SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Analysis and Simulation of CSP and Hybridized Systems

https://doi.org/10.52825/solarpaces.v3i.2304

Published: 27 Jan. 2026

Utilization of Spillage in Solar Particle Power Plants With Concentrating Photovoltaics

Jens Rheinländer[1], Reiner Buck[1,*], Werner Bensch[2], and Markus Stetka[3]

[1]DLR, Institute of Solar Research, Stuttgart, Germany

[2]AZUR SPACE Solar Power GmbH, Heilbronn, Germany

[3]MAN Energy Solutions, Deggendorf, Germany

*Correspondence: Reiner Buck, reiner.buck@dlr.de

Abstract. Concentrating solar power plants are considered an important contributor to renewable energy supply due to their high efficiency and cost-effective storage. Solar tower systems using solid particles as a heat transfer and storage medium, in combination with concentrating photovoltaics (CPV), promise to reduce the levelized cost of energy. This study evaluates the cost potential from hybridizing solar power plants with CPV modules integrated into the radiation shield of a particle receiver, to capture spillage radiation that is otherwise lost. Simulation results for a commercial configuration case show that the annual electricity production could be increased by up to 12%, with levelized cost of electricity from the CPV part ranging from 0.02 to 0.024 €/kWh. The electric components of the CPV subsystem have by far the highest single component cost contribution, the cooling water loop adds a minor contribution. Further improvement options exist and are discussed briefly. A demonstration test in a real receiver application is currently under preparation in DLR's solar tower test facility. Six CPV modules will be integrated into the radiation shield of a particle receiver. Solar testing will validate the performance and also provide information about potential dust contamination problems.

Keywords: Particle Receiver, Techno-Economic Optimization, CSP, Concentrating Photovoltaics, CPV, Spillage

1. Introduction

1.1 High Temperature receiver technology

Concentrating solar power (CSP) plants are considered an important contributor to renewable energy supply due to their high efficiency and cost-effective storage. However, in order to increase the market share of CSP a significant cost reduction is necessary. Raising the receiver operating temperature is one measure to achieve this cost reduction, allowing for the integration with higher efficiency power cycles like supercritical CO_2 cycles. Another application of CSP technology is for industrial process heat applications. In several of these applications operating temperatures above 800°C are required, e. g. to perform thermo-chemical process steps like calcination.

Typical for receivers with such high operating temperatures is an increased level of spillage losses, i. e. concentrated solar radiation that is not hitting the active receiver aperture, but the radiation shield around the aperture. This so-called spillage is usually lost and reduces the receiver and overall system efficiency. The reason for the increased spillage loss of high temperature receivers is that the receiver optimization is a mainly a trade-off for the receiver aperture size. Due to the near Gaussian shape of the focal spot, a larger aperture results in higher intercept, i. e. lower spillage losses. This is associated with an increase in aperture-area-based radiative and convective heat losses. For high temperature receivers the area-based thermal losses become more important, and the trade-off is therefore more towards smaller aperture areas, increasing spillage loss. Depending on the optical system and the operating temperature this spillage loss can be up to 25% of the concentrated solar radiation reaching the receiver region.

Several options exist to reduce the spillage loss in such receivers:

- use of mirror segments on the aperture shield (secondary concentrators)
- integration of concentrating photovoltaics (CPV) into the aperture shield
- integration of lower temperature receiver sections around the main receiver aperture

Combinations of these measures are also possible.

This paper investigates the option to use concentrating photovoltaics to capture spillage losses. A centrifugal particle receiver ("CentRec") system is taken as an example for a high temperature receiver system [1]. This receiver uses a rotating cavity where particles are fed from the back and are then forced against the cavity wall by centrifugal force. Appropriate setting of the rotation speed leads to a controlled movement of the particles towards the receiver aperture, driven by gravitational force in the inclined receiver. While moving along the cavity wall, the dark particles directly absorb the concentrated solar radiation entering through the open aperture. The heated particles then exit at the front end into a collector ring and are then conducted to a high temperature storage. Fig. 1 shows a CentRec receiver scheme and an IR image of a test campaign where temperatures up to 965°C were achieved.

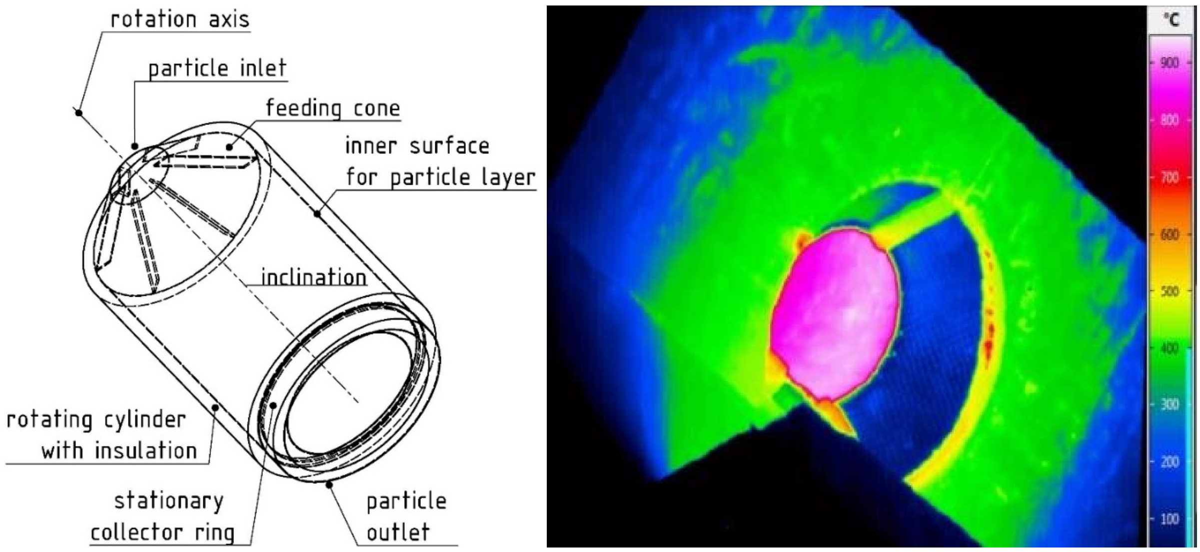

Figure 1. *CentRec particle receiver concept (left); solar test in DLR Solar Tower Test Facility in Jülich*

1.2 Concentrating photovoltaics system to capture spillage losses

The application as spillage CPV takes advantage of developments for electric-only CPV receivers. In this concept high-efficiency CPV cells are mounted on a cooling structure, e. g. a micro-channels heat sink for highly effective water cooling. A first detailed assessment of this concept and associated CPV module development were done in the project HiConPV [2]. Currently, the Australian company Raygen is following this concept using an array of 10cm x 10cm CPV modules integrated to a receiver [3]. Each of the CPV modules integrates a large number of CPV cells (e.g. 100 cells) that offer highly efficient direct conversion of concentrated solar radiation. The CPV receiver of Raygen consists of several hundreds of their "PV Ultra System" CPV modules arranged next to each other.

Figure 2. *Raygen's CPV module (left [4]); Raygen pilot plant at Carwarp, Australia [5]*

State-of-the-art is the use of triple-junction cells, with a cell efficiency of about 44% under lab conditions. Ongoing development aims to increase the cell efficiency and reduce manufacturing cost, mainly by using five [6, 7] or even six active junctions [8], improving the cell efficiency to more than 47% under lab conditions. The 5-junction cell technology is currently in commercial market introduction phase at AZUR SPACE. In practical use in a technical system the efficiency is reduced by several effects like increased operating temperature, solar flux inhomogeneities and the need of a protective cover glass with some reflection losses.

The integration of concentrating photovoltaics (CPV) into the aperture shield was analyzed by Ho et al. [9]. The authors concluded that levelized cost of electricity (LCOE) as low as about $0.02/kWh are possible for three-junction CPV cells at high concentration levels (300 suns). Ruhwedel et al. [10] evaluated several options for integrated concentrating solar/PV hybrid concepts and concluded that the use of CPV modules for spillage integration is attractive in regions with peak concentrated solar flux densities above 350kW/m².

2. Techno-economic assessment

For the techno-economic assessment the integration of CPV modules into a high temperature particle receiver is used as an exemplary case. Since the underlying physics holds for every high temperature receiver, the results should be applicable to other such receivers as well.

2.1 Integration of CPV modules into receiver aperture

To capture part of the spillage loss numerous CPV modules are integrated into the radiation shield around the receiver. A CPV module size of 0.1m x 0.1m is assumed, the module size that is described by Raygen for their PV Ultra modules [3]. The modules can be integrated into the conical section in several rows, covering nearly all the surface of the cone. The adjacent flat front section can also be covered by CPV modules installed in rows. Fig. 3 shows an example of such an arrangement.

As the CPV modules are expensive, a certain minimum annual solar flux level must be available at the place of installation to make the use cost-effective. The following analysis takes the local flux into account to determine the benefit.

Operation of CPV modules under highly concentrated solar radiation requires additional components. Although the CPV cells are less sensitive to increased operating temperature, a suitable water-cooling loop must be installed to provide efficient cooling for the CPV modules to prevent overheating, including piping. Electric equipment like inverters with maximum power tracking capability and connecting gear are also required.

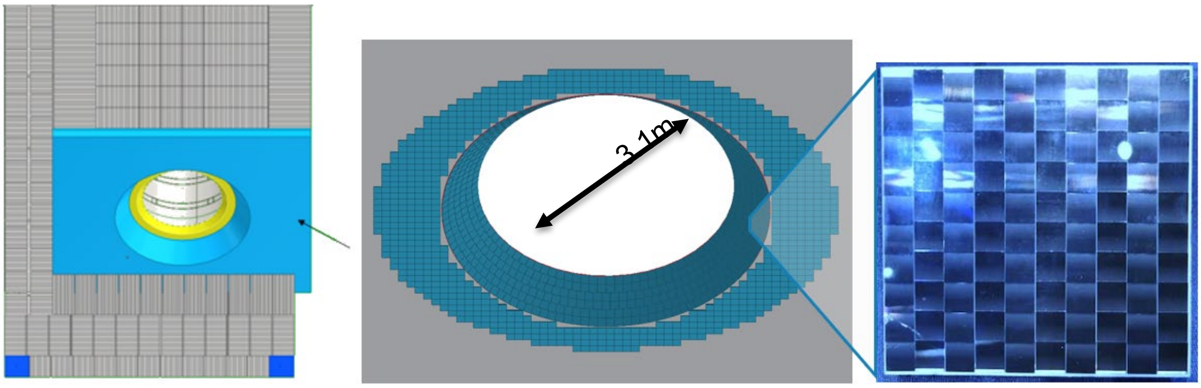

Figure 3. *Scheme of the integration of CPV modules into the receiver front shield*

When CPV modules are used on the front shield, the need for expensive high temperature refractory materials in the shield can be significantly reduced. This benefit is neglected in the following analysis.

2.2 Performance and cost assumptions

For the evaluation of the benefit of adding CPV to a high temperature receiver system, a typical layout for a particle receiver system was made based on the following assumptions:

- steam power cycle with 100MW$_e$, 43% net efficiency
- Multi-tower configuration: receiver power: 12MW per tower @ design point
- receiver outlet temperature: 1000°C
- site: Ouarzazate, Morocco, latitude 31° north
- annual direct normal insolation: 2518 kWh/m²a

For the modular arrangement, heliostat, tower and storage subsystems the same assumptions were made as described in [11]. The size for the particle receiver aperture is set to a diameter of 3.1 m. This size is based on an evaluation of the maximum aperture size with the constraint that the factory-assembled receiver can be transported on normal streets. This receiver is a so-called “street-size” particle receiver.

The solar system layout is based on the cost and component data assumptions similar to [11]. For simplicity reasons in this paper only a single tower module is considered for the integration with CPV. The layout was done using the software tool VisualHFLCAL [12] and resulted in the following module configuration:

- heliostat field: 192 heliostats, each with 144m² mirror area
- Tower height: 69.17m
- Receiver center position: 59.17m
- Receiver tilt angle: 27.5°

The used aim point strategy has all heliostats aiming at the aperture center.

The LCOE of the commercial hybrid system was determined based on cost estimates for the CPV subsystem. Table 1 lists the assumptions used for the cost analysis of the CPV subsystem.

Table 1. *Parameters CPV part of commercial hybrid system*

Parameters	Value	Unit	Comments
Amortization period	25	years	Default value
Interest rate	5	%/a	
Annuity	7.1	%	Calculated using values above
BoP CPV	20	%	Default value
O&M set	1.5	%	Default value
Efficiency cover glass	96	%	Assumption 4 % reflection losses
Inverter efficiency	98	%	Acceptance based on expert discussion
Efficiency of high-voltage switchgear	98	%	Acceptance based on expert discussion
Overall efficiency of CPV modules	32.9	%	Expected efficiency under the given operating conditions, 5-junction cell technology
Specific costs of CPV subsystem (CPV modules, inverters, electric auxiliaries)	46000	€/m²	Expert discussion and assumption from AZUR SPACE
Specific costs cooling circuit (incl. profit and installation)	42.8	€/kW_{th}	Based on a procurement at the DLR multifocus tower in 2019
Specific costs table cooler (incl. profit and assembly)	28.8	€/kW_{th}	Based on a procurement at the DLR multifocus tower in 2019
Surcharge for installation and profit	20	%	

The overall CPV module efficiency is significantly lower than the peak cell efficiency, and accounts for effects like increased operating temperature, non-optimal and inhomogeneous solar flux conditions and manufacturing tolerances. The analysis focusses on the CPV sub-system, so the cost of the standard CSP system is not evaluated in detail, but based on preliminary work using only the overall performance and cost results. Table 2 summarizes the parameters for the CSP reference system.

Table 2. *Parameters of reference particle CSP plant*

Parameters	Value	Unit	Comments
Annual thermal energy CSP	24058	MWh/a	Simulated using the DLR tool SPRAY
Storage efficiency	98	%	estimated
Efficiency of power block	43	%	experience value for steam cycle
Annual electric energy CSP	10138	MWh/a	Calculated using values above
LCOE CSP	0.072	€/kWh	From BMWK-KOSTPAR [13] final report
Total annual costs CSP	729946	€/a	Calculated using values above

2.3 Results

For the evaluation a front cone with an angle of 35° (relative to receiver rotation axis) was considered. Up to 5 rows of CPV modules were placed on this conical section. The solar flux distribution on each module was then evaluated by raytracing for a variety of sun positions, leading to both a thermal receiver and a CPV efficiency matrix. For annual evaluation, a hourly time series was applied with instantaneous performance calculated from actual DNI and the interpolated efficiencies from the efficiency matrices. Fig. 4 shows the design point irradiation situation on a 5 row CPV arrangement in the conical section, with some additional modules arranged in the flat front section. For the following analysis only CPV modules in the cone section are considered.

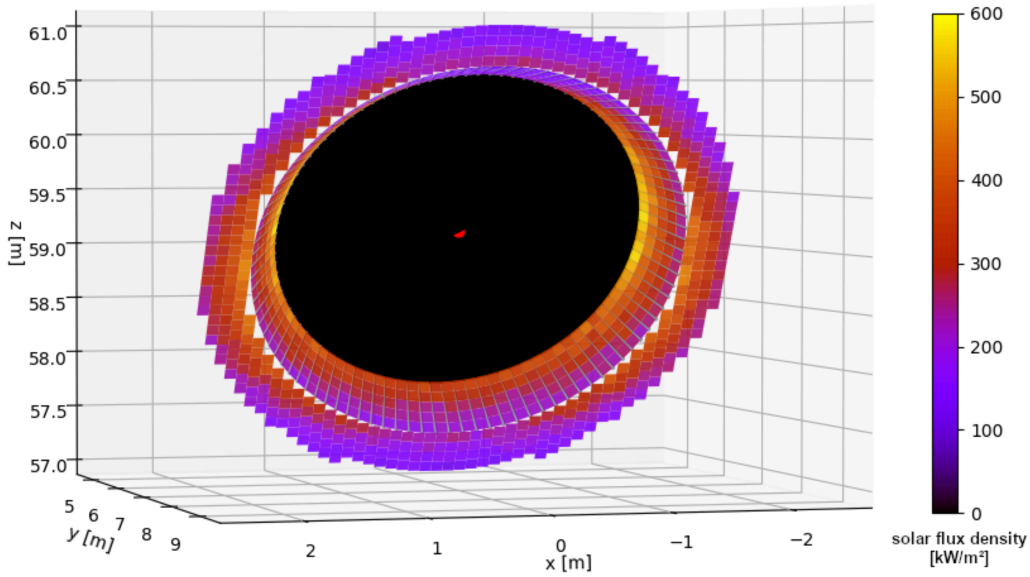

Figure 4. *Solar flux distribution on CPV modules around aperture at design point*

For the annual evaluation the additional electric energy and the associated cost were calculated, for a varied number of CPV rows in the conical section. Fig. 5 shows the results of the evaluation. Depending on the number of installed CPV rows, up to 12% more annual energy can be produced by using the otherwise lost spillage radiation. Extracting the LCOE cost of the CPV subsystem results in a range starting at about 0.02 €/kWh, increasing to about 0.024 €/kWh when more CPV modules are installed in lower irradiated regions further away from the aperture. This is an attractive cost level for the additional power. With the additional cost for the CPV subsystem, this results in a hybrid system LCOE cost reduction of up to 7.5%.

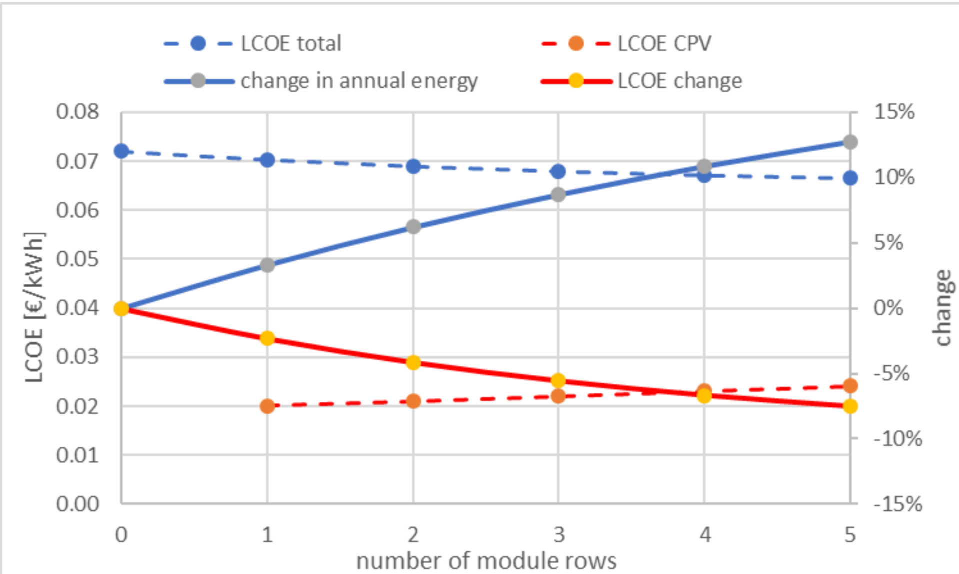

Figure 5. *Energy gain and LCOE reduction for a varied number of CPV rows*

Fig. 6 shows the cost contributions of the CPV subsystem for the case with 5 rows of CPV modules covering the complete conical shield section. The electric components (CPV modules, inverter, auxiliaries) are by far the largest cost contribution, the cooling system has a relatively small cost share.

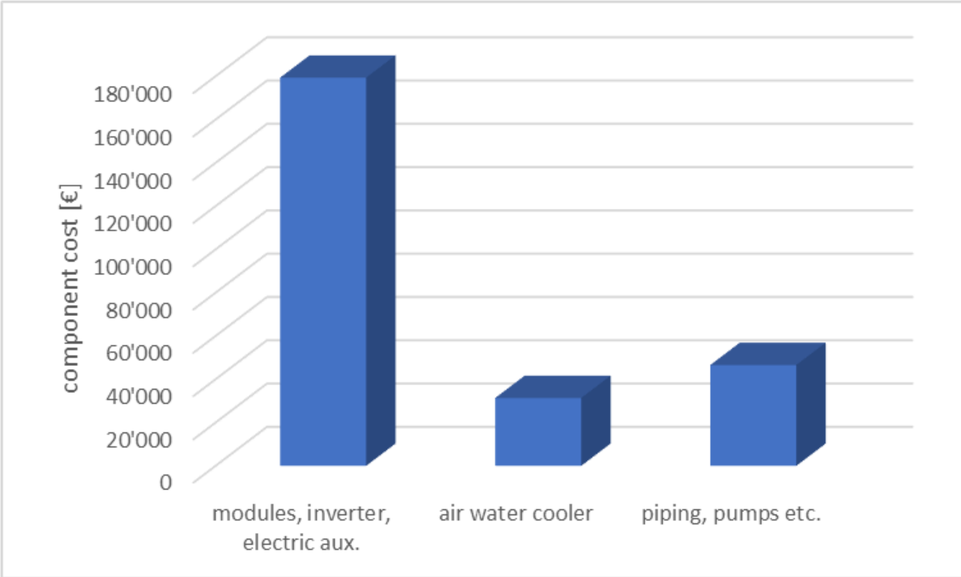

Figure 6. *Cost share of main CPV subsystem components*

3. Planned Validation Tests

A new centrifugal particle receiver, the “High Efficiency High Temperature Receiver System” (HEHTRES) is currently under commissioning in DLR’s solar tower test facility in Jülich, Germany. Start of solar operation is foreseen in August 2024. Within the SpiCoPV project three groups of CPV modules will be integrated into the aperture shield of the HEHTRES receiver, with each group having 2 ADAM (”Advanced Dense Array Module”) modules from AZUR SPACE. The groups will be positioned at the top, bottom and one side position of the aperture shield. The ADAM modules use 96 CPV cells with triple-junction cell technology, mounted on a water-cooled copper structure. Fig. 7 shows an ADAM module. To protect the bypass diodes at both sides of the modules an additional water-cooled shield is applied that covers the bypass diodes.

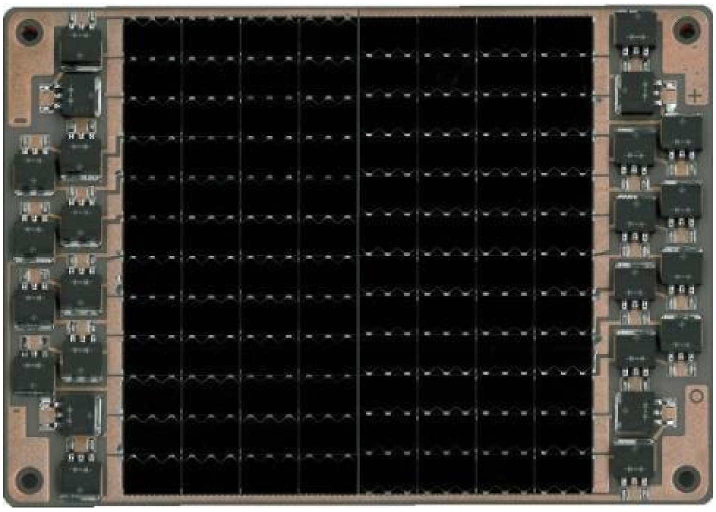

Figure 7. *Advanced Dense Array Module (“ADAM”) from AZUR SPACE*

Each CPV module will be connected to a controllable electric load that ensures operation in the maximum power point, enabling detailed evaluation of the produced power. Integration of the SpiCoPV test setup into the HEHTRES receiver will start in fall 2024.

Since the CPV modules are operated with the particle receiver there is a risk of particle dust settling on the irradiated module front. To prevent this, the additional shield includes channels for pressurized air in order to provide an air stream passing over the module surface to keep the CPV modules clear from dust. Characterization of this dust prevention method is another main objective of the SpiCoPV project.

The ADAM modules do not represent the actual state-of-the-art, since less efficient 3-junction CPV cells are used. Recent cell development shows about 15% higher power generation at an operation temperature at 90°C with advanced 5-junction cells. In addition, the new module development of Raygen has the bypass diodes hidden behind the CPV cells, i. e. no additional shielding is required to protect the diodes. Nevertheless the ADAM modules can serve well for the demonstration of the installation with a high temperature receiver.

4. Further Improvement Options

Several options are under consideration that are expected to improve the performance and cost situation of the hybrid system. These options are:

1. Combined optimization: in the current version first the CSP-only system is laid out, then the CPV subsystem is integrated into this configuration. A new software tool is under preparation that does an integrated optimization with both subsystems jointly modified during the process.
2. Increase flux levels on CPV modules: this can be achieved by further optimization using the above-mentioned combined approach, or by modifying the placement / orientation of the CPV modules (changing the shield cone angle, optionally with ring-wise angle variation)
3. Change heliostat aimpoints: in situations when the thermal part cannot use all heliostats (dumping, e. g. due to fully charged storage) part of the heliostats can be aimed to the aperture shield with the CPV modules. This will reduce dumping losses while increasing CPV production.
4. Reduce CPV module cost with mass production

Options 1 to 3 will be addressed in ongoing work, option 4 would be a consequence when Raygen successfully commercializes its CPV system.

5. Conclusions

The paper reports on the evaluation of the use of CPV modules to capture part of the otherwise lost spillage radiation around the receiver aperture. The specific case of integrating CPV modules into the radiation shield of a high temperature particle receiver is discussed. Simulation results for a commercial configuration case show that the annual electricity production could be increased by up to 12%, while the LCOE will be decreased by 7.5%. The electric components of the CPV subsystem have by far the highest single component cost contribution for the CPV subsystem, the cooling water loop adds a minor contribution.

Further improvement options exist and are briefly discussed. Combined optimization of the thermal and the CPV parts and improving the placement of the CPV modules will further increase the annual performance gain. Progress in mass production of CPV modules will help to lower cost.

A demonstration test is currently under preparation in DLR's solar tower test facility in Jülich to demonstrate the approach in a real receiver application. Six CPV modules will be integrated into the radiation shield of a particle receiver. Solar testing will validate the performance and also provide information about potential dust contamination problems.

Data availability statement

Non-confidential data can be provided by the corresponding author upon request.

Author contributions

Jens Rheinländer: conceptualization, formal analysis, data curation, writing – original draft; Reiner Buck: methodology, data curation, formal analysis, software, writing – review and editing, visualization; Werner Bensch: data provision, writing – review and editing; Markus Stetka: data provision, writing – review and editing.

Competing interests

The authors declare that they have no competing interests.

Funding

This work was funded in part by the federal republic of Germany – Federal Ministry for Economic Affairs and Energy in the “SpiCoPV” project under Award Number 03EE5087.

Acknowledgement

The authors want to acknowledge Rafael Schiewe and Moritz Beschel for their valuable contributions to the hardware development for the SpiCoPV test setup.

References

[1] M. Ebert, L. Amsbeck, J. Rheinländer, B. Schlögl, S. Schmitz, M. Sibum, R. Uhlig and R. Buck, „Operational experience of a centrifugal particle receiver prototype”, AIP Conference Proceedings 2126, 030018 (2019); https://doi.org/10.1063/1.5117530

[2] O. Pereles et al., “High Concentration PV System”, https://www.um.edu.mt/library/oar/bitstream/123456789/26275/1/Paper%2024_HICON.pdf

[3] J. Lasich, R. Payne, W. Hertaeg, D. Shirley, I. Thomas, S. Carter, W. Mosley, Z. Lasich; “Central receiver photovoltaics - A new generation of solar power”. AIP Conf. Proc. 13 September 2018; 2012 (1): 020007. https://doi.org/10.1063/1.5053495

[4] The Story of RayGen, Part I – Commercial Assessment Report, Raygen 2021, https://arena.gov.au/assets/2021/05/raygen-commercial-assessment-report.pdf

[5] https://raygen.com/carwarp/ (accessed 03.08.2024)

[6] R. H. van Leest, D. Fuhrmann, A. Frey, M. Meusel, G. Siefer, S. K. Reichmuth, “Recent progress of multi-junction solar cell development for CPV applications at AZUR SPACE”". AIP Conf. Proc. 2019; doi.org/10.1063/1.5124177

[7] P. Schroth, R. Löckenhoff, D. Fuhrmann, M. Meusel, A. Frey, M. Steiner, G. Siefer, “AZUR’s new 5C46 CPV cell: Final design for optimized outdoor performance”. AIP Conf. Proc. 2022. doi.org/10.1063/5.0100397

[8] J. Geisz, R. France, K. Schulte, M. Steiner, A. Norman, H. Guthrey, M. Young, T. Song, T. Moriarty, “Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration”. Nature Energy, 2020. doi.org/10.1038/s41560-020-0598-5

[9] C. K. Ho, C. McPheeters and P. Sharps, “Hybrid CSP/PV receivers: Converting optical spillage to electricity”. AIP Conference Proceedings. 2033. 170006. 2018, doi: 10.1063/1.5067170.

[10] M. Ruhwedel, K. Gehrke, E. Lüpfert, F. Sutter, P. Heller and R. Pitz-Paal, “Integrated Concentrating Solar/Photovoltaic Hybrid Concepts—Technological Discussion”, Energy Yield,

and Cost Considerations. Energy Technol. 2024, 2301181. https://doi.org/10.1002/ente.202301181

[11] R. Buck und J. Sment, “Techno-economic analysis of multi-tower solar particle power plants”, Solar Energy: Elsevier, 2023. doi.org/10.1016/j.solener.2023.02.045

[12] P. Schwarzbözl, R. Pitz-Paal, M. Schmitz, „Visual HFLCAL - A Software Tool for Layout and Optimisation of Heliostat Fields”. 2009, Proceedings SolarPACES 2009, ISBN 9783000287558

[13] DLR, BMWK Project "KOSTPAR", final report, BMWK 0324320, 2022