Design Concepts for a Spectral Splitting CPVT Receiver

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Abstract

The technology of combined photovoltaic and solar thermal energy conversion (PVT) can have certain advantages compared to separate solar systems, if the corresponding PVT collectors are utilized in proper applications. However, if the considered heat sink requires temperatures beyond 100°C, the conventional PVT collector would not be suitable anymore, as thermal absorber and PV cells are thermally coupled in typical PVT systems. This would lead to an undesired temperature level in the PV part that makes the electrical energy conversion highly inefficient. This discrepancy between the optimum operating temperatures of the thermal and the electrical part becomes even more significant for concentrating PVT (CPVT) collectors. The approach of Spectral Splitting can provide a possible solution for this challenge. The basic principle is to split the solar spectrum into several wavelength ranges and impinge the PV cells only with the specific spectral range of highest conversion efficiency. The remaining parts of the spectrum are absorbed in the thermal receiver part and directly transformed into heat. Thermal decoupling between electrical and thermal receiver parts supports both the thermal and the electrical conversion efficiency. This presented paper describes the development of novel design concepts for the implementation of Spectral Splitting in a CPVT receiver for a linear Fresnel collector. A quantitative assessment revealed two favorable designs with different PV technologies that will be used for further investigations.

Keywords: Concentrating solar, Spectral Splitting, CPVT, Fresnel collector

1. Introduction

PVT collectors combine both solar technologies Photovoltaics (PV) and solar thermal energy conversion (ST) in one single device. In most of the current PVT concepts, the PV cells are thermally coupled to a thermal absorber that extracts a part of the cells´ waste heat, which is transferred to a thermal storage or a heat sink by the hydraulic system. If operated in the optimum temperature range, PVT collectors can provide several advantages compared to separated systems, like an increased PV-yield due to the reduced average temperature of the PV cells, increased total energy yield per m² of roof area and reduced installation costs. On the other hand, the essential thermal coupling between the two systems implicates the challenge that conventional PVT collectors are hardly suitable for heat applications with a temperature demand above approx. 80°C. The PV cells work very inefficiently in this temperature range and some constructive parts like the cell encapsulation or the back sheet reach their specification limits (Zenhäusern, 2017).

If PVT collectors shall be applicable to support thermal industrial processes with temperature requirements above 100°C, concentration of the solar irradiance is essentially needed. However, a thermally coupled construction like the conventional PVT collectors is not sensible for this case, due the above-mentioned discrepancy between the PV efficiency and the thermal output temperature. Nevertheless, the concept of Spectral Splitting can provide an approach to work on this technical challenge.

2. The Concept of Spectral Splitting

The central idea of Spectral Splitting is to irradiate on the PV cells in a PVT collector only a selected range of the solar spectrum that can be converted into electricity with maximum efficiency. This is the segment of wavelengths where the spectral response SR (resp. the external quantum efficiency EQE) of a PV cell reaches its maximum, meaning that the incident photons have suitable energy in order to generate electron-hole-pairs efficiently, e.g. without causing relevant heat losses within the cell due to thermalization. The remaining parts of the spectrum containing photons with less-suitable energy for the electricity generation are converted into thermal energy directly. On the one hand, this is the infrared range (IR) of the spectrum, where the photon energy does not exceed the bandgap energy of the PV. On the other hand, the photons´ energy in the ultraviolet

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range (UV) is far beyond the bandgap energy so that it can only be converted partly into electricity. Figure 1 illustrates this described wavelength separation for an exemplary configuration, where the spectrum in the range of 700 nm to 1100 nm is transmitted to crystalline Silicon (c-Si) PV cells, while all other parts of the incident solar irradiance are converted into heat by a thermal absorber. The ASTM G173-03 Reference Spectrum, AM1.5, receiving surface at 37° tilt, published by NREL (no date) is used in this figure. The SR curve of c-Si is an exemplary one and was extracted from Quaschning (2011).

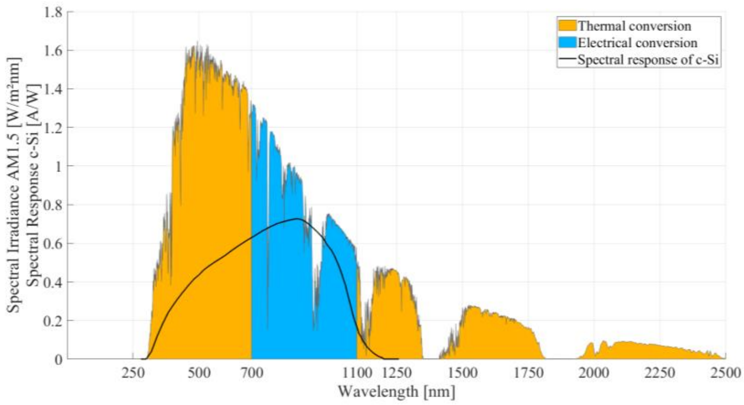


Fig. 1: Wavelength separation in an exemplary Spectral Splitting configuration

Imenes and Mills (2004) described the Spectral Splitting concept and provided a thorough review of different constructive approaches that significantly depend on the considered concentration system as well. However, the research work presented in this paper only focuses on the development of a compact CPVT receiver for a linear concentrating Fresnel collector in order to deepen already gained experience in this field during previous projects (Everett et al., 2012; Resch, 2012; Hangweirer et al., 2015; Reinbrech et al., 2016). Furthermore, the final developed receiver concept will be realized as a prototype and tested on an existing Fresnel mirror field.

The principal implementation of the considered Spectral Splitting concept can be explained by a schematic illustration from Everett et al. (2012), see Figure 2. The incident sunlight (red arrow) is reflected by the Fresnel mirrors and enters the thermal part of the compact receiver, realized as a glass fluid channel. An absorptive filter is implemented in the fluid channel and represents the "thermal absorber" with specified spectral characteristic. The spectral transmittance of the filter shows a steep rise from ideally 0% to 100% at a selectable wavelength, e.g. at 700 nm. Hence, the short wavelengths between 280 nm and 700 nm are absorbed by the filter and converted into heat, while the spectral range > 700 nm is directed further upwards to the PV cells. The absorptive filter is fully immersed in heat transfer fluid that transports the generated heat to any storage or heat sink. Furthermore, applicable fluids like water or propylene glycol (Resch, 2012) also provide an essential spectral property, as its transmittance for the passing irradiance decreases significantly for wavelengths > 1100 nm. Therefore, only the spectral range between 700 nm and 1100 nm reaches the PV cells, where it can generate electricity with maximum efficiency (SR resp. EQE). All other wavelengths are converted into heat, either in the absorptive filter or in the heat transfer fluid directly.

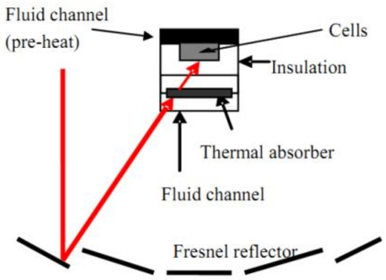


Fig. 2: Schematic assembly of the beam splitting receiver concept (Everett et al., 2012)

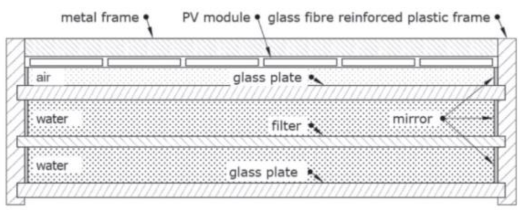


Fig. 3: Cross section of a Spectral Splitting CPVT receiver proposed by Hangweirer et al. (2015)

Hangweirer et al. (2015) proposed a construction for a compact Spectral Splitting CPVT receiver as it is depicted in Figure 3. Following the concept of Everett et al. (2012), it consists of an absorptive filter implemented in a glass fluid channel with rectangular cross section. The PV cells are spatially separated from the thermal receiver part by an air volume in order to improve thermal decoupling.

Stanley et al. (2016) contributed substantial results in this research field, as they also performed experimental work with the developed compact Spectral Splitting receiver. In this case, circular cross section was chosen for the thermal receiver part by using a glass tube that contains the absorptive filter. This approach appears to provide improved durability for prototyping and experimental investigations, e.g. due to higher pressure resistance of a circular tube compared to a rectangular fluid channel.

These described research results were used as a basis for further developing the compact Spectral Splitting receiver concept. The following section 3 summarizes the receiver design phase.

3. Novel CPVT Receiver Design Concepts

3.1 Objectives and approach for designing new CPVT receiver configurations

The principal way of implementing the method of Spectral Splitting within this project is restricted to a compact construction of the receiver, as described above. Moreover, the following requirements for the CPVT receiver had to be considered during the design phase:

- Aperture width of the receiver sufficient for existing Fresnel mirror field
- Operating temperature range up to 200°C
- Heat transfer medium only in liquid phase
- Solid absorption filter with selectable characteristic
- Covering glass for thermal receiver to reduce losses
- Crystalline Silicon or thin-film PV technology for the electrical receiver
- Material availability for building a receiver prototype with an approximate length of 2 m
- Durability for experimental work
- Limited budget for material costs

High importance was attached to the aspect of practical realizability and economic feasibility, because the following prototyping and experimental phase are seen as significantly relevant for the final outcomes of the entire project. Therefore, the receiver designs were kept as simple as possible, but fulfilling the requirements above. The aspect of production costs was taken into account in terms of respecting the limited budget for the receiver material. Although it is important on the long hand to develop low-cost solutions, as the economic competitiveness is always a key indicator for new components, there was no special emphasis on reducing the costs for the receiver within this design phase. At this stage of the development, the focus lays on the technical feasibility and the functional demonstration of the Spectral Splitting concept. Cost optimization is seen as a subsequent step towards a possible product development, which is not an aim of the project described in this paper.

3.2 Optical modelling of the Fresnel mirror field

Before starting the development of different receiver designs, it was necessary to calculate the expected width of the focus image on the receiver incidence plane. On the one hand, this depends on the geometric arrangement of the mirrors (mirror width, number of mirrors, gap between the mirrors…), which is given in this case by an existing Fresnel mirror field with a length of 5.8 m and a total width of 2.3 m, see Figure 4. A number of 28 mirrors are mounted in parallel with a width of 70 mm each, all mechanically interconnected by one central control rod. On the other hand, the mounting height of the receiver has significant influence on the focus image width. If the mounting height is small, internal shading of the Fresnel mirrors reduces the optical performance of the collector, the focus image on the receiver incidence plane is wide and therefore the concentration ratio (CR) is low. By contrast, a big mounting height results in higher mechanical effort and higher optical losses due to inaccuracies of the mirror planes and the tracking system. Basing on experience with the thermal version of the Fresnel collector, a receiver mounting height of 1.5 m above the mirror mounting plane was chosen for performing a two-dimensional (2D) optical modelling of the planned arrangement.

Fig. 4: Fresnel mirror field available for experimental work

The 2D optical modelling was done in MATLAB[TM] in order to obtain several performance parameters of the Fresnel system like the concentration ratio CR, the optical losses by internal shading, and the width of the focus image or the distribution of irradiance on the receiver incidence plane. This model is not restricted to the specific Fresnel mirror field considered in this project, but it can be parametrized to any kind of linear Fresnel mirror system. It calculates the performance parameters mentioned above in dependence on the elevation angle of the sun, although only the transversal mode is considered yet. An extension of the model to include also the longitudinal mode is planned for the following project phases.

Figure 5 depicts the shading simulation for an elevation angle of 30°. The orange lines represent the incident solar beams, and the red dashed lines illustrate the reflected beams. A schematic receiver is assumed as a rectangular cross section in light green. The following four internal shading mechanisms are considered in this model:

- Mirror self-shading: The incident radiation on one mirror can cause shade on the following mirror.
- Mirror backwards shading: The reflected beams of one mirror can be partly blocked by the previous mirror.
- Receiver shading: The receiver itself can cause shade on the mirror field.
- Frame shading: The frame of the mirror field construction can shade mirrors at the edge.

All of these shading mechanisms are strongly depending on the elevation angle of the sun. Therefore, the simulation was performed stepwise for elevation angles between 5° and 90°, calculating all four shading mechanisms for each mirror.

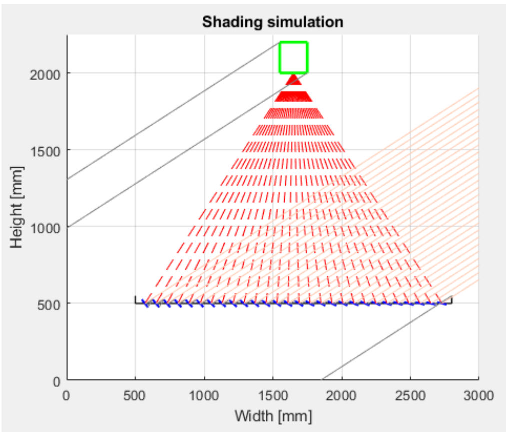


Fig. 5: Modelling of internal shading (elevation angle 30°)

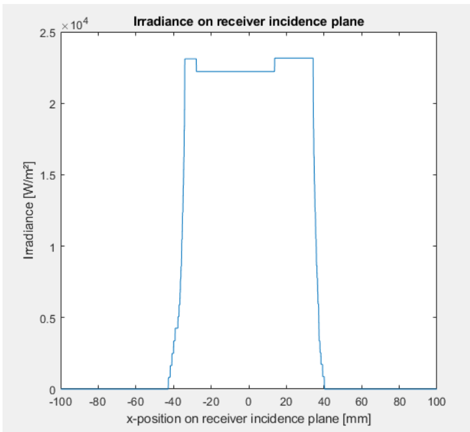


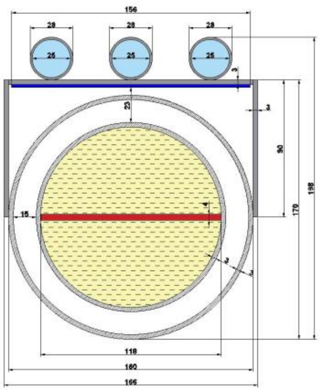
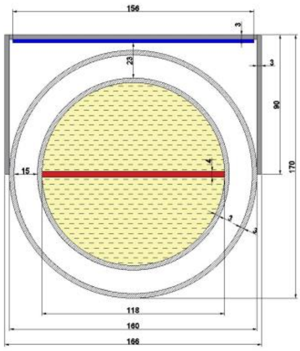
Fig. 6: Resulting irradiance distribution on receiver incidence plane (elevation angle 68°)

For the receiver design phase, it was most important to derive the expected maximum width of the focus image on the receiver incidence plane, as this is a crucial information for constructing the aperture of the receiver accordingly. The width of the focus image and the received irradiance are highly influenced by the internal shading in the mirror field and therefore depend on the elevation angle as well. The optical modelling with varying elevation angles reveals that the maximum width of the focus image is expected to be 83 mm at an elevation angle of 68°. Figure 6 illustrates this step of the simulation and shows the distribution of irradiance along the x-position on the receiver input plane. The maximum irradiance at this elevation angle is calculated with 23.1 kW/m². The stepped reduction of irradiance between x = - 28 mm and x = + 14 mm is caused by the receiver shading.

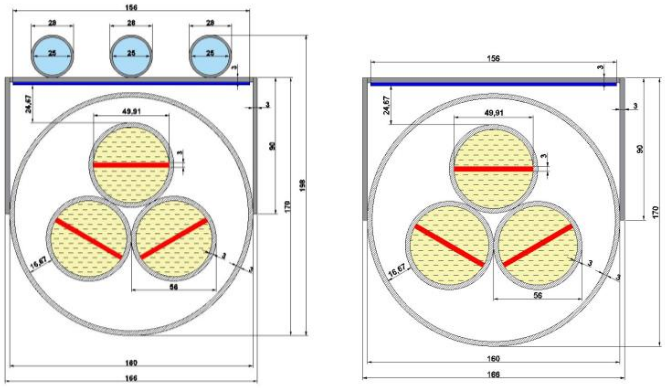
3.3 Development of novel CPVT receiver designs

Basing on these simulation results, the required aperture width was chosen to be 100 mm in order to provide some tolerance for possible inaccuracies like in the tracking system or in the alignment of the mirrors. Seven different receiver designs have been developed taking into account the requirements mentioned at the beginning of this section. Five of the designs are constructed to use crystalline Silicon (c-Si) PV cells, and two design proposals are developed using thin-film PV technology. The necessity of an additional cooling circuit for the remaining waste heat of the PV cells has to be clarified by the subsequent thermal modelling. Therefore, each receiver design consists of one version with backside cooling tubes for the PV and another version without backside cooling. The absorption filter is implemented in one to three inner glass tubes with different dimensions and arrangements. Common for all design proposals is an enveloping outer glass tube, providing an air gap to the inner glass tube(s) that serves on the one hand as thermal decoupling to the PV cells and on the other hand as thermal insulation for the hot fluid, in order to reduce convection losses to ambient air. The following Table 1 summarizes all developed receiver designs in both versions with and without backside cooling and describes the most important attributes of each design proposal. The cross sections of all constructions are illustrated.

Tab. 1: Overview of developed designs for a compact CPVT receiver

Receiver designs with backside cooling of PV	Receiver designs without backside cooling of PV	Description of designs
Design #1		
		c-Si PV with a width of 156 mm (8”) One central inner glass tube → difficult stability due to the weight of the fluid One absorption filter with a width of 118 mm → high costs expected Distance between hot fluid and PV: 23 mm

Design #2



c-Si PV with a width of 156 mm (8")

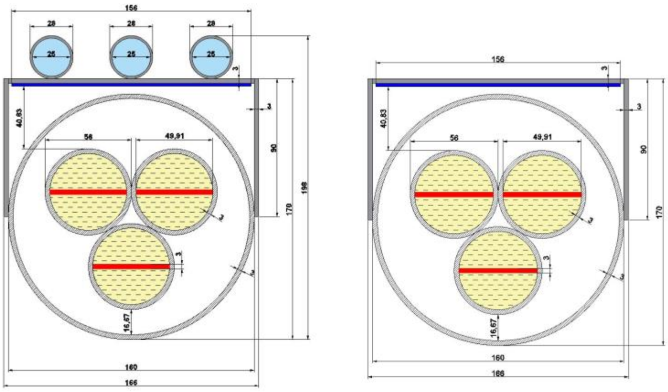
Three inner glass tubes → good stability expected

Three absorption filters with a width of 50 mm → acceptable costs expected

Overlapping of the glass tubes economically inefficient

Distance between hot fluid and PV: 25 mm

Design #3



c-Si PV with a width of 156 mm (8")

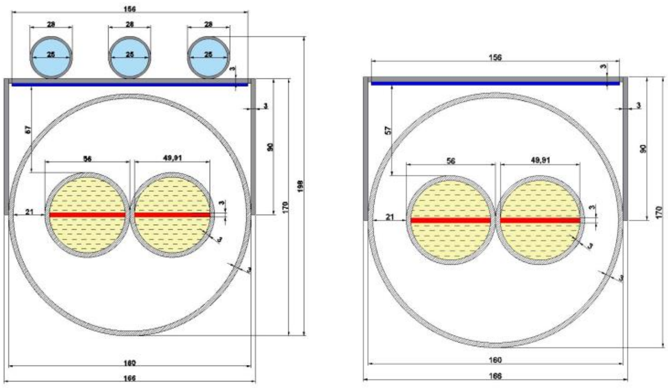
Three inner glass tubes → good stability expected

Three absorption filters with a width of 50 mm → acceptable costs expected

Overlapping of the glass tubes economically inefficient

Distance between hot fluid and PV: 41 mm

Design #4



c-Si PV with a width of 156 mm (8")

Two inner glass tubes → good stability expected

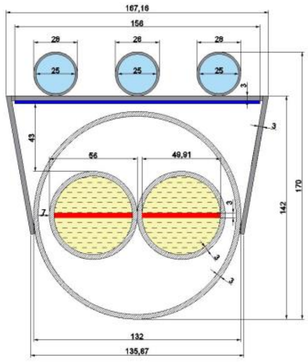
Two absorption filters with a width of 50 mm → reduced costs

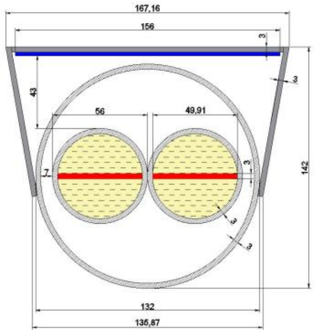
No overlapping of inner glass tubes

Large gap between inner and outer glass tubes

Distance between hot fluid and PV: 57 mm

Design #5





c-Si PV with a width of 156 mm (8")

Two inner glass tubes

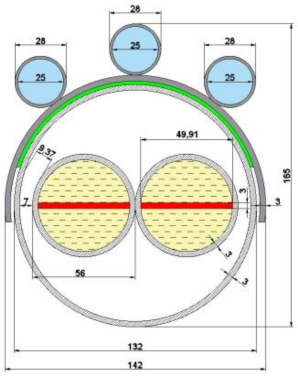
Two absorption filters with a width of 50 mm

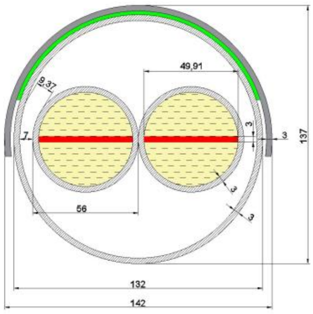
Reduced gap between inner and outer glass tubes

Skewed walls of receiver housing → more effort for assembly

Distance between hot fluid and PV: 43 mm

Design #6





Thin-film PV bended over outer glass tube

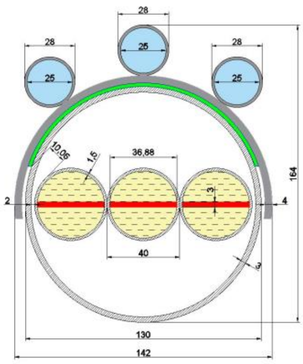
Two inner glass tubes

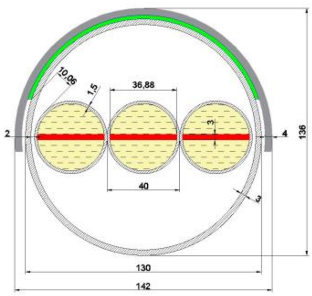
Two absorption filters with a width of 50 mm

Half-shell as receiver housing → low costs and low assembly effort expected

Minimum distance between hot fluid and PV: 9 mm

Design #7





Thin-film PV bended over outer glass tube

Three inner glass tubes → improved stability, but higher assembly effort

Three absorption filters with a width of 37 mm

Half-shell as receiver housing → low costs and low assembly effort expected

Minimum distance between hot fluid and PV: 10 mm

3.4 Qualitative assessment of developed receiver concepts

The subsequent task in the project will be a thorough modelling of the compact CPVT receiver in terms of optical, thermal and hydraulic behaviour. As this cannot be done with all developed receiver concepts due to limitations of time and budget, a qualitative assessment was applied in order to select the best concept for further investigations.

This assessment contained technical criteria as well as aspects regarding the planned experimental realization of the receiver.

The following technical criteria have been considered for each receiver design:

- Pressure resistance of the thermal receiver part
- Heat transfer from the absorption filter to the fluid
- Weight of the thermal receiver part
- Heat transfer between thermal and electrical receiver part
- Absorption losses on the inner side walls of the receiver housing
- Inhomogeneous cross section and therefore inhomogeneous distribution of irradiance within the receiver
- Temperature control of PV cells
- Reflection losses due to multiple optical interfaces
- Relation between filter width and receiver aperture width

With respect to the planned prototyping and experimental work with the receiver, several more criteria have been evaluated for the receiver designs:

- Availability of the PV cells, the absorption filter and the glass tubes
- Costs of material
- Location and accessibility of the suppliers

Each criterion has been evaluated for each receiver design by assigning a grade of 1 to 5. An evaluation of "1" represents the positive compliance of the criterion, whereas "5" indicates a severe deficit of the respective design in the considered aspect. The assessment was done separately for the technical and the experimental criteria.

Table 2 depicts the evaluation matrix of the technical criteria. Each receiver design number is listed twice, one time for the variant with backside cooling of the PV and one time without, indicated by the additional *. The arithmetic average in the bottom row represents the result of the technical assessment.

Tab. 2: Assessment of receiver designs by technical criteria

Technical criteria	Receiver design #													
	1	1*	2	2*	3	3*	4	4*	5	5*	6	6*	7	7*
Pressure resistance thermal receiver part	3	3	2	2	2	2	2	2	2	2	2	2	1	1
Heat transfer absorption filter to fluid	3	3	2	2	2	2	2	2	2	2	2	2	1	1
Weight of the thermal receiver part	5	5	4	4	4	4	3	3	2	2	2	2	1	1
Heat transfer thermal to electr. receiver part	4	4	4	4	3	3	1	1	2	2	3	3	3	3
Absorpt. losses on inner side walls	3	3	3	3	3	3	3	3	2	2	1	1	1	1
Inhomogeneous distribution of irradiance	2	2	2	2	2	2	2	2	3	3	1	1	1	1
Temperature control of PV cells	1	5	1	5	1	5	1	5	1	5	1	5	1	5
Reflection losses due to multiple interfaces	2	2	4	4	4	4	2	2	2	2	2	2	2	2
Relation filter width - receiver aperture	2	2	4	4	3	3	4	4	2	2	2	2	1	1
Average	**2.8**	**3.2**	**2.9**	**3.3**	**2.7**	**3.1**	**2.2**	**2.7**	**2.0**	**2.4**	**1.8**	**2.2**	**1.3**	**1.8**

Similarly, the experimental criteria were evaluated, as shown in Table 3.

Tab. 3: Assessment of receiver designs by experimental criteria

Experimental criteria	Design #													
	1	1*	2	2*	3	3*	4	4*	5	5*	6	6*	7	7*
Availability of PV cells	2	2	2	2	2	2	2	2	2	2	3	3	3	3
Availability of absorption filter	4	4	2	2	2	2	2	2	2	2	2	2	1	1
Availability of glass tubes	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Costs of material	3	3	2	2	2	2	2	2	2	2	2	2	1	1
Location and accessibility of suppliers	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Average	**2.2**	**2.2**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.8**	**1.8**	**1.4**	**1.4**

The results of the technical and the experimental evaluation were merged by calculating the average values for each receiver design. Table 4 presents the final results of the assessment.

Tab. 4: Final assessment of receiver designs

	Design #													
	1	1*	2	2*	3	3*	4	4*	5	5*	6	6*	7	7*
Results of technical assessment	2.8	3.2	2.9	3.3	2.7	3.1	2.2	2.7	2.0	2.4	1.8	2.2	1.3	1.8
Results of experimental assessment	2.2	2.2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.8	1.8	1.4	1.4
Final average	**2.5**	**2.7**	**2.2**	**2.5**	**2.1**	**2.4**	**1.9**	**2.1**	**1.8**	**2.0**	**1.8**	**2.0**	**1.4**	**1.6**

This performed qualitative assessment did not yield any decision about the two considered PV technologies. Further quantitative investigations will have to point out, if c-Si or thin-film PV will be more feasible for the planned CPVT receiver. Therefore, the best receiver designs for each PV technology were chosen for the further work. In case of c-Si technology, the design #5 with backside cooling obtained the best evaluation, and design #7 with backside cooling was assessed to be the most promising solution for thin-film PV. The following sub-section describes the two final receiver design concepts in detail.

3.5 Final receiver designs for further investigation

The CPVT receiver design concepts that are illustrated as cross sections in Figures 7 and 8 obtained the best evaluation during the qualitative assessment process. Both of them appear to be technically feasible, according to the criteria mentioned above. Moreover, the design proposals are expected to be realizable as a prototype of 2 m length in order to fulfil the experimental tasks of this project.

The thermal part of the receiver is designed similarly for both proposals. The key component is the absorption filter (illustrated in red) that is implemented in the inner glass tubes with an inner diameter of 50 mm (design #5) resp. 37 mm (design #7). Therefore, the total width of the absorption filter will be 100 mm resp. 111 mm, as it was the requirement, given by the optical simulation of the expected focus image width. The outer glass tube with an outer diameter of 132 mm (design #5) resp. 130 mm (design #7) serves as an insulating envelope for the inner parts, as its air volume reduces heat transfer to the ambient air and to the PV cells as well.

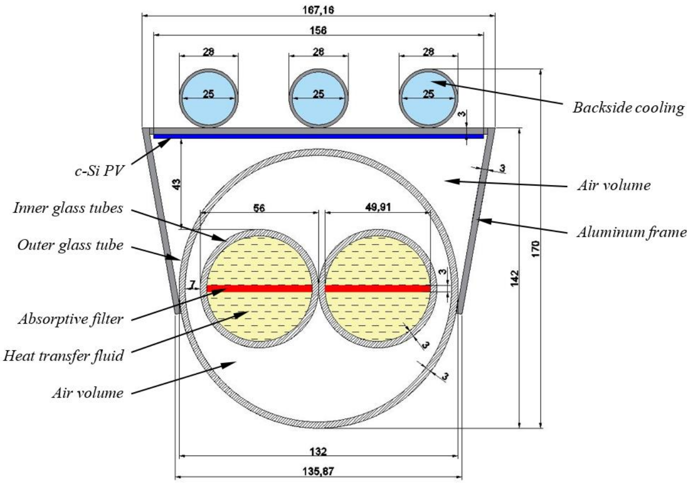


Fig. 7: Cross section of CPVT receiver design #5 with c-Si PV technology

The electrical part of the receiver is constructed differently for the two design proposals. If c-Si PV technology will be implemented, the arrangement could be chosen as illustrated by the cross section in Figure 7. The PV cells (colored in dark blue) are positioned above the thermal receiver with a distance of 43 mm to the hot surface of the inner tubes. Thermal modelling will reveal the effect of this thermal decoupling between the thermal and electrical receiver part. The backside cooling pipes are intended to provide a possibility of maintaining the temperature of the PV cells, in case this is required for the experimental work with the prototype. The total width of this receiver design is mainly given by the width of the PV part, which was chosen with 156 mm, as this corresponds to a standard PV cell size (8-inch wafer). In this way, 12 PV cells in a row could be connected to one string, without further treatment of the cells itself (e.g. cutting to any other size). Skewed sidewalls of the Aluminum receiver housing are necessary, but raising the effort for assembling. The planar construction of the PV cells results in an inhomogeneous air volume between the outer glass tube and the PV layer, that is expected to lead to a less-than-ideal distribution of irradiance, e.g. due to reflections on the sidewalls. By contrast, the second design proposal in Figure 8 utilizes bendable thin-film PV technology, colored in green. This arrangement can be advantageous in terms of internal irradiance distribution as well as in terms of total compactness of the receiver, because dead volumes are reduced.

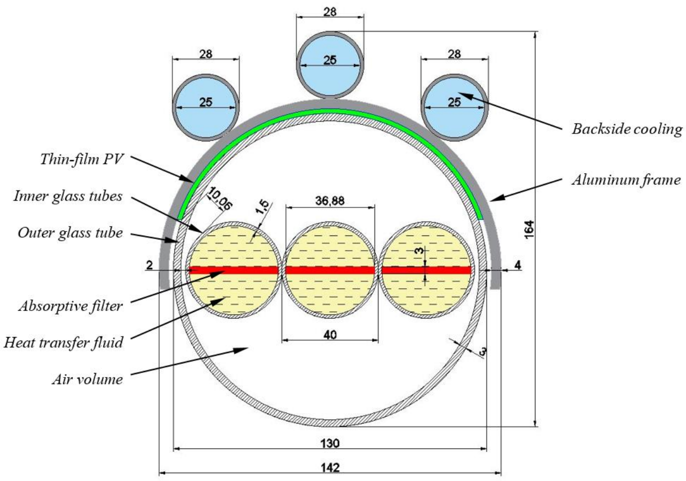


Fig. 8: Cross section of CPVT receiver design #7 with thin-film PV technology

The thin-film PV layer in design #7 is directly attached to the outer glass tube and backwards covered by a half-shell aluminum housing. Backside cooling pipes are planned as in design #5 and can be even more important in this configuration, as the geometrical distance between the hot surface of the inner tubes and the PV varies between 10 mm and 37 mm.

4. Further Investigations and Outlook

The two receiver designs described above will be the basis for further development steps. These will firstly involve a detailed modelling phase:

- Enhancement of the optical mirror field modelling in terms of integrating both transversal and longitudinal modes
- Modelling of the irradiance distribution within the receiver
- Modelling of the Spectral Splitting effect including an optimization of the absorption filter characteristic
- Thermal and hydraulic modelling of the entire receiver
- Calculation of electrical and thermal characteristic values

This modelling phase will yield quantitative results regarding the specified requirements and will point out the potential for possible improvements in the receiver designs. Furthermore, it will deliver a comparison of the two considered PV technologies, which is of high importance in order to take a subsequent decision about the receiver design to be used for prototyping.

In parallel to the modelling phase, material investigation needs to be performed. This includes:

- Thermal life-time validation and UV exposure tests of candidate fluids and absorption filters
- Spectral transmission measurements with candidate fluids, glass tubes and absorption filters
- Spectral response measurements with the considered PV cells

The final stage of the project consists of the prototyping phase, where the developed compact CPVT receiver will be assembled with a length of 2 m and installed on the existing Fresnel mirror field. Optical, electrical and thermal performance measurements of this novel CPVT collector under real conditions will reveal, if the theoretical results can be confirmed by experimental data.

5. Acknowledgments

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6. References

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