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SPACE SOLAR ARRAYS

AND

CONCENTRATORS

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1. ABSTRACT

This paper presents some research activities conducted at the Centre Spatial de Liege (CSL) in the field of space solar arrays and concentration.

With the new generation of high efficiency solar cells, solar concentration brings new insights for future high power spacecrafts. A trade-off study is presented in this paper. Two different trough concentrators, and a linear Fresnel lens concentrator are compared to rigid arrays. Thermal and optical behaviors are included in the analysis.

Several technical aspects are discussed :

- Off-pointing with concentrators induces collection loss and illumination non uniformity, reducing the PV efficiency.
- Concentrator deployment increases the mission risk.
- Reflective trough concentrators are attractive and already proven. Coating is made of VDA (Aluminum). A comprehensive analysis of PV conversion increase with protected silver is presented.
- Solar concentration increases the heat load on solar cells, while the conversion efficiency is significantly decreasing at warm temperatures.

To conclude, this paper will point out the new trends and the key factors to be addressed for the next generation of solar generators.

2. INTRODUCTION

The increasing electrical power demand onboard telecommunication spacecrafts leads the solar generator industry to develop new types of solar arrays. Progress in the field of high efficient photovoltaic cells give new insights for the solar power generation, but those new elements also bring new constrains from both technical and economical points of view.

A general study has been initiated at Centre Spatial de Liège (CSL) in order to find out the state-of-the art in space solar generators and to identify enabling technologies and new concepts that may reach the achievement of new solar arrays able to satisfy the new power requirements. About 200 documents (papers, patents, datasheet, communications,…) are compiled.

The present study will point out the relevant concepts for short-term (2005, 15 to 20 kW) and mid-term (2010-2015, 30 kW) new generation of solar arrays.
Space solar concentration is one of the main topics that are addressed in this paper. Two main types of concepts will be investigated and compared to classical solar arrays. Finally, this trade-off study will highlight the advantages and drawbacks of several configurations.

3. ARRAY CONFIGURATION AND CONSTITUTION

On high power geostationnary (GEO) spacecrafts, the solar arrays are usually extended as 2 large wings that can reach a wingspan of 40 m for 15 kW class systems. Those wings are made of several arrays connected together by a hinge system. During launch, the stowed configuration requires a very compact arrangement in order to comply with the fairing dimensions.
The design of space solar arrays is mainly dictated by mass limitation. Basically, as shown in figure (1), a solar array consists in a honeycomb structure that supports an insulating layer and the photovoltaic cells. A cover glass mosaic is used to protect the cells from the space environment where radiations, atomic oxygen (AO), ionized particles can damage the cell itself, depending on the orbit.

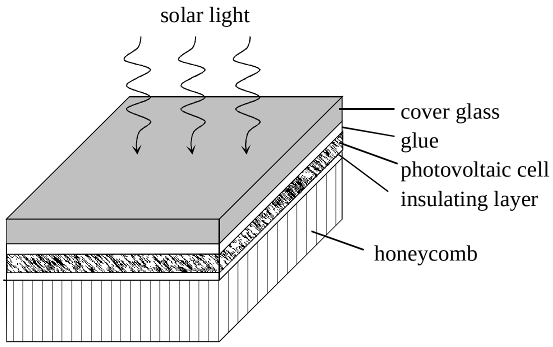


Figure (1): Schematics of a typical solar array

A mass breakdown is detailed in table (1) that points out the importance of the solar cells [5].

Array Components	Typical mass (kg/m²)
Cover Glass (GEO)	0.24
Cover Glass (LEO)	0.36
Circuitry, adhesives	0.61
Cells (GaAs/Ge)	0.83
Mechanisms/Deployment	0.39

Table (1): solar array mass breakdown

4. PHOTOVOLTAIC CELLS

Space PV cell technology is currently changing. GaAs-based cells are now mature and space qualified. High-eta thin Si cells still reach impressive performances when price, weight, maturity, and efficiency are balanced. From the compilation of manufacturer datasheet, table (2) summarizes typical performances of cells. Price is a major variable, not only depending on technology evolution. Manufacturer policy with respect to geographic location for getting into the market is influencing prices in a non predictable way. So, cost information is only representative.
Quadruple junction cells are not yet space qualified but that is an extensive research field, presently.

Cell Type	AM0 28°C BOL		Mass	Cost
	η (%)	P (W/m²)	(kg/m²)	($k/kg)
Si (200 µm)	13.5	182.3	0.55	20
High η Si (100 µm)	16.0	216.0	0.28	50
Double J (140 µm)	22.0	297.0	0.83	140
Triple J	25.0	337.5	0.85	150
Quadruple J	28.0	378.0	0.86	?

Table (2): Space photovoltaic cells and their expected performances

5. LIFE TIME AND AGING PARAMETERS

We will limit our discussion to GEO missions, which all have similar parameters, while LEO missions can encounter very specific conditions.
The parameters used in this study are summarized in table (3).

Mission parameters	
Life Time (Years)	15
Satellite Power (kW)	15
e^- radiation/year/cm² (1 MeV)	$1.4\ 10^{13}$
p^+ radiation/year/cm² (10 MeV)	$2.3\ 10^{10}$

Table (3): GEO mission characteristics

The equivalent radiation dose is about
1.25 10^{15} e^{-}/cm^2 (1MeV) for Si-based cells and
5.7 10^{14} e^{-}/cm^2 (1MeV) for GaAs-based cells.
A first estimate can already be evaluated for the loss of efficiency reached by the cells at the end-of-life (EOL). Table (4) shows that GaAs do withstand the GEO environment better than Si cells.

Cell Type	**Efficiency loss**
Si (200 µm)	24 %
High η Si (100 µm)	24 %
Double J (140 µm)	13 %
Triple J	13 %
Quadruple J	13 %

Table (4):Radiation aging of solar cells (EOL)

Those performances are resulting from a log dependency of the aging effect [6]:

$$\text{Loss} = C * \log(1 + \phi / \phi_0)$$

where C and ϕ_0 depend on the cell,
and ϕ is the radiation dose.

6. CONCENTRATION CONCEPTS

Solar concentration is a very wide subject that has been intensively developed for terrestrial applications. However using concentration in space is not straightforward, it needs detailed analyses and assessments. A lot of parameters need to be addressed: pointing sensitivity, deployment systems, thermal design, aging in space, compact stowed configuration, compatibility with deployment schemes, ...

Among all the concepts that have been studied, we focused our study on 2 main types of configurations: the V-trough reflectors and the Fresnel lens systems. Those are the only concentrator systems that are currently used in space.

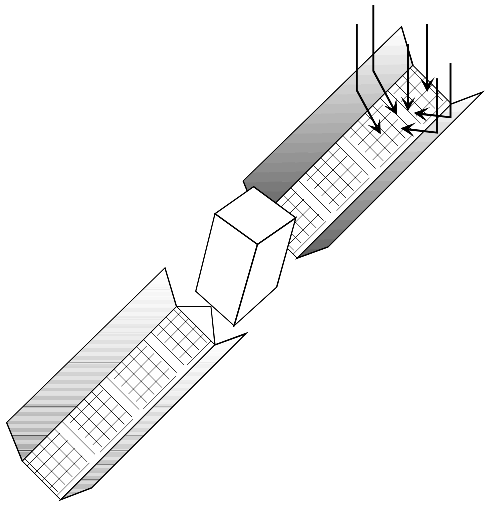


Figure (2): V-trough concept

V-trough concentrators are based on reflective surfaces that collect and redirect the solar radiation on the solar cells (fig. (2)). In practical applications, those systems can provide an additional effective collecting area similar to the cell surface. In that case, with ideal reflective coatings, the concentration reaches a geometric factor 2 along one direction. This concept has been studied and tested by several groups [1] [2] [3]. Several parameters can be modified, such as reflector width, reflector coatings, reflector orientation, ...
The other class of concepts is based on refractive systems, such as Fresnel lenses. They can provide high concentration factors. In the proposed example, the solar array is covered by a mosaic of Fresnel cells that concentrate solar light on cells that cover only part of the array (fig. (3)). Concentration factors of 10 can be reached with this concept.

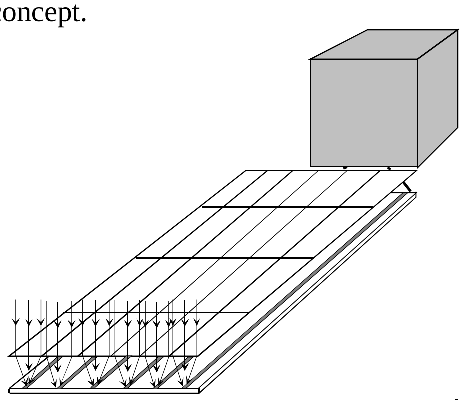


Figure (3): Fresnel concentrator concept

7. AGING EFFECTS WITH CONCENTRATORS

Concentrators have an ideal concentration factor defined by geometrical considerations. When optical efficiencies are taken into account, the real concentration factor is reduced. This loss will increase once the system will be exposed to space environment.
V-troughs behave better, but concentrated UV will damage cover glass and/or adhesives.
Fresnel lenses need protection on top of the lens that could replace the cover glasses. Aging will opacify the lenses and will reduce their efficiencies. Aging of cells under high concentration (and high temperature) also needs to be investigated.

8. OFF-POINTING SENSITIVITY

The off-pointing sensitivity is an important parameter for concentration in space applications. When in orbit, spacecrafts usually provide an accurate pointing along one axis (typically ±2 arcdeg), while a wide angular pointing range must be expected along the other axis (±23 arcdeg for seasonal variations).
Figure (4) shows the off-pointing dependency of a typical V-trough array (C_{geom}=2) compared with the cosine law which is the only dependency of rigid array. When off-pointing occurs, non uniformity of flux collection/concentration produces electric current mismatch. The current collection is dropping more dramatically than the solar flux collection. The power management must be optimized to reduce this effect which does not exist in arrays without concentration.

Fresnel lens behavior is not as easy to predict since it depends on a lot of parameters. Actually, the off-pointing requirement is the starting point of the optical design of Fresnel lens concentrator. Typical results are published in the literature [4]. The off-pointing is fitting with the satellite tracking capability (with some margins).

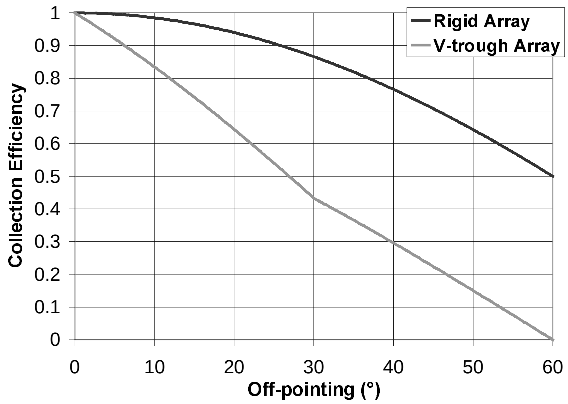


Figure (4): Off-pointing behavior of 60°-V-trough reflector array (in the direction of concentration) and rigid array.

A 60°-V-trough concentrator (C_{geo} = 2) will still collect 90% of the flux for a pointing error of ±6 arcdeg. The solar flux is fully reflected out (and lost) when off-pointing is larger than 60 arcdeg. Pointing error in the perpendicular axis induces a cosine law similar to the rigid array without concentration.

9. THERMAL ISSUES

Introduction

With the introduction of efficient, lightweight solar arrays, heat dissipation has replaced power generation as the limiting design factor in today's communication satellite payloads.
With solar concentration, the absorbed solar heat flux is significantly increased. It can induce severe drawbacks as efficiency reduction, thermo-mechanical distortion of the array, or even internal damages to the array constituents.

Photovoltaic Efficiency

Cells efficiency is significantly decreasing when the temperature increases. Since concentration is responsible for additional heat inside the cell, one of the drawback of concentration is the conversion efficiency loss. Table (5) gives an estimate of the cell efficiency at 58°C (~rigid array) and 100°C (~concentration array). GaAs-based cells depict a lower loss which indicates that it is better adapted to concentration.

Cell Type	η (%)		
	28°C (Ref.)	58°C (C = 1)	100°C (C~1.75)
Si	13.5	11.9	9.7
High η Si	16.0	14.2	11.6
Double J	22.0	20.7	18.8
Triple J	25.0	23.3	20.9

Table (5): Typical PV conversion efficiencies with respect to cell temperature

Thermal behavior

Basically, the thermal behavior is dictated by the balance between the fraction of infrared solar flux that is thermally absorbed by the substrate of the cell and the radiating capability of the array toward cold space.
GaAs cells commonly use Ge substrate that has a higher solar absorptivity than conventional Si cells with Si substrate. For this reason, GaAs arrays are naturally warmer than Si arrays.
Concentration becomes meaningful when used with high efficiency cells. Therefore GaAs cells are very good candidates, as well as new multi-junction stacks. Even if they are warmer (Ge substrate and concentrated solar flux), their efficiencies show a low temperature dependence (see table (5)).
Table (6) shows the array parameters used in our trade-off with the calculated cell temperature. Foil reflector is close to the design of the Hughes HS702 solar array [2]. Rigid reflector array is inspired by the Astro Aerospace design [3]. Linear Fresnel lens is deduced from the Entech/Scarlet II array [4].

	No reflector	**Foil reflectors (VDA type)**	**Rigid reflectors (VDA type)**	**Linear Fresnel**
Concentration	1	~1.5 (diffusion)	~1.76	~7.14
Mass	π	+ (lighter)	-	-
Array temperature	+50°C	+87°C	+101°C	+100°C
Cooling		Reflectors unable to cool cells	Reflectors can cool cells	Cells at rear side of panel

Table (6): Typical array parameters

The ratio of diffuse/specular reflection directly affects the concentration and the thermal behavior. This effect is illustrated in figure (5) that indicates the average temperature that will reach the overall panel wearing the cells. For C = 1, one can find the average temperature of a standard GaAs solar array without concentrator. Those values do not account for local warmer/colder regions that will arise with conductive effects in the array.

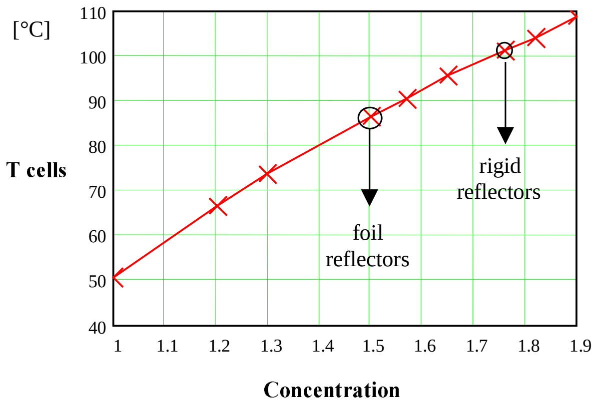


Figure (5): Average temperature of the solar array for different concentration factors

The rigid reflectors reach a quite low temperature (~ -80°C). Therefore they can be conductively linked to cool the panel and cells. This effect is shown in figure (6) where the cell temperature is decreasing when the conductive link with the reflector is increasing. This is to be compared with the foil reflectors that have a lower concentration efficiency (diffusion) and no possibility to cool the cell.

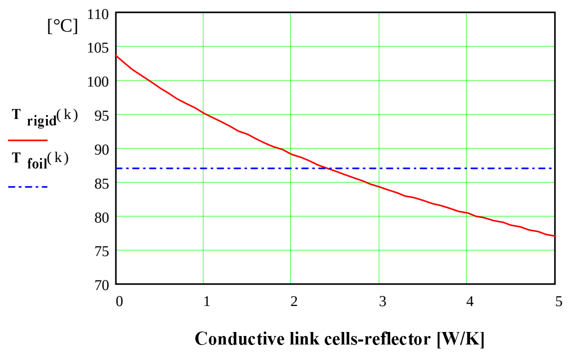


Figure (6): Average temperature of the solar array

10. COST BALANCE / TRADE-OFF PENALTIES

The cost of a solar panel is related to the cost of each part. In addition, the launch cost is important to take into account. It is mainly related to the solar array mass and volume (stowed configuration). The volume has to fit in the fairing anyway and it is not obvious that cost will be lower if volume is reduced. A mass penalty can be introduced to enhance the advantage of using a high-efficiency lightweight array [5]. Launch price ($k/kg) is variable because it depends how the reduced mass will be used. Some trade-offs [7] mentioned the ability to introduce an additional payload to the spacecraft which results in a very efficient panel cost reduction.
When deployed, the large panel surface induces a need for attitude control. Surface penalty results from low efficiency panel with high fuel consumption (additional mass) [5].

Anyway, future solar arrays will need to be cheap even without introducing system level cost penalty/gain. The solar panel cost must be evaluated without this stratagem and mass/surface penalty are given for information.
Table (7) shows the mass and price estimate of four types of solar arrays that we analyzed, based on several publications.

Array type	Mass (kg/m²)	Cost ($k/m²)
Rigid Panel	2.7	41.3
V-Trough (foil)	2.9	46.9
V-Trough (panel)	3.6	61.9
Linear Fresnel	2.8	50.5

Table (7): Mass and cost estimate of four solar arrays (without cell mass and price).

The cell mass and cost (table (2)) has to be added for a complete mass and cost evaluation.

11. FIGURE OF MERIT

The easiest way to characterize the solar array is probably the specific power. Figures (7) and (8) give the specific power of the arrays under analysis (15 kW / 15 years).

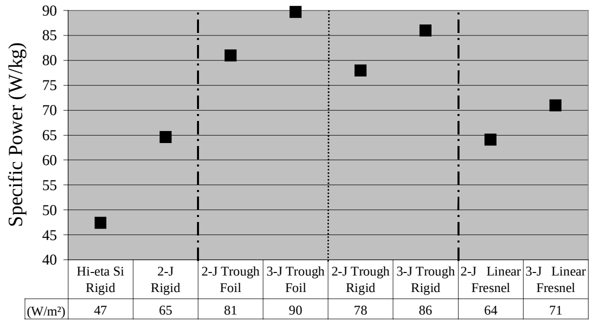


*Figure (7): Specific power (**W/kg**) of several solar array concepts (EOL)*

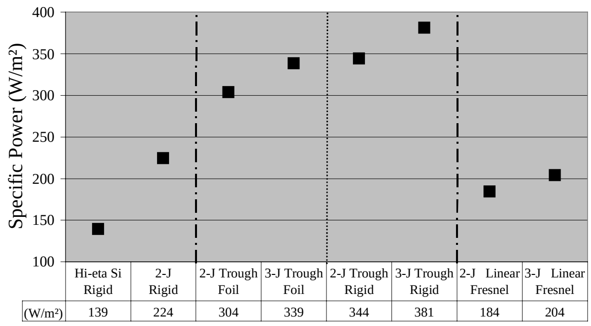


*Figure (8): Specific power (**W/m²**) of several solar array concepts (EOL). V-trough area is the area in the stowed configuration.*

High specific power of the V-trough explains why they are intensively studied. Of course, the cost is not concerned yet. Figure (9) shows the cost estimate of the solar panel manufacturing.

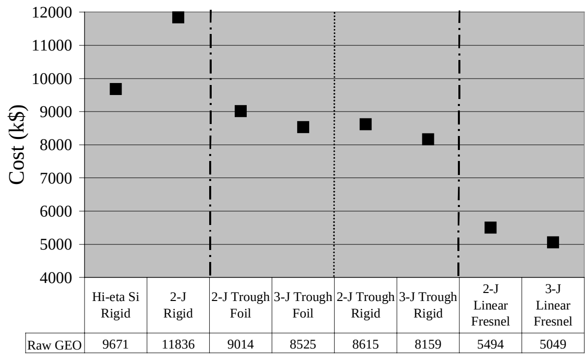
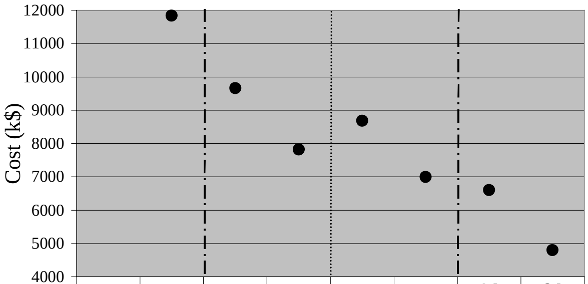


Figure (9): Raw cost of solar arrays

Clearly, a rigid array with GaAs cells is not cheaper than a Si array. Concentration reduces the cost of the expensive high efficiency cells.

Both kinds of V-trough panels are competitive with the Si rigid panel. The linear Fresnel concept is very attractive since it uses less cell area (C > 7). Obviously, the cost analysis does not take into account the R&D and qualification of new concepts, which would dramatically increase the cost of Fresnel lens arrays.



	Hi-eta Si Rigid	2-J Rigid	2-J Trough Foil	3-J Trough Foil	2-J Trough Rigid	3-J Trough Rigid	2-J Linear Fresnel	3-J Linear Fresnel
Adj GEO	15571	11836	9663	7818	8683	6989	6603	4798

Figure (10): Adjusted cost of solar arrays (mass+area penalty/gain are included). Reference is 2-junction / rigid array.

If we consider mass and area penalty, the data of figure (9) become differently balanced. That is illustrated on figure (10) where tandem GaAs-based cells on rigid array (C = 1) is used as a baseline.
Rigid arrays are clearly more expensive than concentration arrays. A comparison of figures (7)-(8) with figures (9)-(10) proves that the specific power is not the most realistic design goal. For instance, linear Fresnel lens array depicts a bad specific power but the lowest cost.

A valid figure of merit should include the cost of manufacturing, mass and surface, R&D, space qualification and risks.
It is clear that V-trough concentrators offer a cost efficient alternative to rigid arrays. They require less R&D and qualification efforts than Fresnel lens arrays. Additional deployment mechanisms and risks are also limited : if the deployment fails, the solar array would still deliver 60-70% of the nominal power (C~1.5 ∏ C = 1).
Fresnel concentrators are still very promising for the future but a lot of work is still to be accomplished to demonstrate the validity in the space orbital environment (very different than the deep space environment of Scarlet II [4]).

12. IMPROVEMENT OF REFLECTOR PERFORMANCES

In the field of V-trough concentrator, the use of enhanced metallic coating instead of VDA (Al) is questionable. Silver offers a higher reflectivity but the coating does not resist to AO. Protective coating need to be over-deposited. The most common product is SiO_2 but it slightly reduces the reflectivity. However, the protective coating thickness can be optimized to retrieve the initial Ag reflectivity in a large spectral range. In this section, we give results of calculation of reflectivity of Ag and Al film at 60° incidence (V-trough configuration with C_{geom} = 2). The Al film is self-protected by natural oxidation with 5 nm Al_2O_3 over-layer and the Ag film is protected by a specific over-coating of 160 nm SiO_2. Aluminum oxide has only a small effect in the visible range. It decreases reflectivity in the UV range (large effect in the VUV only).
Figure (11) gives the reflectivity of both films with unpolarized light.

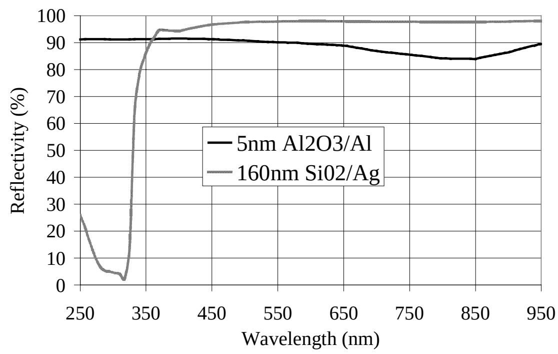


Figure (11): Comparison of Al and Ag reflectivity at oblique incidence (60° w.r.t. reflector normal)

In order to determine the power conversion gain that would result from using silver instead of aluminum, the cell response and the solar spectral irradiance [8] must be considered. The response of a multi-junction cell get cut-off at about 350 nm and 900 nm. The solar spectrum has a peak value around 450-500 nm with a large extend to the IR.

The integral calculation of
reflectivity **x** *solar irradiance* **x** *cell QE*
within the spectral range of figure (11) allows for a power conversion comparison between both types of reflective films.
An Ag reflector increases the conversion by 9.5%.
Within the geometric configuration of the V-trough (with 2 reflectors and direct light simultaneously), it still produces a net increase of 4.5%.

As explained in section 7, another drawback of concentration is the radiation concentration. In the V-trough configuration, the UV radiation is efficiently concentrated. From figure (11), it is obvious that the use of an Ag reflector could significantly decrease the UV concentration. Based on the same integral calculation, we deduce the UV flux incident on the cell cover glass in the V-trough geometry. Three integration limits are shown on table (8).

Integration wavelengths	250 - 400 nm	250-350 nm	250-300 nm
Al reflector irradiance	224 W/m²	108 W/m²	27 W/m²
Ag reflector irradiance	192 W/m²	76 W/m²	16 W/m²
Ag/Al **UV Reduction**	14%	30%	43%

Table (8):UV radiation on cell cover glass in the V-trough configuration

The near UV is still concentrated but UV radiation at $\lambda<330$ nm are very well reduced, compared to Al coating.

The power conversion increase and the UV concentration decrease of Silver coating show that it is probably a good candidate for next generation V-trough concentrator, even if the price is significantly higher.

13. CONCLUSIONS

The trade-off discussed in this paper defines the parameters to evaluate whether a given concept (cell type, concentrator) becomes appropriate.

We clearly give the evidence that low concentration is cost effective with respect to present rigid panel.

Among the two classes of concentrators that were considered in this study, there are specific reasons to select one or the other. In table (9), we list their advantages and drawbacks.

	V-trough	**1-D Fresnel**
+	- no thermal gradient - reflectors are radiation resistant - wide pointing acceptance angle	- large heat radiating surface - Medium concentration (C~5-15) is possible
-	- small heat radiating surface - incompatible with 2-D deployments schemes - only small concentration ($C_{geom} < 2.5$) - UV concentration on cover glass	- mass penalty - thermal gradients - thicker arrays/focus deployment - possible radiation damages - small pointing acceptance angle - low concentration is not desirable.

Table (9):Advantages and drawbacks of Fresnel and V-trough concentrators

V-trough is now on the market. Fresnel concentrator will potentially get a lower cost. Since the array concept is radically different, the qualification need more investigations before entering the market. It is a promising concept for mid-long term solar arrays only.

14. AKNOWLEDGMENTS

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