Liquid Solar Array PV Concentrator

A Means to Resolve Key Economic Limitations in Solar Concentrators.

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Abstract

PV concentrators appear to offer significant potential savings in cost over flat plate semiconductor PV systems. This potential advantage derives from the trading of large areas of high grade semiconductor and glass (silicon) for similar areas of cheap acrylic plastic in the form of a thin Fresnel lens or a thin glass mirror, plus a small area of PV cells (typically silicon) and a tracking mechanism. However, to date the potential savings have not yet been realized due to complexities arising mainly from the mass of the physical structure needed to provide adequate support for the concentrator, cells and tracking mechanism in adverse weather conditions.

This paper shows a means whereby all major limitations, and costs, may be considerably reduced by adopting a configuration, termed the "Liquid Solar Array" (LSA) where each element of a floating array comprises a raft supporting a solar tracking lens and partially-submerged water-cooled PV cell assembly. An important feature of the LSA is that the lens can be submerged in windy conditions thereby reducing structural requirements in comparison to PV (land-based) concentrator cell arrays. The paper shows that the LSA structural cost savings outweigh the cost any associated complications and lead to a projected capital cost of under US$1 per watt.

The LSA mimics techniques employed by some plants that lie down to accommodate the wind, and others such as the Lotus flower that emerge from the water completely dry.

1. POTENTIAL OF PV CONCENTRATORS

The main potential advantage of PV concentrators over one-sun flat plate PV derives from reducing costs by trading large areas of high grade semiconductor-under-glass (silicon) for similar areas of cheaper materials, such as acrylic plastic in the form of a thin Fresnel lens or a thin glass mirror, needing only a small area of PV cells. The light is concentrated so the area of silicon typically required is reduced 50 to 200 fold for a given output.

Silicon cells in concentrator systems are quoted as low as US$0.20 per watt; however, difficulties arise from the lens or mirror structure that focuses the light onto these economical cells as the structure needs to be substantial. Added to this is the cost of the tracker that, along with the structure, needs to withstand winds of at least 150 km/hr in many locations. Table 1 (Appendix 1) gives the approximate forces to be expected at different wind speeds, using Bernoulli's formula. Thus it may be seen that the structure must withstand pressure of 120 kg/m^2 if exposed to winds of 150 km/hr. If exposed to wind forces at only 60 km/hr, the peak forces per square metre acting on the structure are reduced to 20 kg/m^2 , thus if the effective pressure could be reduced, there would be less need for such a substantial structure and tracking mechanism. Around one sixth of the strength and mass should be possible without compromising performance.

The substantial structure of the present PV concentrators is keeping their cost in the $2 to $4/W range (see Ref. 6 for estimates), only a little better than flat plate PV, which is currently about $4-5/W. Very high efficiency PV cells are advantageous for these exposed heavyweight systems despite the considerable extra cost of such cells relative to the standard silicon variety (as the higher output per square metre helps offset the structural cost). A lighter structure would be a big cost saving, both directly and in a reduction in the size of tracking drive required.

2. SOLUTION

By arranging the PV concentrators in an array that is placed on water rather than on land, a simple solution has been realised that gives efficient cooling of the PV cells and allows a lighter structure to be used, resulting in major cost savings. A buoyant raft comprising moulded plastic members supports a tracking mechanism and light weight lens as shown in Figure 1. The lens system can be rotated into the water at any time that wind-speeds exceed some threshold, or according to weather predictions and thereby obviate the need for the large area components to withstand high winds. An array of such rafts and immersible collectors might be termed a liquid solar array (LSA).

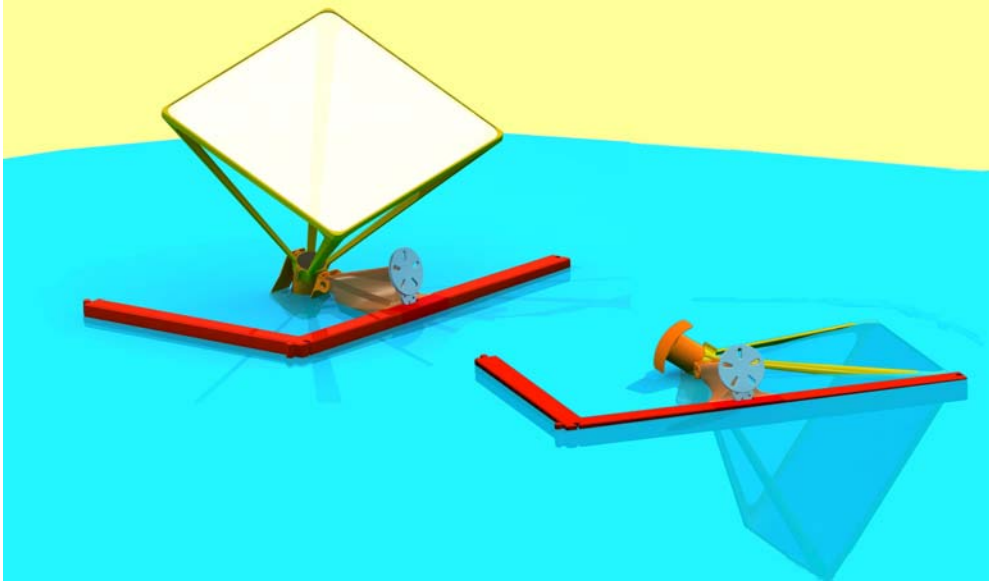

Figure 1 Collector in operating and protected positions.

With such a design the lens and its supports can be very light – as little as 3 or 4 kg for a square metre of Fresnel lens with its frame (versus 20 kg/m^2 for a standard concentrator). So the mass of the moving components is greatly reduced. Hence the tracking motor drive is also reduced in size and power.

An extra and substantial benefit of the LSA situation is free cooling from the surrounding water, creating a very low operating temperature at the PV cells (resulting in longer life and better efficiency). In comparison, the equivalent land-based 1 m^2 concentrator must be provided with 1 m^2 of convection cooled aluminium fin area to dissipate the 700 W of radiation absorbed by the PV cells and not converted into electricity just to achieve 80 °C cell temperature. (To achieve a smaller heatsink or lower working temperatures would require forced cooling or liquid cooled heatsinks and the consumption of additional electrical power to drive the cooling system). Note that the water is not heated above its normal equilibrium temperature in the sun by the LSA system and there is no effect on the water composition.

Another significant advantage of this approach is that the system is likely to survive coastal cyclonic conditions that are expensive to manage with existing solar collectors and wind farms, leading to lower insurance costs for the LSA.

With this method, it is possible to get nearly the same output as a more traditional concentrator or present one-sun PV systems for about one third to one sixth the cost (See Appendix 3 and Ref. 5 for detail).

3. REAL-WORLD ISSUES

There are a few issues that need to be addressed in a practical implementation:

- Waves need to sufficiently subdued so that they not affect power output.
- There needs to be a means to prevent salt or solids residue build-up on the lens after immersion.
- All components that are exposed must withstand saltwater and direct sunlight.
- Algae must not foul the critical components.

Appendices 1 and 2 discuss the details of wind pressure and the basis for minimizing the effects of waves. Correct use of breakwaters around the array can eliminate waves within the array of collectors.

The possible build up of residues on the lens has been addressed by a number of experiments to determine salt residue after many cycles of dipping of the hydrophobic lens cover material – a fluoropolymer similar to Teflon. These showed that residues did develop after around a dozen dips in saltwater (sea-water equivalent). This seemed related to gradual accumulation of dust which reduced the hydrophobic nature of the surface. A strategy was determined to wipe the dust from the surface with a thin rubber vane while the lens cover is underwater. This was tested and found to keep the lens cover dry and salt-free for over 500 immersion cycles. Hence it is expected that similar wipers will be required on production models.

The need to withstand saltwater and sunlight is a matter of materials selection and good design. Correctly tinted polypropylene has good life for many components, along with PMMA acrylic for the lens. Both are often quoted suitable for 20 years in sunlight. The PV container would typically be thin pressed stainless steel with a glass entrance window (or lens).

Algae can potentially create a bio-film on all wetted components. For some sections this is not a problem. The raft and anchor chains are not likely to be adversely affected by algae. The lens is also unlikely to be fouled by algae as it is not wetted for long periods (only during extreme weather). The component most vulnerable to algae is the PV container, whose rear is almost permanently immersed. There are several ways to deal with algal growth on the PV container including heating above the tolerance of the algae, occasional mechanical cleaning, occasional treatment with ozone bubbles generated electrically, and the use of a small amount of copper on the surface. The last is the simplest and most tested in existing marine situations.

4. IMPLEMENTATION AND PROTOTYPE RESULTS

To determine the general feasibility of the technique, a simple but complete model was constructed with a 400 square centimeter Fresnel lens of 1mm thickness - see Figure 3 below. It used 30 sun silicon concentrator cells provided by the Australian National University, operated at 20 suns. These were well-characterised, but only medium efficiency PV cells (14%).

The plot in Figure 2 shows a few hours operation of the first Liquid Solar Array prototype from 10am in mid-winter, at 34 degrees south. The lens was maintained normal to the incoming sunlight by an automated tracking system.

The concentrator output (upper) was sustained near 80 W/m^2. The concentrator lens was enclosed in a fluoroplastic envelope, giving realistic conditions.

The measured 5.3 amp steady output from the concentrator corresponds to 3.2 W (at 0.6 V out) or 80W/m^2. The lens area is 16 by 25 cm or 0.04 square metres. The plot is scaled up to watts per square meter. The solar input is assumed to be 770 W/m^2 of direct insolation in calculating the efficiency (clear sky in midwinter at 34 degrees latitude). The lens intercepts 31 W of direct sunlight (roughly 400*770W/10000). Hence the direct sun overall efficiency is about 10% (from 3*100/31 %) with all optical and electrical losses. This represents the minimum that can be achieved with a poor grade of PV cell (the one used is about 14% efficient). Any production system is likely to do at least 35% better overall, simply by using a better grade of PV cell (19% is available cheaply).

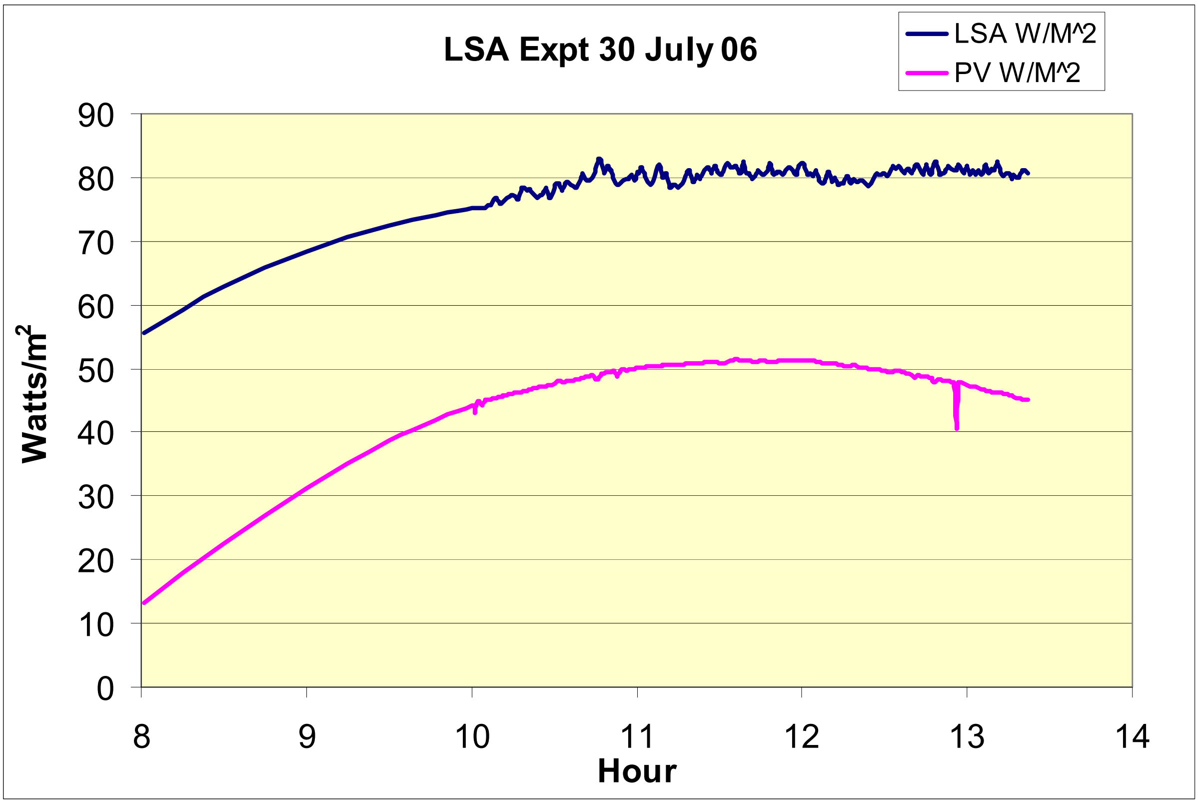

Figure 2 Measured power output density from the LSA prototype (upper plot) and a fixed flat plate PV cell nearby (lower) in July 2006 (with extrapolation before 10am).

Figure 3 First prototype, 2006.

Figure 4 Stepper Driven Model - 2007

The result implies an optical efficiency of around 70%. This can be improved, to perhaps 75-80%, using normal anti-reflective techniques. An overall efficiency of 14-15% could then be expected in production with standard silicon concentrator cells, giving an expected 115-125 watts per square metre through the year.

The Measurement Conditions:

The geometric concentration used in this model was approximately 20. A 400 sq. cm lens was used in conjunction with 19 cm^2 PV cell mounted at the end of a 12 cm long reflective cone. In this experiment the tracker drive is derived from sensors with limited angular resolution so that there are some variations in output (+/-3%). The tracking accuracy is +/-0.75 degrees – about ten corrections per hour. The outside temperature of the PV container under the PV cell was less than 5 degrees kelvin above the surrounding water (which was about 16 °C).

Ongoing Development

Figure 4 shows a more recent prototype that demonstrates plastic construction and compact two-axis stepper drives. A full-scale model with a 0.8 square metre lens of 1 mm thickness is currently under construction.

5. PRODUCTION MODEL CHARACTERISTICS

The CAD model shown in Figure 5 indicates the simplicity of a proposed production model using mostly injection molded plastic components, except for the PV container, which is stainless steel and glass. Drive details are not shown. It is expected that each drive actuator (motor) can be shared across five to ten collectors on the interlocked rafts that can be walked on for servicing. Each collector would have an optical aperture of about one square metre. This leads to a raft structure and units that are readily managed by one person.

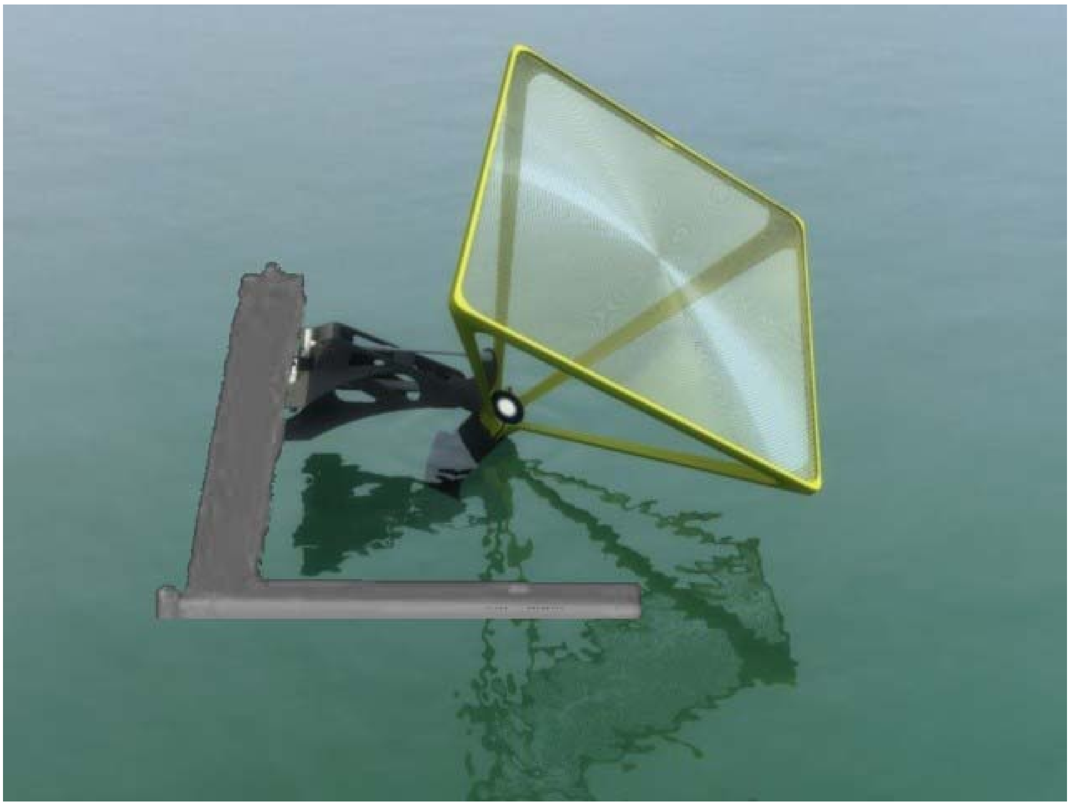

Figure 5 CAD model placed in simulated operational situation.

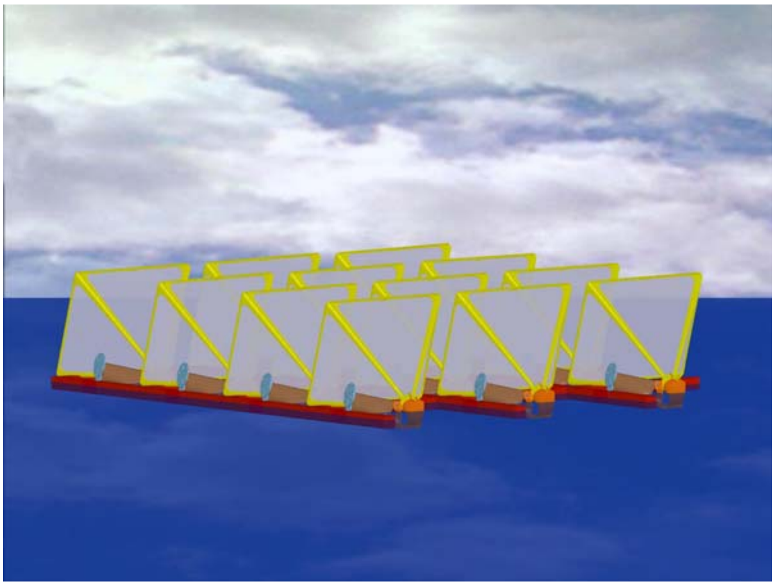

Fig 6. A small array of LSA collectors in operation (CAD Model)

All collectors on a given raft move together and require only one tracking system. Chain and concrete anchors at each end retain the system & assure relatively slow movements with changes in wind, so that a sensor driven tracking system can maintain reliable pointing at the sun.

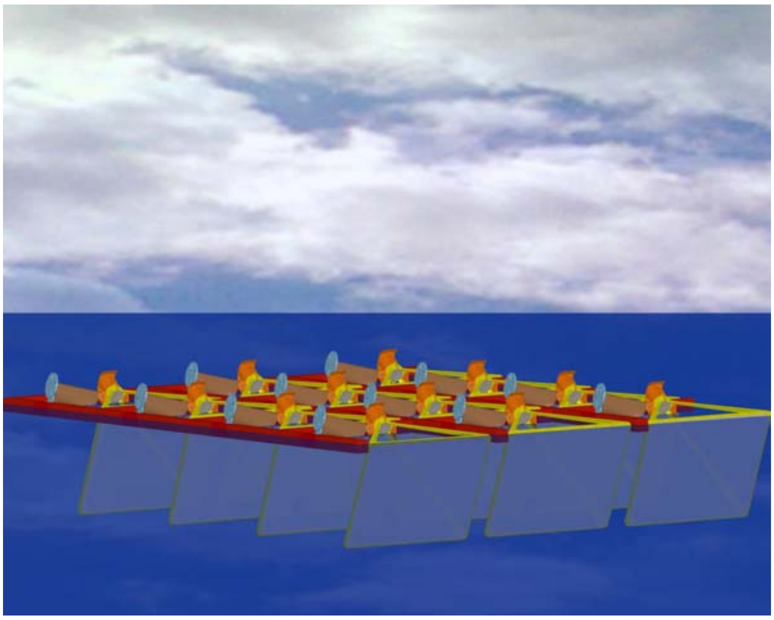

Fig 7. The array in protected position.

When winds exceed around 50 km/hr the tracking system is used to turn the collectors under the water for protection as shown in Fig 7. A single wind sensor and computer controller can be used for a large field of collectors. A reasonable optical concentration ratio for a production model using readily available silicon cells is between 30 and 80.

6. LIKELY COST

The details of how costs are derived are given for one early mass production case in Appendix 3. This shows that costs of about US$1.35 per watt are likely to be achievable at low levels of production (including installation, mounting and wiring). Figure 8 below gives an impression of the costs of each component for a higher mass production case (using well known silicon concentrator cells). This case results in costs around $1 per watt or 5 cents per kwhr. Estimates for higher volumes indicate that $0.70 per watt, or less, is possible with silicon concentrator cells. Note that these are not hopeful, long-term projections, but estimates based on the costs of similar existing components that are available now. In all estimates the PV cells are assumed to cost more per unit area than existing one-sun mono-crystalline cells. If one were to assume that high production volumes will drive technological improvements in the LSA system, such as the incorporation of multi-junction PV cells and lightweight composites, the cost of DC power could go below US$0.50 per watt in the long term (or two cents per kwhr in excellent locations).

The embodied energy cost for the current design has been estimated to take about 12 to 18 months to repay in normal operation (which could be further improved).

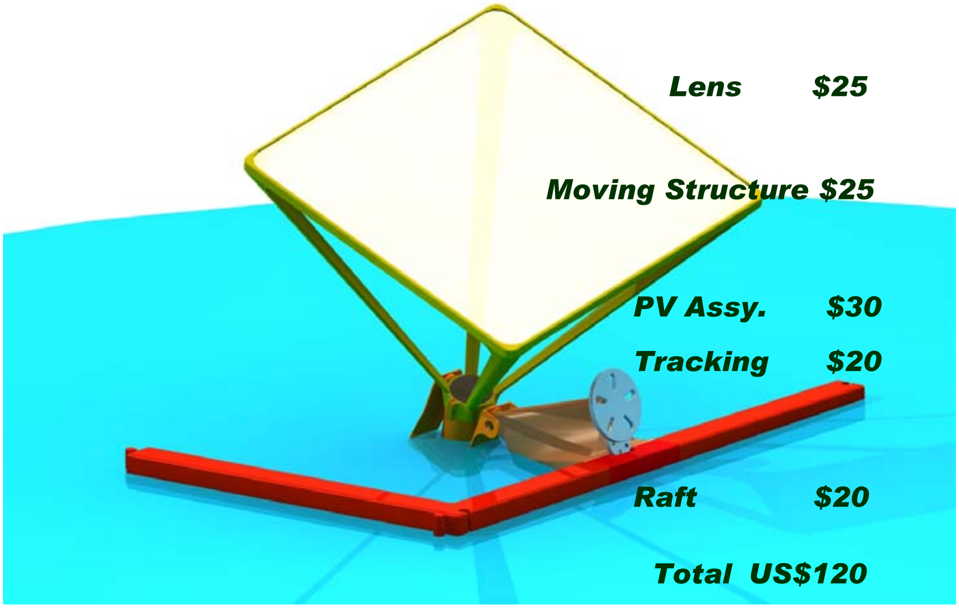

Figure 8. A mass production cost estimate, giving about US$1 per watt.

These cost estimates include some of the usually hidden costs of PV systems such as mounting, installation and wiring. They do not include inverters to create AC power. These are currently around US$0.30 per watt and reducing rapidly as production volumes increase.

7. APPLICATIONS

Most coastal areas and inland reservoirs within 35 degrees of the equator could be suitable for application of the LSA. The basic requirement is a protected area of water between one and ten metres deep (with some flexibility). About 25 square metres of water area is required for each kilowatt of electrical output if using silicon concentrator cells of 19% efficiency (at 40 degrees C). Where suitable bodies of water are already available, and the sunlight availability is over 2000 hours per year the LSA system could offer an extremely competitive source of raw electric power. Lesser hours of sunlight give higher power costs but in many situations this may be acceptable. Likewise, in some good solar situations, custom built ponds may be economically feasible. In each case the water itself is not consumed or changed at all, so multiple usage of the water is possible (drinking, aquaculture).

Given that the basic one square metre module of this system will generate about 120 W, quite small systems should still have good economics. Thus the LSA would suit farm or village scale power systems of 1 to 20 kW nearly as well as 1GW systems. Bigger is generally better.

If contributing to a national power grid, the LSA component would be most effective if broken into hundreds of systems each of about 10-100 MW, as this would be least affected by local cloud. One hundred megawatts requires about 2.5 km^2 of water area (1.6 x 1.6 km).

8. ASPECTS TO BE PROVEN AND FURTHER POTENTIAL

The lifetime of the Fluoro-polymer lens cover (25 um) has not been proven in actual operating conditions. The lifetime due to UV effects is very long (30 years tested so far by Dupont) but there could be abrasion issues. Several suitable cover materials are being considered. Partial tests have been done on a cleaning wiper that is likely to be used. These tests show a reasonable life for the cover is likely when wiped every few days– at least five years.

A well-sealed and durable tracking drive is necessary. Such drives have been in use for many years in related applications (especially marine systems).

So the feasibility of building such economical collectors is clear, but details of the best design details for durability in water are not yet demonstrated. Testing of large arrays in real conditions has not been executed. The best economical module efficiency achievable is also not fully explored. It seems that 10 to 14% overall is relatively straightforward, but much higher may be achievable.
High efficiency triple junction PV cells may allow LSA system efficiencies around 30%, but will need to have much lower costs than their current level to suit the LSA design. The important issue for solar collectors is not their technical efficiency, but rather their economic efficiency, and from this perspective the LSA design is extremely effective.
It should be noted that the LSA collector method can be used with many forms of energy converter, not only silicon photo-voltaics. Multi-junction and Gallium Arsenide PV cells are highly suitable, along with thermoelectric and chemical energy converters. Kucherov and others (refs 7 and 8) have shown that a new form of thermoelectric converter can have efficiencies up to 28% where heat is supplied at 400 degrees and removed at 30 degrees. These conditions can be readily created in the LSA system (Ref 5).

9. CONCLUSION

The results shown in this paper indicate that the major cost drivers for concentrated solar electricity collectors can be considerably reduced by this technique of selective immersion of the concentrator. The LSA design effectively addresses the ‘Achilles Heel’ of conventional PV concentrators – their sensitivity to extreme weather. The LSA design is working with nature to accommodate these extreme conditions economically.

Given that a prototype shows that this economical assembly works with good efficiency and that its components are readily available, making the costs highly predictable, it should be considered that the LSA cost estimates are both credible and achievable with relatively little effort.

Furthermore, given that the LSA method is estimated to give DC power in the $0.70 to $1 per watt range within a couple of years, making it very economically competetive, a significant effort should be made to fully develop and utilise this system immediately. No other solar electricty generator has such promising near-term prospects.

It may not suit every locality, but those areas with the necessary resources will benefit from economical clean power. The environmental and socio-economic implications of widely available cheap solar power are extremely significant. When solar power is available at under US$1 per watt it becomes more economical than coal and other fossil fuel sources for daytime electricity generation (in many regions) making massive carbon emission reductions possible without economic stress.

APPENDIX 1 – WIND LOADS

1. WIND LOAD ON THE EXPOSED LENS

The one square metre lens sheet is exposed to wind pressure when it is in operation. The airflow past the lens creates drag that tends to push the whole structure away from its position and this force must be resisted by the supports and anchor system. We can assume low wave loads, as the collector field will have many wave breaks (the collector rafts are effective wave breaks).

The drag force is calculated from Bernoulli’s formula:

$D=(1/2)*C_d*A*D*V^2$,

where C_d is called the drag coefficient, which is a number that depends on the shape of the object [for a smooth sphere, C_d is ~0.5, or for a flat disc ~1], A is the cross sectional area of the object ($A = 1\ m^2$), D is the mass density of the air (about $1.2\ kg/m^3$), and V is the speed of the object with respect to the

air in metres per second.
(See http://carini.physics.indiana.edu/E105/drag-force.html).

For operation in a 32 km/hr wind (8.8 m/sec, or 20 mph), the maximum drag on a round exposed 1 m^2 lens is about 46.4 newtons or the equivalent of 4.7 kgf. This is roughly the strength needed in the tracking system linkages (wires) and the anchor during energy collection. At some chosen wind velocity above this example (perhaps 45 km/hr) the collector would be rotated into its immersed, protected position.
The table (1) below gives an approximate estimate of the wind forces for a range of wind velocities.

Table 1

Wind Speed	Force on a Sq. Metre
30km/hr	5 kgf/m^2
60km/hr	20 kgf/m^2
120km/hr	80 kgf/m^2
240km/hr	320 kgf/m^2

1.1. Wind Load on the Rafts

In a similar fashion the wind load can be calculated for a set of rafts when the collectors are immersed and the wind velocity reaches 150 km/hr to estimate the anchor requirements. The exposed vertical area in this situation is very small, under 0.1 square metres per collector of one square metre.
For a 100 mph (150 km/hr) wind the load could be 20.8 N or about 21 kgf per 1 m^2 collector raft. Depending on the final raft shape and exposure this could be considerably lower. Hence the anchor requirements are not very large.
It is expected that a maximum anchor force of about 20 kgf per square metre of collector would be adequate for all conditions.

2. APPENDIX 2 -- LIMITING WAVES

The LSA system is not intended for open sea deployment. It is more suitable for protected lakes, lagoons, reservoirs, harbours etc. Secondly, it cannot be used where fast water currents flow (ie. not in channels).
In an enclosed harbor environment the solar array system will occupy a certain area, from a few hundred square metres to many thousands. Within that area the is no opportunity for waves to develop as the array has floating rafts which create a very complete wave break grid with gaps around two metres (but separated into manageable blocks). At the edge of the array a much more substantial set of wave breaks are required to prevent waves entering the array area. In shallow water this can be a conventional loose-rock-fill wall. In deeper water it might be best achieved using floating concrete pontoons (this has been done successfully for open sea in the past).
So the basic idea is to use the LSA where there are very low wave energies and to create such areas as required. Of course, if the array nearly fills the water area (of a dam for instance) there is no free water surface where waves can develop, so the problem will not arise.

3. APPENDIX 3 - LSA SYSTEM COST

An estimate for production at a small scale of about 1MW per year, in US dollars.

- **Available Energy:** The approximate energy available from a concentrator PV system is the product of the direct insolation (900 W/m^2 max) with the optical transmission (0.7 – 0.8), and the PV cell efficiency (0.16 - 0.21). The optical transmission is the product of all optical components' transmission (0.96* 0.96 * 0.92 * 0.92 * 0.95 = 0.74 typical). If the cells are 0.19 efficient at 40 ^{0}C and the optical transmission is 0.74, the system will produce about 126 W/m^2, for an overall efficiency of 14% from the direct sun. Such a system seems feasible from the experimental results.
- **Materials** quantities required for a one square metre module producing 125W electrical output (in early stage of production- 10,000 units): (Masses determined from the CAD model)
    - *Photovoltaic cells*. With an area concentration of 80 (flux concentration of 60), the area of silicon is 10000 cm^2 / 80 = **125cm^2**.
    - Reflector/lens area 1m^2 or 10000cm^2 (113 cm diam.) of Acrylic plastic. Thickness 1.5mm average. Volume required is 10000 * 0.15 = 1500 ml. Mass at 1.2g/ ml is 1800g, **1.8 kg**. (Resin is US$2.2/kg, so material is $4)
    - *Outer layer* of Fluoropolymer is 50um thick (25um ea side). Area is 1m^2, or 10000 cm^2. Volume is 10000 * 0.005 = 50 ml. At 2.1g/ ml, mass is 50 * 2.1g/ ml = 105 g or **0.1 kg.** (Resin US$31/kg.) giving $3 material cost. Expensive fabrication is assumed, but may not be required.
    - *Concentrator moving structure of 6 kg is **$20**, plus PV container **$10.***
    - *Tracking, shared over ten collectors:*
        - *Tracking motors* (2 of) are about 10W motor driven geared pulleys, costing about $40 each in mass production. Total $80 over ten collectors or **$14** for each collector with linkages**.**
        - *Tracking electronics* module is about $20 or **$2** per collector.
    - *Raft float modules*, about 2 m * 2 m with 0.2 m * 0.1 m hollow plastic edges, **$20**, plus ten-collector shared anchor of 200 kg concrete & chain, $40 or **$4** per collector.
- **Components cost** (US$ per square metre of collector):
    - PV cells 125 cm^2 at $20 per 100 cm^2 = $25
    - Inter-unit wiring $10
    - Reflector/lens 1.8 kg at $10 per kg, cast = $18
    - Outer protective layer $20 (reducible)
    - Moving structure $20
    - Secondary lens and PV container $10
    - Tracking electronics and mechanism $18
    - Raft and anchorage $20 + $4 = $24.

Total cost for one square metre is US$145 for components, most of which could be called concentrator structure and mounting. In-field assembly cost is about $20, totalling $165. Cost per watt is 165/125 = $1.32/W$_p$ (or about 6 cents per kilowatt hour). This is for year two, when mass production is just beginning. Lower costs are likely with refinements and volume production. It is possible this cost could be halved over time.

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