The definition of a low cost CPV design based on known and industrially accepted processes

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Abstract: at Philips Applied Technologies new concepts for concentrated photovoltaic systems have been compared with respect to production costs (€/Wp) and time to market availability. Two concepts have been chosen and elaborated in more detail specifically focusing on the feasibility for manufacturing on large scale using low-cost production methods. In the presentation an analysis of cost aspects is presented to show the rationale of the choices made. Results of optical and thermal simulations as well as an overview of relevant competences within Philips Applied Technologies are given.

CPV economical viability scout

For economic comparison of a CPV system with conventional PV systems a cost model has been developed, which provides insight in the costs per Watt peak (€/Wp) and the cost breakdown of these systems.
The analysis has been limited to CPV systems using silicon PV cells. High concentration PV systems with more efficient but also more expensive PV-cells from other conversion materials were out of the scope of this investigation.
A series of parameters has been taken as input for the calculation, e.g. Si-feedstock price, cell efficiency, PV-cell dimensions, CPV concentration ratio and the number of optical elements. Interfacing to the electrical grid has been left out to enable comparison between conventional PV solutions and possibly innovative CPV solutions.

Cost model PV module (reference model)

For a conventional PV module consisting of 36 H-cells the calculated total cost given the assumed realization process is 2.17 €/Wp ±0.20 €/Wp. The cost breakdown is shown in figure 1:

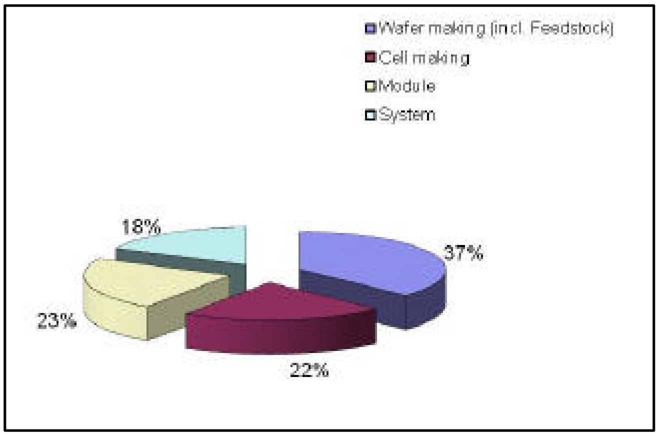

Fig. 1: cost break-down of a conventional PV system

Feedstock material and the wafer making process make up for the majority of the cost of a standard module. The remaining costs are spread over cell- and module making and system installation.

If the parameters in the spreadsheet are varied by +/-10% one can define the 'worst offenders' – the parameters which have the highest impact on the cost per Wp, see
figure 2.

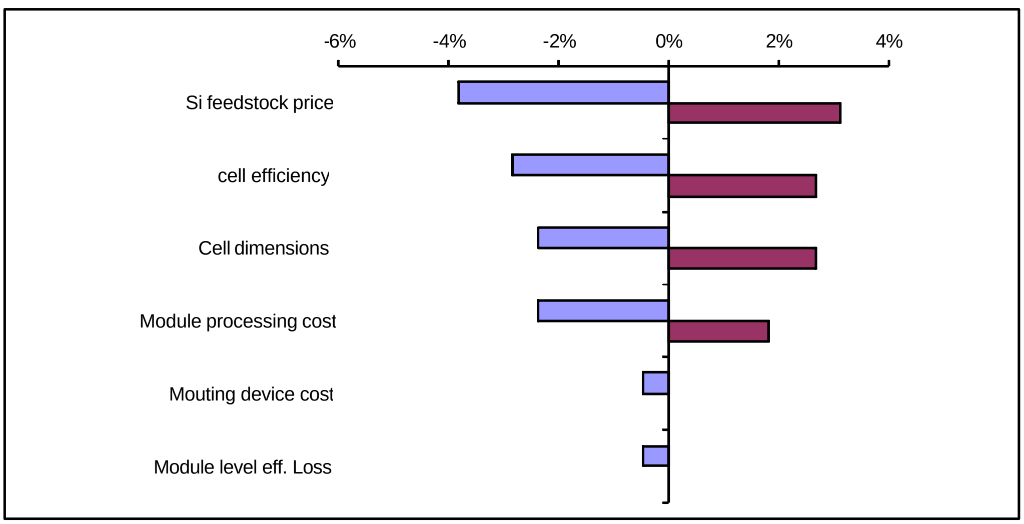

Fig. 2: Tornado diagram; effect on €/Wp for PV when varying parameters +/-10%

Clearly Si-feedstock pricing and cell efficiency have the largest impact on €/Wp.

Cost model CPV module

For a CPV module with Fresnel lens for 10x concentration the cost model indicates a cost-price comparable to conventional PV modules. The cost breakdown (figure 3) shows that the main cost driver has been shifted away from wafer costs to module and system setup and the price of optical elements.

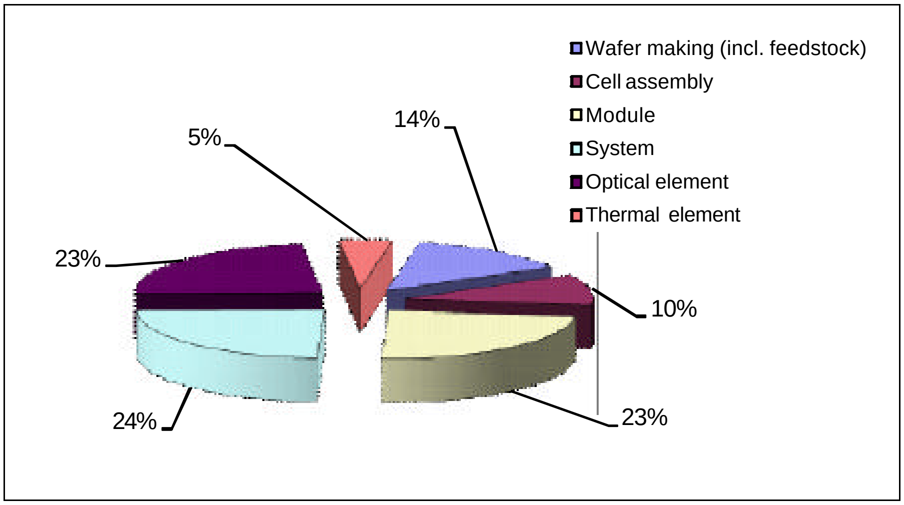

Fig. 3: cost break-down of a 10 x CPV system

The Tornado diagram (figure 4) indicates that (for a fixed concentration ratio) cell dimensions have a big impact on module costs: larger units are more favorable with respect to costs per Watt peak because of lower assembly costs. The second most important parameter is cell efficiency.

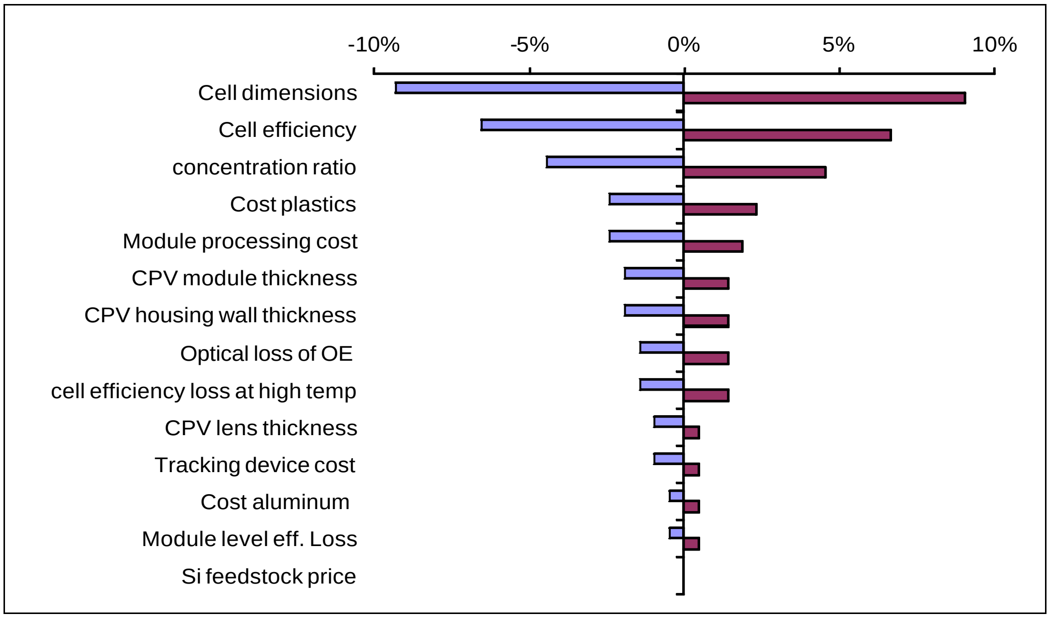

Fig. 4: Tornado diagram; effect on €/Wp for 10x CPV when varying parameters +/- 10%

Comparison CPV versus conventional PV systems

To elaborate the potential of CPV systems PV and CPV have been compared for three scenarios:

- basis case scenario – parameter settings as-is
- worst case scenario – setting with all parameters varied with 10 % in the unfavorable direction
- best case scenario – setting with all parameters varied with 10 % in the favorable direction

Figure 5 shows that although PV and CPV systems are similar with respect to €/Wp for the as-is settings CPV has the potential to beat conventional PV systems if system parameters can be improved. For CPV systems module costs of 1.50 Euro per Watt peak seem possible.

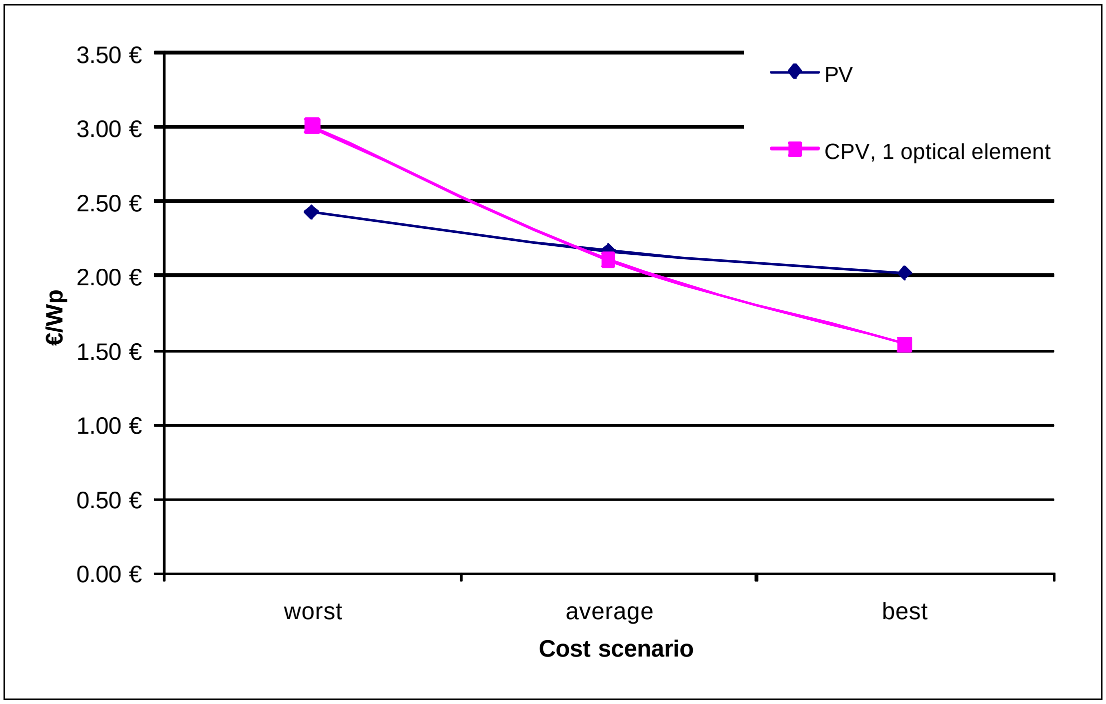

Fig. 5: comparision of CPV and PV systems

Conclusions from economical analysis

- CPV systems can compete with conventional PV systems with respect to €/Wp costs.
- For CPV systems the main cost drivers are the optical elements, costs for assembly and cell efficiency. The design of a CPV system should focus on these subjects.
- CPV systems need a careful thermal design to avoid efficiency losses due to heating up of the PV cell.

Description of CPV designs

Two designs with moderate concentration ratios of 8-10 times have been elaborated. Both designs essentially make use of elements with linear geometry for high efficient roll-off production and minimum assembly effort. The concepts can be realized within a short time to market and with standard industrial processes.
Demonstrators of both designs will be ready at Philips Applied Technologies in April 2009.

Fresnel lens design:

Figure 6 shows a cross section through our linear Fresnel lens design: the lens refracts light in the central area and focuses light by means of total internal reflection at the edges. This shape has been chosen to minimize optical losses due to back reflections, final surface slopes and final edge radii. Shape tolerances of ±0.1 mm for low frequency lens deformations and ±5 μm for facet errors are reasonable values for production. A tracking accuracy of ±1.5° has been taken into account.
Given these tolerances and production restraints the optical efficiency of the Fresnel lens system is 80 %.

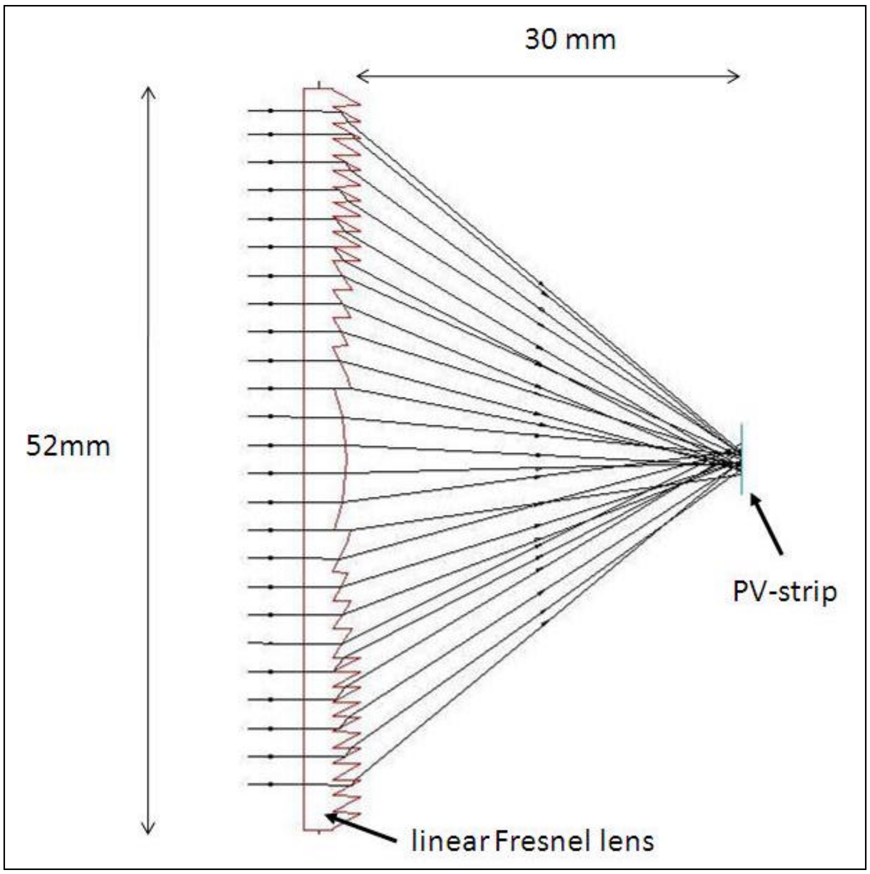

Figure 6: optical design of Fresnel lens for CPV.

Parabolic mirror design:
Figure 7 shows our design with parabolic mirrors. In contrast to many other parabolic troughs the PV strip is not opposite to the mirror but at its bottom, making thermal management much easier.
Shape requirements are low in longitudinal direction of the strips but should be met carefully along the parabola: low frequency deformations (half a

sinus across parabola) must be below ± 0.1 mm. Surface roughness should be limited to a full width half maximum scatter angle of 1°.
Taking product tolerances and 1.5° tracking accuracy into account the optical efficiency of the parabolic mirror system is 80 %.

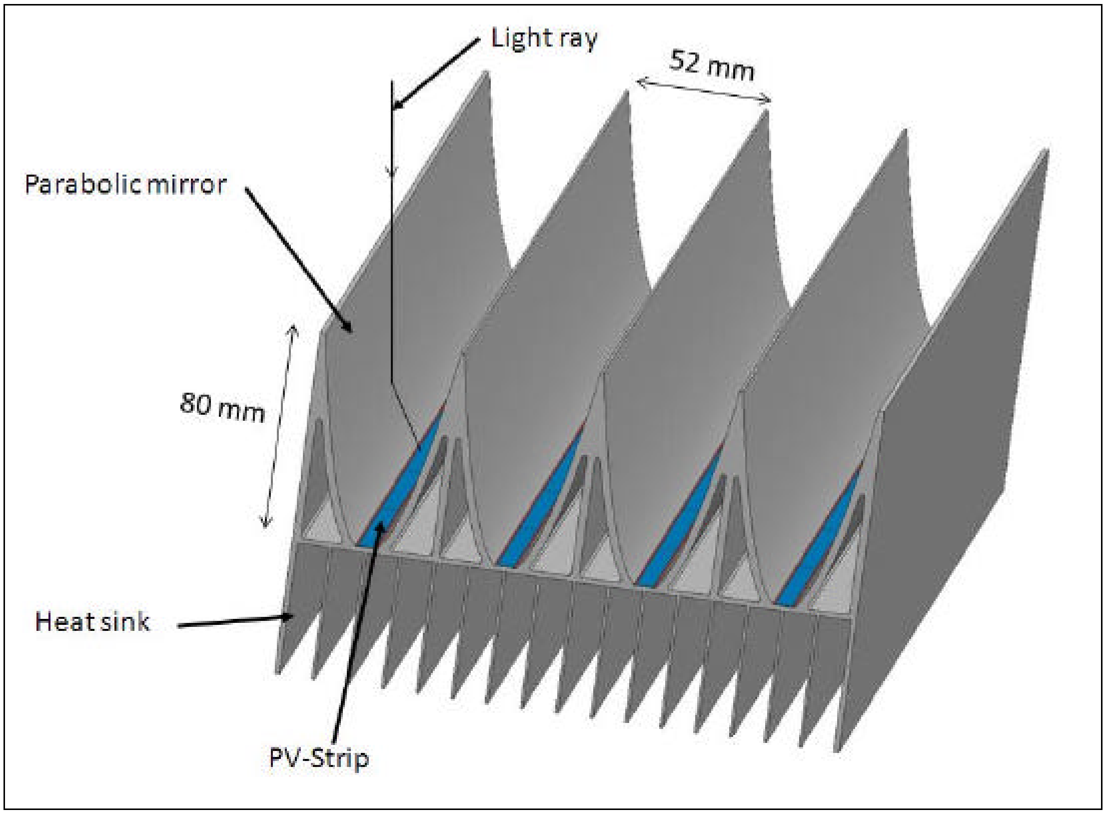

Figure 7: design of parabolic mirror concept for CPV.

Thermal design
The efficiency of Si cells is reducing significantly when the cell temperature increases. The laboratory test to determine the €/Wp performance is very short leading to a minimum heat up of the cell because of the thermal inertia. In real situations like a very sunny or a windless day the considerable heat up of PV systems with a poor thermal design will experience a dramatic loss of efficiency and thus a disappointing output of electrical energy. Because of the energy concentration in CPV systems the thermal design requires even more attention to prevent efficiency loss using Si cells.

Without active cooling the main heat transfer mechanisms for a CPV system on a windless day are by radiation and natural or free convection, both mechanisms are of the same order of magnitude. For radiation cooling attention should be given to the infrared emissivity value of the surfaces. The convection can be improved by increasing the heat transfer area using heat fins. When the gap distance between the heat fins is very small the effective heat transfer will also be small because the development of an air flow between the fins is limited (see figure 8).

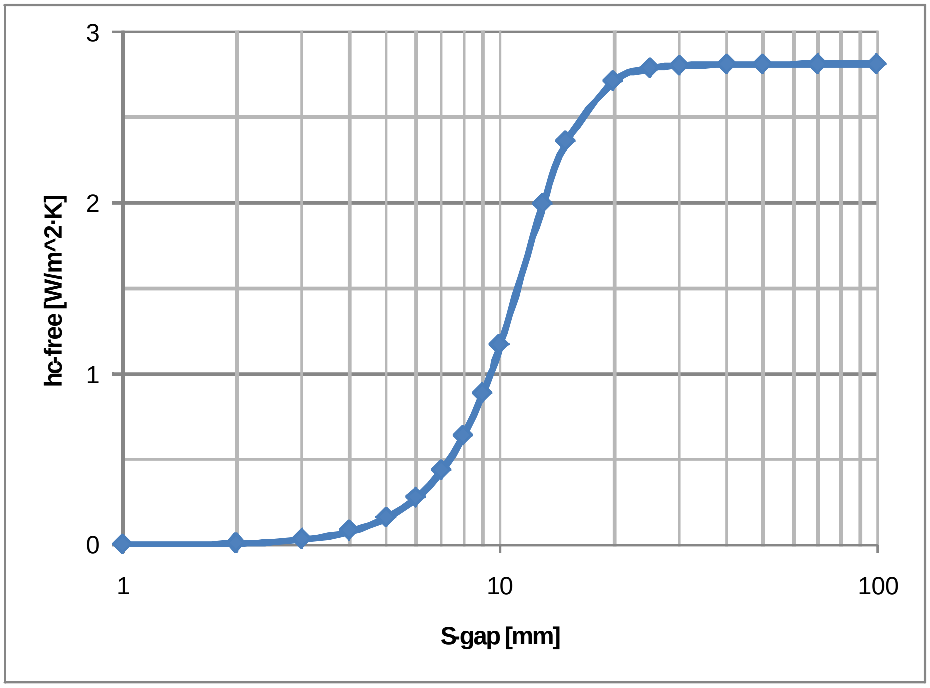

Fig. 8: natural convection heat transfer coefficient as function of the distance between vertical parallel plates (length 1.2 m)

On the other hand a large distance between the heat fins will lead to a limited increase in heat transfer area. By combining both effects in one graph the optimal fin distance can be selected (see figure 9).

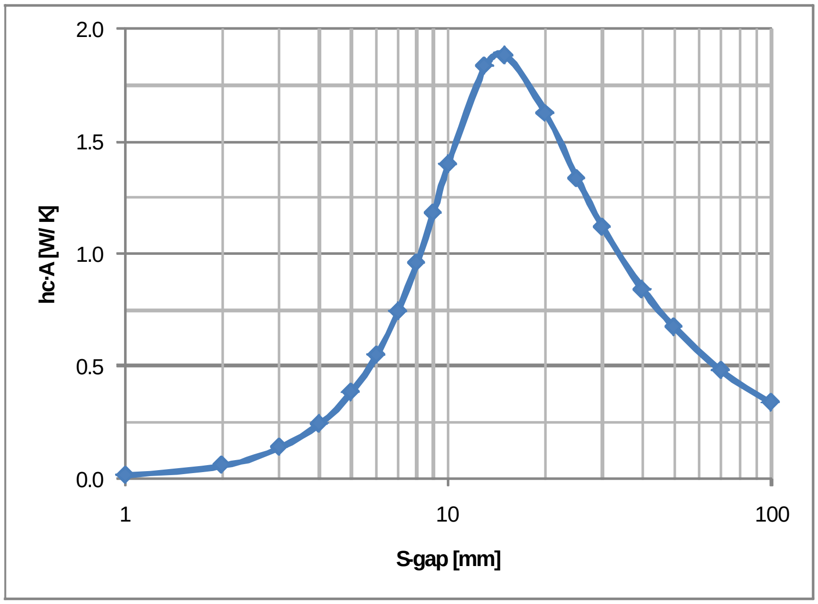

Fig. 9: effective heat convection as function of CPV heat sink fin pitch

Figure 9 illustrates that for this design an optimal fin distance of 13 mm should be selected. Using FEM analysis the temperature distribution of the CPV heat sink and cell can be calculated for several values of fin lengths and wind speeds. An example is depicted in figure 10.

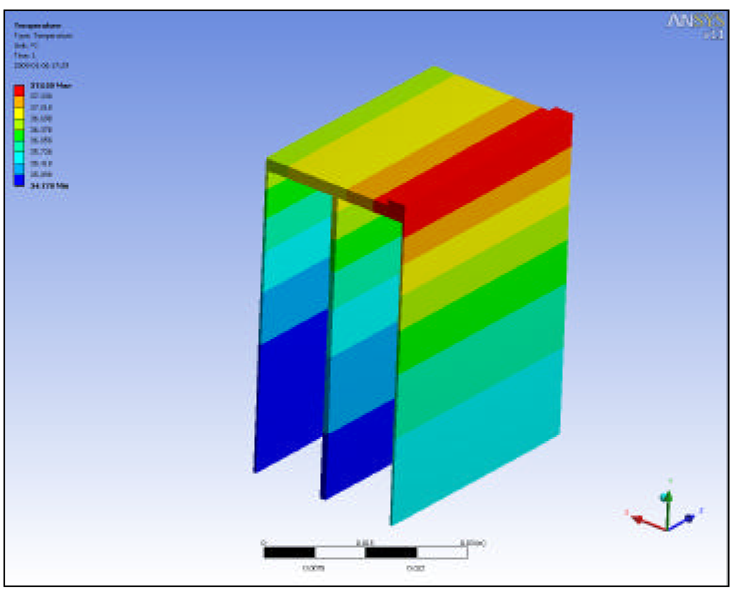

Fig. 10: temperature distribution of the CPV heat sink with 8x concentration factor and 50 mm fins (because of symmetry only part of the total design is modeled).

Combining this thermal calculation with the Si cell efficiency temperature sensitivity the efficiency loss as function of the wind speed and fin height can be determined (see figure 11). This figure illustrates that for a fin height beyond 50 mm the effect on the efficiency of the design is limited.

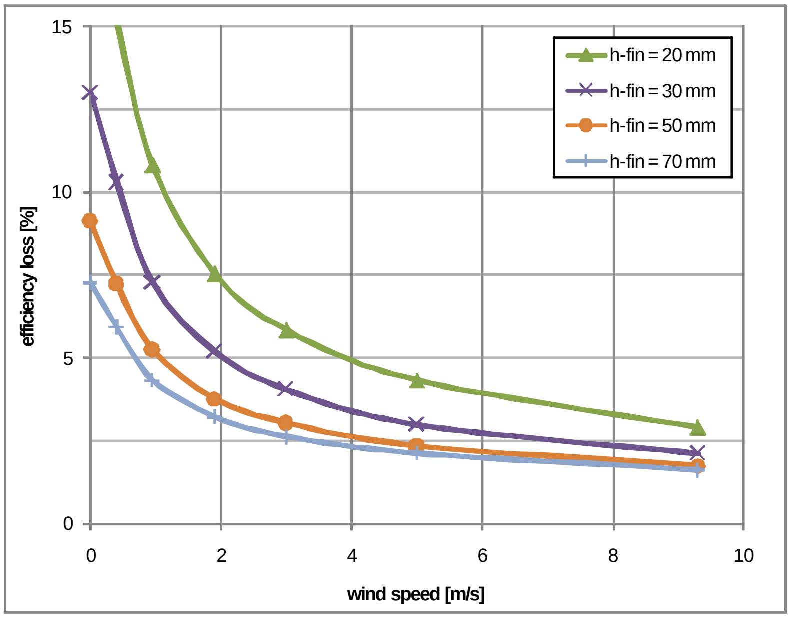

Fig. 11: efficiency loss as function of wind speed around the CPV installation for several heat sink fin height

Tracking system design

Since in CPV systems only the direct light from the sun is used effectively, a tracking system is required. For focus point CPV designs a 2 DOF tracking system will be required to keep the concentrated light beam onto the cell. For a linear system a 1 DOF tracking system can be used. Besides the costs also the possibility to create a louvered system is a major advantage of a 1 DOF tracking system, since this requires only a limited amount of moving space. A louvered system can be mounted onto a pitched roof or even a vertical wall. As indicated by figure 12 the panel shift of a louvered system limits the angle of rotation because of shadow effects. These shadow effects will only occur in the early morning and late evening when the sun intensity is limited. For the location of Eindhoven the effect of this rotation limit on the direct light incident energy on the panel has been calculated using the sun positions and typical amount of direct light intensities throughout several typical days of the year. In figure 13 the fraction of the direct light energy of a 1 DOF tracking system w.r.t. a 2 DOF tracking system is depicted as a function of the rotation limit. This figure illustrates that at Eindhoven a 1 DOF tracking system will typically have 5 to 6 % less sun energy incident compared to a shadow-less 2 DOF panel.

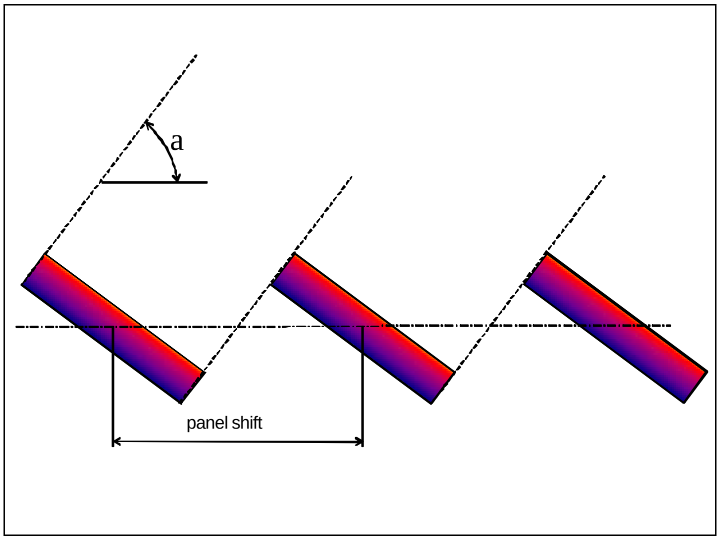

Fig. 12: shadow effect of louvered system leading to rotation limit

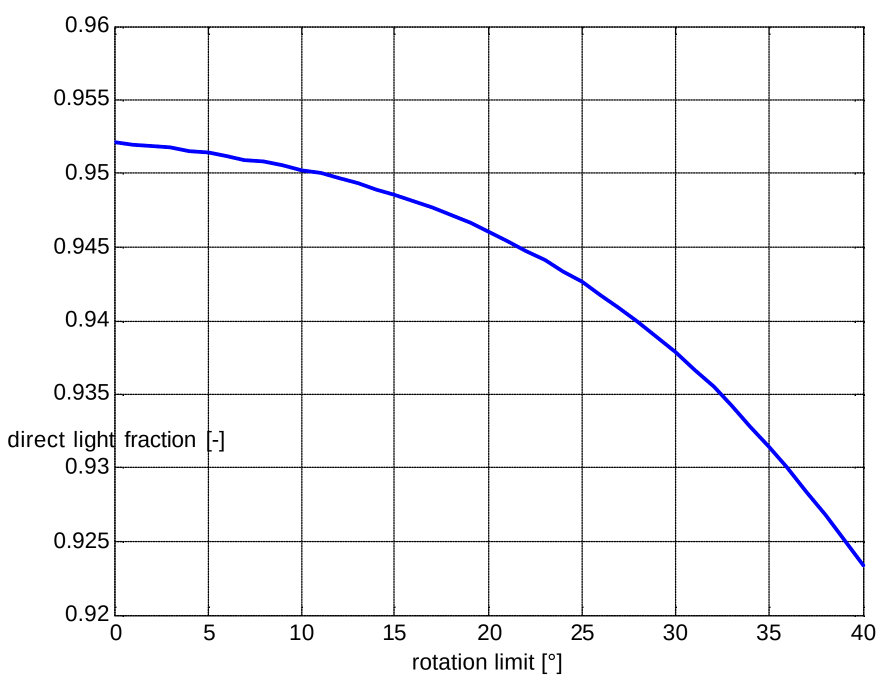

Fig. 13: fraction of total incident energy of a 1 DOF tracking system as function of the panel rotation limit.

Mass production

For low cost and reliable mass production standard industrial processes and materials need to be chosen. At Philips Applied Technologies we have experience from customer projects in all product creation phases: starting from concept designs via engineering to production ramp up. We have a broad competence portfolio with among others competences in:

- Wafer processing
- Cell processing (e.g. doping, drilling, ablation, laser processing, screen printing)
- Product processing (e.g. injection molding of Fresnel lenses, encapsulation, interconnections)
- System design (e.g. thermal, optical, mechanical modeling, experimental verification)
- Reliability testing
- Industrialization (e.g. identifying cost down opportunities, industrial consultancy)

For the CPV concepts described in the preceding paragraph the costs for mass production have been analyzed in detail using an MMM-cost model (man, machine, material). For production of 100,000 m^2 of Fresnel lens systems the costs excluding tracking device and mounting are 1.00 €/Wp ± 0.10 €/Wp. For the parabolic mirror design the costs would be 1.20 €/Wp ± 0.12 €/Wp. The main part of the costs - 78 % - is caused by material costs. Nevertheless there is some room left for further improvement.
Taking into account that the costs for a tracking device and for mounting are approximately 0.53 €/Wp these numbers are in good agreement with the results of the economic viability scout.

Conclusion

Two designs of CPV systems with moderate concentration ratios have been analyzed with respect to optical and thermal features, tracking device design, possibilities for efficient and short time to market mass production and last but not least with respect to production costs in Euro per Watt peak.

According to our analyses mass production of CPV systems with production costs of approximately 1.50 €/Wp (Fresnel lens design) respectively 1.70 €/Wp (reflector design) seems possible.