sided nonimaging (NI) CPC type troughs; b) interior NI CPC type troughs with evacuated tube (ET) collectors; c) solar bowl fixed spherical segment reflector with 2-axis tracking linear receiver; d) 2-axis tracking heliostats with elevated receiver; e) exterior and interior 1-axis tracking linear Fresnel heliostats with elevated fixed linear receiver; f) storage

BI-CSP R&D Program initiative (4) with selected project engineering evaluations, and inclusion in elementary and advanced: architecture, urban design, building technology and engineering curriculums (1). CSP 200MW plant ground plan area ratios are: CFLR = 1; tracking troughs = 1.5; and heliostats tower = 2 (6). CSP tracker-controls are: bowl (one 2-axis); linear Fresnel (several 1-axis); and heliostats-tower (many 2-axis). Linear Fresnel reflector trusses span: 13.1ft/4m, 19.6ft/6m, and 52.8ft/16.1m; and receiver options include ET, CPV/T, and air. Fixed NI trough and bowl reflectors on low energy masonry structures for non-seismic regions may have less embedded energy than concentrated load metal frame tracker structures. Interior and exterior ET are: heat pipe (inclined, top EW manifold, condenser length in-out clearance); and U tube (horiz. high or low, vertical manifolds, full length glass tube in-out clearance, low manifold drain-back and eased drip pan design) which may better remove higher temperatures. Exterior ET have snow-ice shading concerns. Exterior and interior NI fixed reflector troughs can be based on ET standard lengths, and longer CPV/T collectors.

Shuman's 1911 Philadelphia plant had fixed F-P 3x3ft hot boxes and adjustable 3x3ft flat mirror sides (12). Passive reflector augmented basin stills increase water production (13); and added active thermal collectors had 50% higher yield (14). Heat pipe ET heated cooking oil to 347F/175C (15); and ET interior reflectors have durability concerns (16). Volumetric air receiver-loops above glycol temperature limits avoid: oil leak damage (to roofing, sealants, etc.), high-pressure steam and freezing; and R&D includes: CR heliostats-tower (wire <750C) (18); fan sucked air thru metal fiber-matt of 2-axis tracking dish pivot flex tube at 400C/752F in S. Africa (17); and 1-axis tracking troughs (20). Inclined NS polar axis short CFLR with fixed back reflectors have increased collection (7). Reported for solar bowls in 1983: "…The potential cost effectiveness of bowl-building integration should be closely examined…"(11)(10)(3). The 1874 ship Novgorod had a hull plan 30.78m/101ft diameter.

2. EXTERIOR FIXED NI TROUGHS

Building size exterior NI fixed reflector trough schematics include: box cookers (Fig 2a-e); thru-wall oven house (Fig 7a-b) and mid-size kitchen (Fig 7c); dryers (Fig 2z); stills (Fig 2f-n); solar ponds (Fig 7d); and augmenting solar thermal collectors (ET, F-P). A vertical reflector wall is a type of NI 1-sided trough (Fig 7d). Tracking parabolic trough used reflectors may become fixed NI reflectors.

A NI thru-mirror wall greenhouse type oven (e.g. HotPot™) and fuel stove house kitchen partial plan (Fig 7b) indicates design factors: solar access, stovepipe, and building-site plan. Construction types for a chair-size NI concentrator are: reflectors glued to masonry, shaped blocks or molded plastic and bolted bent metal reflectors (Fig 7a). A NI reflector top edge aligns with wall-roof construction related to oven counter height. A fixed NI reflector mid-size solar kitchen schematic for non-seismic locations combines: multiple thru-mirror wall ovens with tensed cable reflector facets, and a scoop type 8-sided inlet concentrating down and then up to a cooker in the kitchen (Fig 7c).

A crawl-in 1-slope basin still with 1-side NI trough has: glazing incline B = 35 deg.; vertical hinged door H = 6.25ft; W = 7ft and Wo glazing = 8ft (Fig 2f-g). A large basin still glazing-cover structure entered for maintenance has adjacent NI fixed reflectors with collector loop in sand under the basin (Fig 2k-n). Other NI augmented still studies are: bifacial (Fig 2h-i) and rooftop (Fig 2j).

A bifacial receiver seashell trough with fluted ceiling on steel pipe beams has concern of fail-safe adjustable end reflectors (Fig 2ff-gg) (Fig 7g). A CPC trough 1-piece end reflector can wind flap without hitting receivers. Standard ET lengths have trough roof residential and small workshop structure spans; and bifacial refractory CPV/T receivers have potential for longer span roof troughs (Fig 2dd).

3. INTERIOR ET+CPC (BI-ET&R)

Building Interior Evacuated Tubes and Reflectors (BI-ET&R)(1) studies for snow accumulation regions include: a fitness facility (gym, pool, climbing wall storage tank); atrium building; horizontal saw-tooth roof; 2-car garage size demonstration test facility, and vertical bifacial ET for high latitude regions (21)(Fig 3wx). The BI-ET&R glass roof walk-in collector system has an inclined monolithic glass cover-roof, ET and reflectors in a controlled temperature boiler-room. Long span potential is with NS open web truss-girders depth sized for maintenance access and EW line CPC reflector troughs. Structural frame bays coordinate with: ET, plumbing layout, reflectors (CPC trough, quasi-track ends), and glass roof. Seasonal adjusted CPC reflector side(s) when cleaning affects NS bay span and passive daylight-heating apertures. A few vertical interior insulated daylight windows open for infrequent big parts replacement (Fig.3r). Typical end bays have stair access and clearance for adjustable end reflectors.

A fitness facility (gym, pool, climbing wall storage tank) with an inclined 80,500sqft/24,535 m2 monolithic glass roof walk-in collector (with augmented ET) has 224 modular bays, and EW line fixed CPC reflector area of: 73,728 sqft (384sqft for each 192 typ. bays), 10,240sqft (320sqft for each 32 end bays), and 1600sqft for 32 adjustable end reflectors (50 sqft each); totaling 85,568sqft of interior reflector area (excluding NS involute reflector for each ET). Collector-roof inclination is influenced by building form of NS dimensions of pool, lockers and gym (1) (Fig.3o-u).

An atrium (hotel, etc.) study has inclined 8 NS bays and e.g., a 36ft EW bay with center piping gap. ET collectors and NS piping gap (1.3 to 3ft)(O in Fig 3e) equals typical bay NS truss-girder EW spacing (S in Fig 3p), e.g. an EW 36ft bay with center piping gap has 90 ET with matching NS CPC per bay (5x18 ET/unit). An atrium hotel schematic has an EW long rectangular plan, shorter block of rooms under the low end of the roof collector, and a taller block of rooms under the higher part of the roof collector, with the inclined roof collector spanning NS over the atrium (23). Storage tank configurations are: tank below ground with atrium level access on top of the tank (Fig 7w); and a slender cylindrical tank in a tensioned screen-fabric in the atrium (Fig 3s).

A saw-tooth BI-ET&R horizontal roof with heat pipe ET and daylight has exterior flat or slight curve reflector roof added

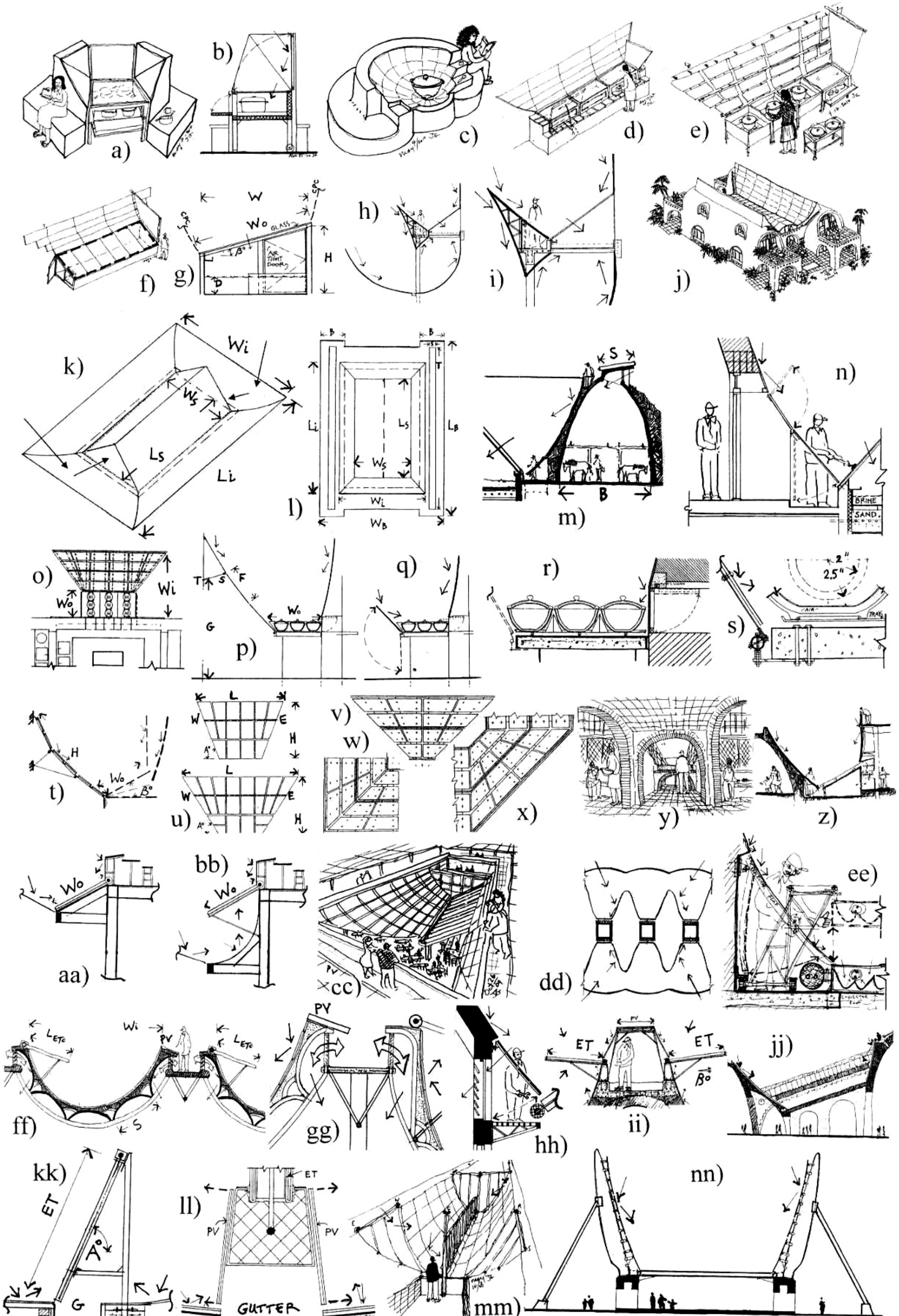

Fig. 2: Exterior NI-CPC troughs- a-c) cooker augmenting exterior furniture; d-e) 1-sided CPC augmenting cookers; f-g) crawl-in water still; h-i) top & bottom augmentation; j) roof top water still; k-n) large augmented water still; o-s,y) slide in-out ovens kitchen; t-x) reflectors on cable-nets; z) dryer; aa-cc) augmented ET; dd) refractory bifacial CPV/T; ee) F-P replacement; ff-gg) "seashell" roof ; hh-ii) ET manifold access; jj) section between vaults; kk-mm) ET at CPC bottom; nn) wind blades CPC

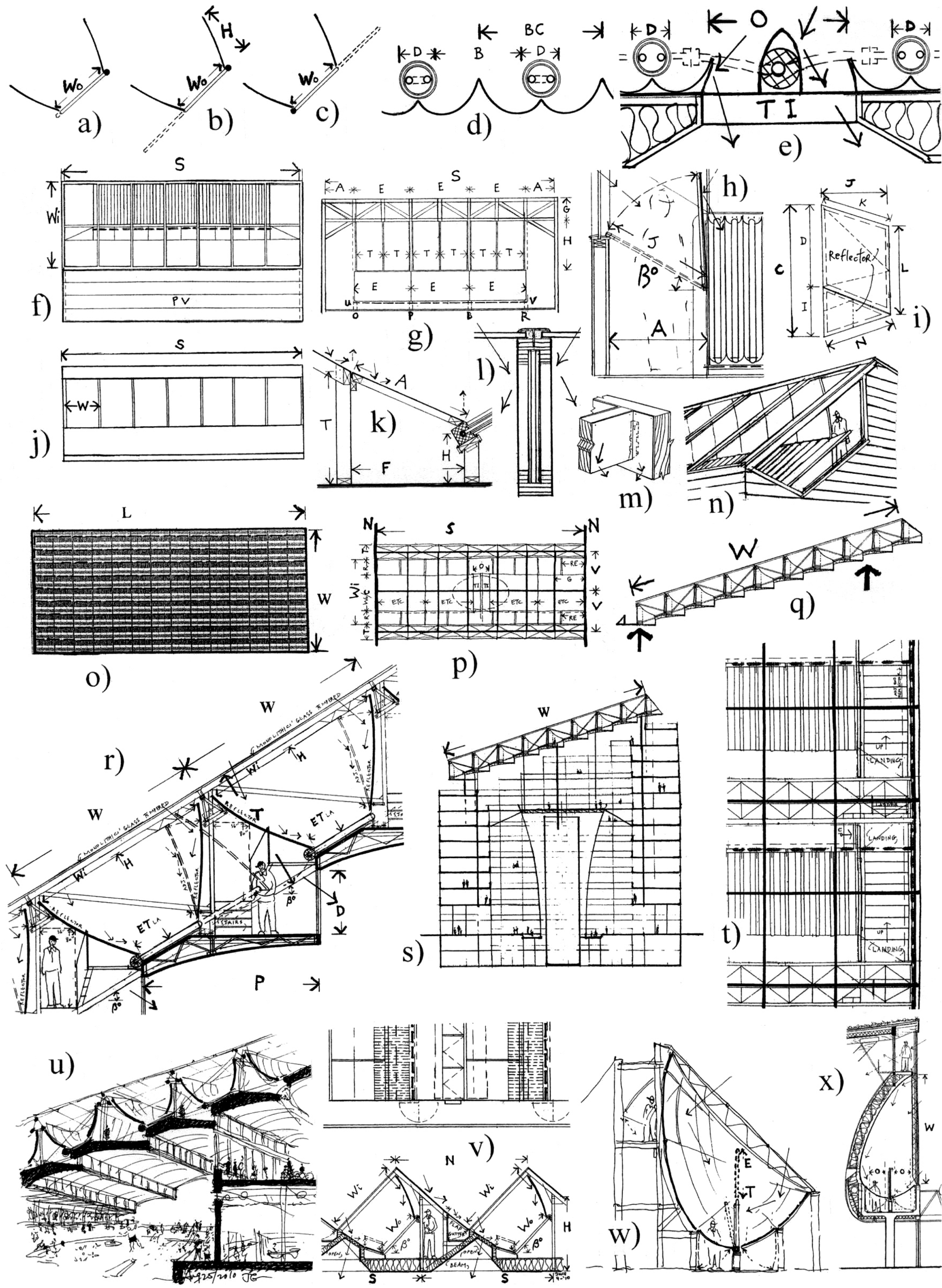

Fig. 3: Building Interior ET & Reflectors (BI-ET&R) a-c) manifold position; d) ET-CPC spacing; e) NS piping-daylight section; f-n); 2-car garage size wood frame demonstration facility schematics; o) roof collector 126 bay plan; p) typical bay plan; q-r) roof-collector SN sections; s) storage tank in atrium; t) end bays plan of access stairs, adj. end reflectors; u) roof collector; v) plan-section of horiz. daylit saw-tooth roof; w-x) vertical ET sections

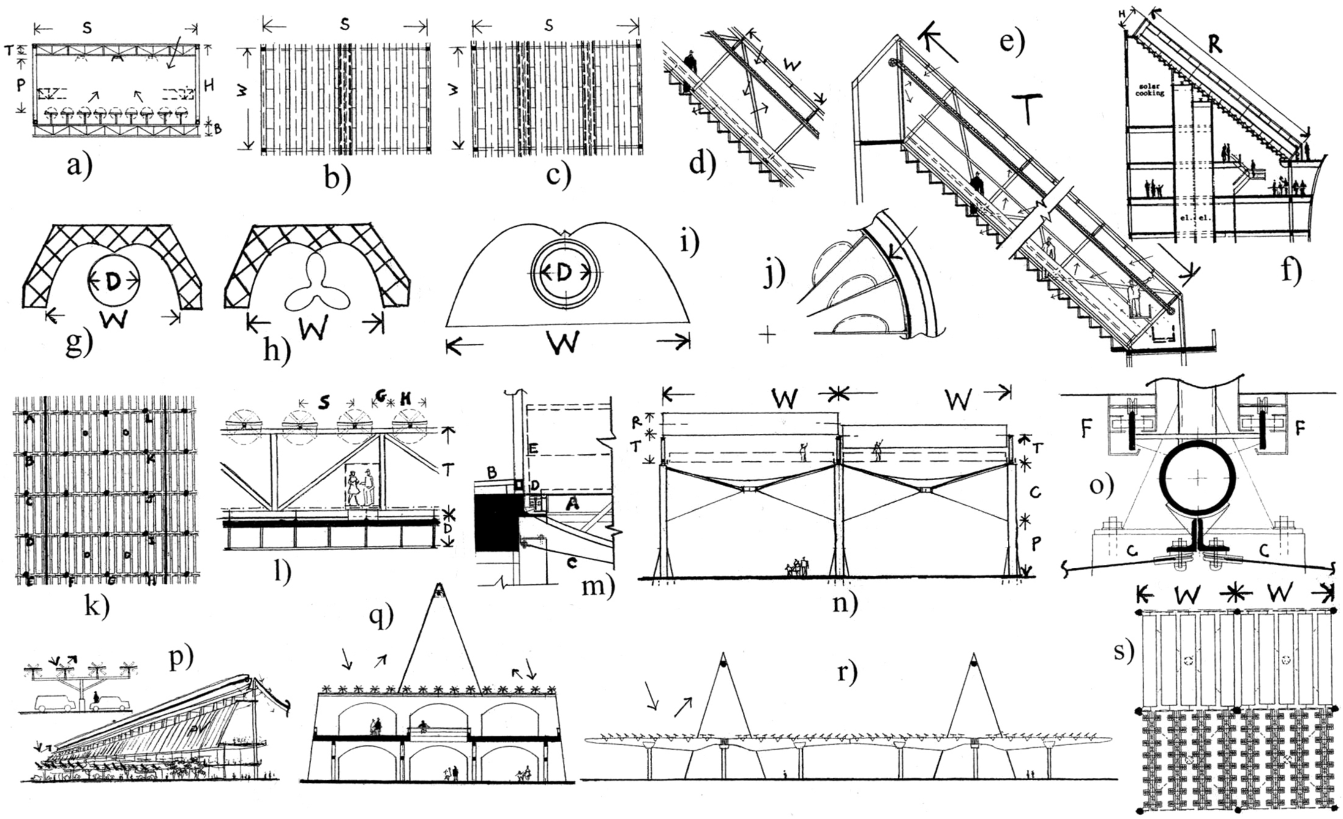

Fig. 4: Interior and exterior linear Fresnel 1-axis tracking systems: a-c) interior typ. bay section and plans; d-f) inclined interior roof collector sections; g-i) fixed reflector receivers; j) air receiver; k) exterior Fresnel systems plan; l) open web truss elevation; m, o) fabric roof and terrace details; n) access trolley under reflectors; p-r) exterior Fresnel building studies; s) Fresnel and small CR heliostats plan

inlet aperture, and reflector flaps structured for exterior loads over access gutters. Access is by: floor hatches at end reflector areas or exterior weather tight doors at each EW collector row (Fig 3v).

A wood frame 2-car garage size BI-ET&R demonstration test facility schematic design is presented in Fig 3f-n. A wood horizontal flat truss spans EW over ET with lightweight lift-off reflectors over low-end manifold access. Adjustable end reflectors share access way at E and W vertical 1-glaze windows. Reflective rafters support a 1-glaze standard size glass roof.

4. INTERIOR TRACKING TROUGHS

Building interior 1-axis tracking parabolic troughs (P-T) with inclined ridged or vault exterior glazing (EG) has some skyline identity aesthetic quality however maintenance access to inside upper areas of the exterior glazing has concerns of collector damage risk and cumbersome access apparatus. P-T clearance to track vertical for access to reflectors-receiver one side at a time influences structure shape, exterior glazing position, and daylight glazing (Fig 7j-k). Air heat transfer fluid (HTF)(20) avoids liquid leaks. A concern is errant concentrations to roof rafters, and reflector rafters would add daylighting. EG valley-gutter may be adapted for the Chromasun™ glazing shape.

5. BI LINEAR FRESNEL

Linear Fresnel 1-axis tracking beam reflector systems include: interior (Fig 4a-f); and exterior for above roof/ terraces (Fig 4k-m, 7o,p). Center bearing (Fig 4l) or hoop bearings (Fig 4n) influence reflector clearance. Interior inclined walk-in collector roof systems for high latitudes have: open-web NS 2D girder-trusses, monolithic flat glass roof and stepped insulated floor with vertical glaze daylighting. Under exterior glass roof access is with trolley on NS girder tracks (Fig 4e) or ladders between vertical reflectors. Reflectors to receiver height (P in Fig 4a) is coordinated with NS girder depth (H in Fig 4a), influencing quantity, size and shape of reflectors per receiver e.g. if S (typ EW bay) =40 ft, R (reflectors per receiver)/H=2.33, and G (typ. ext EW glass-lite width = 5ft (Fig 4a-c). If S/ P=4, and S=36ft, P=9ft, with two receivers per EW bay (Fig 4c). Receivers may be multiples of standard CPV/T or ET receivers e.g. 4m/13ft long (Fig 4i). Air receivers: avoids liquid leak damage, and effects distribution to storage. Concerns are: interior maintenance access (receivers, under glass roof) and errant concentrations. Interior Fresnel and

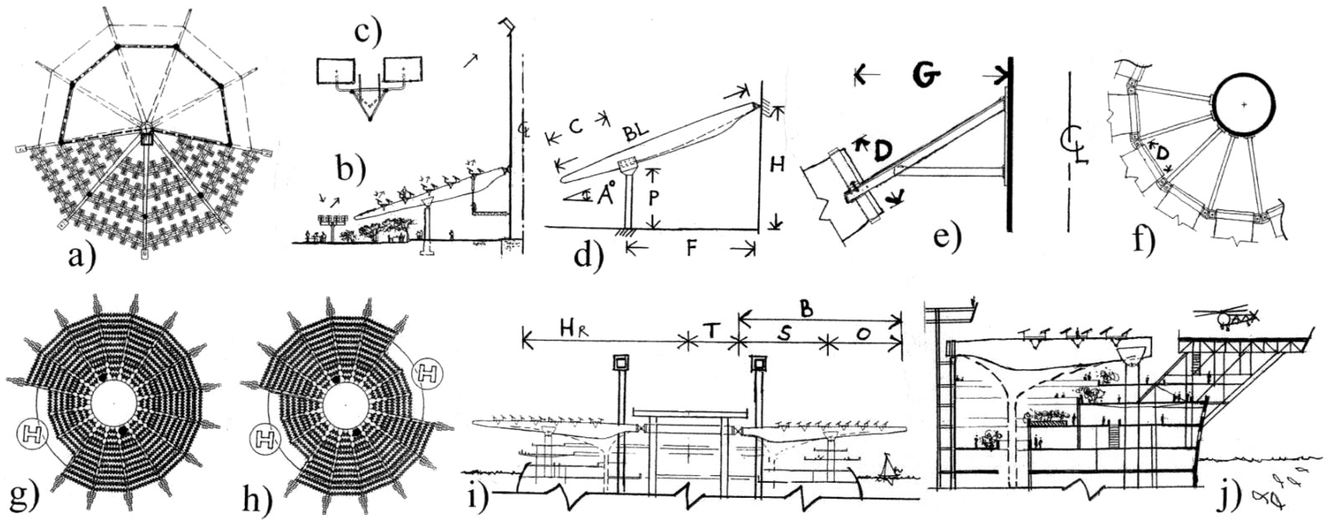

Fig. 5: BI 2-axis tracking small CR heliostats- a,c) 9 radiating beams plan with heliostats on 3d trusses; b,d,e) inclined radiating wind blade beam sections; f) blade root supports plan; g-j) solar ship plans and sections.

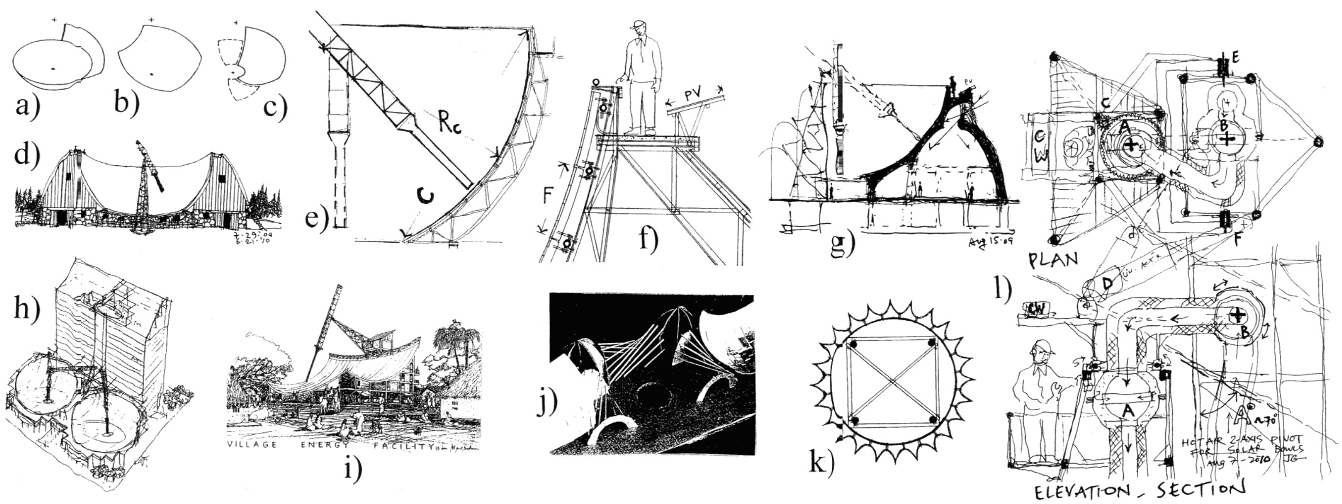

Fig. 6: Building integrated solar bowls a-c) rim shapes; d) solar bowl barn; e-f) sections at typ. longitude truss; g) masonry C-shape vault section; h) 2-bowls building; i) square bowl village facility; j) saddle vaults + domes square rim; k) volumetric air receiver section; l) hot air 2-axis pivot schematic

BI-ET&R fluid loops are compared in Fig 7m,n.

Exterior Fresnel semi-shade building systems include: EW beams (concrete, used wind blades)(Fig 4r); masonry walls (Fig 4q); roof terrace vaults (Fig 7o); steel exterior girders (Fig 4l); fabric inverted cones (Fig 4n); and urban modules, e.g. 390m/1280ft NS x 36 m/118ft wide, over workshops, roof terraces and tall tree greenways (Fig 7q). Roof terraces on EW line masonry vaults, have hoops on EW line bond beams with reflector-trusses segment bolted at O-moment regions to lower for EW movement (Fig 7o). Reflector-substrate perforations overhead have lighter spatial quality. A typical bay multilevel column-beam building system has reflector shafts on exterior parallel EW line open web girders spanning e.g. 54 ft/16.45m with 1.1ft/0.35m gap between 52.82ft/16.1m reflector-trusses. A bridge with adjustable side railings, from roof terrace to roof terrace, over inverted cone fabric roofs or open-air courtyard, has removable cover plates over tracks for a maintenance access trolley that traverses over the bridge when the bridge side railings are in horizontal position (Fig 4m). Concerns are: exterior reflector-truss corrosion, steel costs and embedded energy.

6. BI SMALL HELIOSTATS-TOWER

Small 2-axis tracking heliostats anchored on suitable building structures have field pattern flexibility, e.g. on radial bond beam stiffeners above concentric C-shape masonry vaults (Fig 7r-s); and on 3d trusses between reused blades and tower-foundations of wind farms re-powered with larger turbines. Cluster tower layouts not in a straight line can have several radial blade-beam collectors over semi-shaded agriculture and terraces aimed at a receiver-

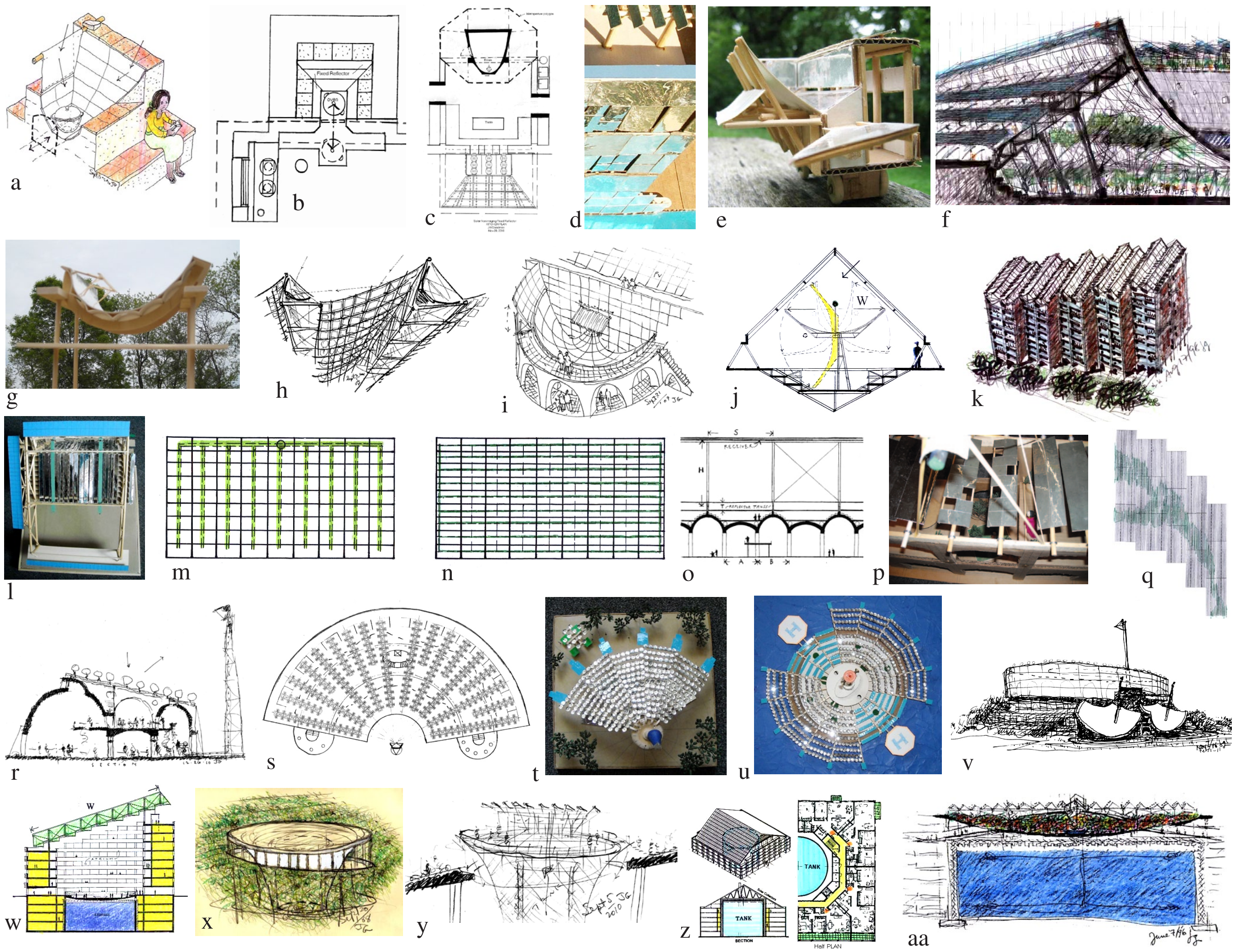

Fig. 7: BI-CSP Supplemental Studies- a-b) house thru-wall oven; c) NI kitchen; d) solar pond augmentation; e) NI kitchen trailer; f) NI roof; g) seashell roof; h) cable-net reflector; i) fixed ET and reflector; j-k) interior tracking troughs; l) interior linear Fresnel; m) lin. Fresnel fluid loop; n) BI-ET&R fluid loop; o-p-q) BI overhead lin. Fresnel; r-u) BI CR heliostats; v) CR heliostats + bowls stadium; w) BI-ET&R atrium; x-y) daylight above tank; z-aa) BI tank storage

tower. Thermal expansion of fiberglass reused wind blade structures is a concern (2).

A radial plan has nine reused wind blade beams with root ends supported at a center receiver tower and new columns at overhanging tips. Blade beams, 127-140ft long, incline according to roof slope and optical design. The 9 pie-sector plan has 5 sectors roofed, forming interior floor plan area, and 4 sectors of small heliostats supported on trusses spanning between radial blades (Fig 5a-f)(Fig 7t).

A circular hull solar ship (for hospitals, desalination, campuses, OTEC, etc.) has radiating reused wind blades supporting small 2-axis tracking heliostats on 3d open web trusses. If blade length B is 90m/295ft (8) and T is 28m/92ft, hull diameter (2Hr) is around 185m/607ft, about two football fields long. Central elevated receivers are near the hull center, and helipad(s) overhang the hull rim to limit helicopter accident damage. Ship design is for stability, not mobility, and ship movements would be part of optical-thermal design (Fig 5g-j)(Fig 7u).

7. <u>BI SPHERICAL BOWL</u>

Fixed spherical segment BI bowls with 2-axis tracking linear volumetric air receivers are considered. Schematics include: fan-shape rim barn C-plan with standard longitude steel trusses (Fig 6d-f) and curved masonry vault (Fig 6g); and square-rim with saddle vaults (9)(Fig 6j). Local transport size limits of prefabricated parts influence design e.g., if standard truss chord = 50ft and rise=7ft, radius of curvature Rc = 45ft, related to bowl inclination (Fig 6e). Bowls require stable foundation-structures for reflector facets imaging optics; and if locally constructed and repaired may have few imported parts. A less than full-length receiver relates to shallow rim shapes. Bowls are unfit for drain-back, and for temperatures above glycol limits without damage of heat transfer oil leaks a volumetric air receiver with sucking fan schematic was designed for insulated hot air thru a 2-axis bowl pivot after undergrads (19) with H. Fricker participation indicated feasibility of 482F/250C deg. outlet air thru a stainless steel ball joint swivel with loose fill insulation. Insulated hot air 2-swivel passage and access fit with an enlarged boom frame (Fig 6l).

8. BI THERMAL STORAGE

Most BI-CSP studies have emphasized the collectors, however, thermal storage technologies (water, pebbles, rocks, sand, concrete, PCM, etc.) would also have to be well understood before building design starts. Insulated cylindrical hot water tanks are considered (Fig 7w-aa). A freestanding tank with hung lid in a stretched fabric has a clearstory daylighting green roof (Fig 7x); and a collector pergola 3d space-frame spans a horizontal or inclined roof opening (Fig 7y). A freestanding water tank foundation is in an atrium (Fig 3s). Apartments surround a tank sized in accord with fire exit building codes (Fig 7z).

9. COMMENTS

Comparative understanding resulted from BI-CSP schematic architectural studies i.e. fit with: solar resource, building types, sizes and spatial forms, structural materials, embedded energy, regional climate factors and applications. Trackers (Fresnel, CR, P-T) only for beam require structure-frames for point wind loads; and NI fixed troughs concentrate some diffuse. Small 2-axis tracking CR heliostats fit with radial plans-structures; and exterior linear Fresnel modules fit with large area rectangular plans-structures. Horizontal and inclined linear Fresnel reflector-trusses with corrosion concern have no contribution to building structure. Fixed bowls and NI troughs on low energy masonry walls and vaults can have protecting reflector finish. Interior linear Fresnel NS bay sizing is more flexible than for the BI-ET&R set mainly by ET length and CPC characterization; and both have NS open web girder-truss depth for atrium long spans.

Projects suggested for advance with optical-thermal analysis for selected sites, building technology integration, and economic evaluations are: fixed NI troughs for house and mid-size thru-mirror wall oven kitchens and water basin still entered for maintenance; BI-ET&R and interior linear Fresnel demonstration facilities compared; small heliostats-tower radial beam test building; exterior linear Fresnel, NI-CPC and bowl masonry building structures; and BI-CSP combinations e.g. small heliostats-tower (Fig 7r) topping off linear Fresnels (Fig 7o). Several schematics provide indication of architectural feasibility. Performance simulation studies with building engineering evaluations are required for advance. Aims are to stimulate funding for BI-CSP R&D with student projects.

10. REFERENCES

(1) Goodman, J.H., Building Integrated CSP Selected Studies, SOLAR 2010 ASES Conf., 5-2010, Phoenix,
(2) Goodman, J.H., Architectonic Reuse of Wind Turbine Blades, SOLAR 2010 ASES Conf., 5-2010, Phoenix
(3) Goodman, Joel H., Solar Concentrating Architectonics, 1993, Library of Congress No. 93-176002
(4) USDoE, S.Kosinski, 7-28-09, ARPA-E #25A1215
(5) Pontin, J., Q & A Bill Gates, MIT Tech. Review, Sept/Oct. 2010, 30-32
(6) Venetos, M., W. Conlon, Solar steam boosters for coal-fired plants, Nov. 2010, Power Engineering, PennWell, 178-192
(7) Mills, D., G. Morrison, Compact Linear Fresnel Reflector Solar Thermal Powerplants, Solar Energy V-68-3, 2000, 263-283
(8) Wind Blade Test Facility Breaks Ground, REW N. America, PennWell, p24, Jan/Feb 2010
(9) Garlock, M. et al, Felix Candela, Engineer, Builder, Structural Artist, Yale U. Press, 2008
(10) Guigan, G., J. Harper, S. Rousseau, 1999, A Solar Bowl in India, ISES Cong., V-III, Jerusalem, 405-408
(11) Weisiger, J., Semiannual FMDF review at Texas Tech, DE-AC04-83AL21557, Oct.1983, USDoE, Albuquerque
(12) Butti, K., J. Perlin, A Golden Thread, Van Nostrand Reinhold, 1980
(13) Tanaka, H., Monthly optimum inclination of glass cover and external reflector of a basin type solar still with internal and external reflector, Solar Energy, 84-2010, p1959–1966
(14) Dwivedi, V.K., G.N. Tiwari, Experimental validation of thermal model of a double slope active solar still under natural circulation mode, Desalination, 250, 2010, 49-55
(15) Esen, M., 2004, Thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants, Solar Energy 76, 751–757
(16) Duff, W, J. Daosukho, Twelve year evaluation of novel ICPC solar collector installation, ASES Solar 2010, Phoenix
(17) van den Heetkamp, R.R.J., The Development of Small Solar Concentrating Systems with Heat Storage for Rural Food Preparation, Physica Scripta 2002, T97, p99-106
(18) Fricker, H.W., C. Winkler, M. Silva, and J. Chavez, Design and test results of the wire receiver experiment Almeria, , 1990, Solar Thermal Technology Research Development and Applications, Proc. of 4th Intl Symposium, Hemisphere, 265-277
(19) Hisel, J., J.Williams, N.LaHam, R.Miller, D.Lenarz-Geisen, Hot Air Passage at 2-Axis Pivot Project, Fin. Report, ME 349, Prof. P.B. Ravikumar, U.of Wisconsin-Madison, Aug. 2010
(20) Bader, R, et al, An air based cavity-receiver for solar trough concentrators, ASME J. of Solar Engineering, V-132, 8- 2010
(21) Tyukhov, I., 2010, Advanced solar energy and educational technology, Global Journal on Technology & Optimization, V-1
(22) Watson, Donald, Designing &Building a Solar House, Garden Way, 1977
(23) Watson, Donald, The energy within the space within, Progressive Architecture, 7-1982, 97-102