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Mapping Solar Flux Distribution in Parabolic Trough Collectors to Assess Optical Performance

State of the Art versus Development and Testing of a New Tool

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Abstract. This paper describes the development and testing of a novel device capable of mapping the flux distribution in parabolic trough solar collectors (PTCs). Accurate knowledge about the flux distribution is essential in any concentrated solar power (CSP) application, in particular PTCs equipped with concentrator photovoltaic (CPV) cells, since their efficiency highly depends on the collector's light focusing properties. However, the assessment of CSP collectors' optical performance requires sophisticated measurement technology, as the error budget of any sun-tracking optical device comprises a variety of factors ranging from physical properties such as mirror reflectivity to mechanical aspects like gravity sag and play in gears. The presented approach features a scanner consisting of a CPV cell mounted on a pair of linear actuators. A thorough state of the art analysis was conducted and numerous technological approaches were assessed. Design aspects such as component selection, cooling, and data acquisition are discussed and finally exemplary measurement results are presented.

Keywords: Concentrated Solar Power, Parabolic Trough Collector, Optical Assessment, Flux Scanning, Flux Mapping;

1 Introduction and motivation

Parabolic trough collectors (PTCs) play an important part in concentrated solar power (CSP) generation as they provide economic heat up to >400°C [1], which can be used for industrial processes or electricity generation [2]. In recent years, several PTCs incorporating absorber tubes equipped with concentrator photovoltaics (CPV) have emerged, resulting in highly efficient hybrid (CPV-T) absorbers providing both, process heat and electricity (e.g. [3], [4], [5] [6], [7], [8]). The state of the art is summarized in [9]. In all thermal PTCs, but even more so in CPV-T systems, optical accuracy of the mirrors plays a decisive role, as it determines the distribution of irradiance on the absorber and hence influences the efficiency of the CPV cell. Consequently, it is not only imperative to carefully design all mechanical components (i.e. support structure, tracking system, etc.) with sufficient precision, but also to properly adjust the system once it is put into operation [10]. While the tracking error budget for large power tower systems (i.e. heliostats) is considered the smallest among all CSP applications due to the long distances the light travels to the target [11], the optical alignment of PTCs has proven to be critical as well. Figure 1 shows the geometric parameters, which influence the optical performance of PTCs. (Physical properties, such as spectral reflectivity of the mirror, are neglected). Please note, that the image is valid for both, collectors incorporating concentrator photovoltaics (CPV) for solar cogeneration (CPV-T), as well as conventional solar thermal PTCs.

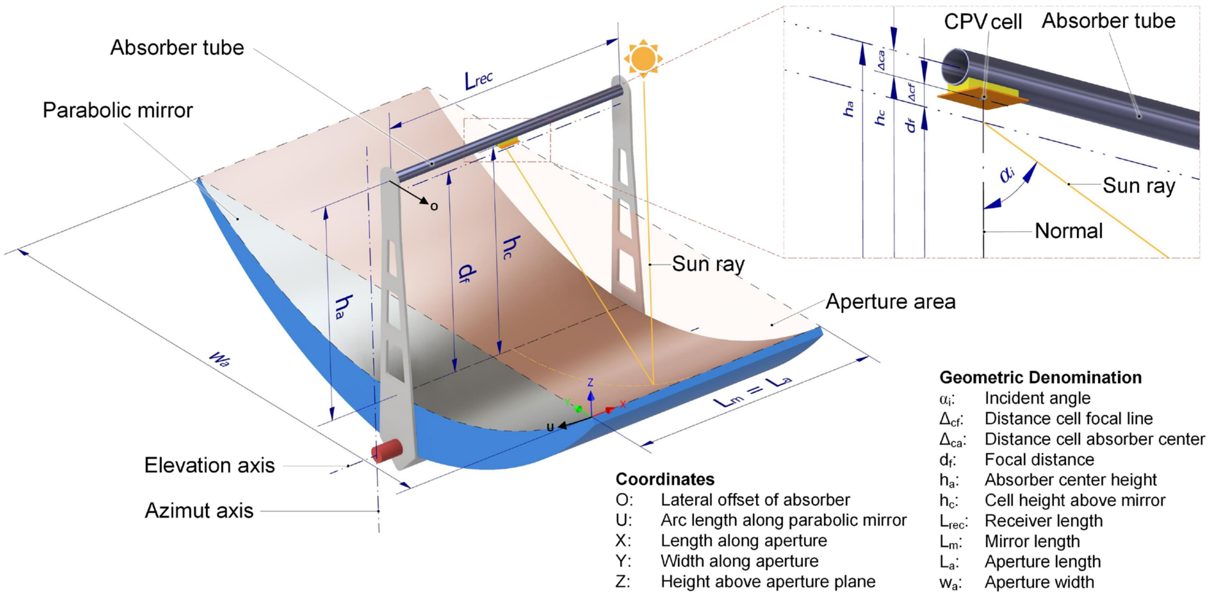

Figure 1. Parabolic trough collector geometric variables (proposed by the authors in [10].)

It can clearly be seen, that there is a multitude of variables, which may in reality be sub-optimally adjusted due to manufacturing and assembly tolerances, errors, or mechanical loads that may lead to unwanted deformations. However, an actual quantification can hardly be performed beforehand, meaning during the theoretical design phase of the PTC, as many parameters (such as play in tracking gears or wind loads / vortex shedding) are nearly impossible to simulate or estimate. This results in the need for:

A) A PTC design allowing a certain degrees of adjustability during assembly and operation.
B) A reliable tool to assess whether the system has been adjusted accordingly to allow maximum energy yield.

As mentioned, this requires profound knowledge of the optical performance of the PTC. There are several ways to measure the geometry of the parabolic mirror and / or the subsequent irradiance distribution on the target, as discussed in the subsequent section.

1.1 State of the art in parabolic trough flux mapping

The design process started with a state of the art and literature research, covering a variety of systems that have been used to optically characterize CSP technologies, with an emphasis on PTC applications. With respect to optical characterization of PTCs in ways similar to the approach described in this publications, only a few publications could be found. The following Table 1 gives an overview of other proposed methods and their measurement principles.

Table 1. Overview of the state of the art in PTC optical assessment.

Year	Author	Principle	DoF[a]	Ref.
2004	Coventry et al.	"Skywalker Project" - moving solar cell along the focal line.	2	[12]
2005	Riffelmann et al.	"PARASCAN Project" – moving array of photodiodes in front and behind the target line, plus camera- target method.	2	[13]
2016	Karathanassis et al.	Array of moving low-cost photodiodes plus thermal imaging.	2	[14]
2016	Cooper et al.	Measurement of electrical PV cell output plus optical characterization using a CCD-camera.	3	[15]

[a]…DoF, meaning degrees of freedom, describing the number of movable axis of the flux scanning system.

What can be concluded from this study is that different measurement principles and technologies have been tested, yet their applicability has always been limited to one concrete use case. Furthermore, certain other optical assessment methods, such as 3D-scanning, have not been investigated in this context yet and will therefore be discussed in the subsequent section.

2 Design of the flux mapper

As the previous section has shown (and the subsequent section “Evaluation of Possible Measurement Principles” will confirm) there are numerous ways to assess the optical performance of PTCs. Based on the main findings of the state of the art analysis and the technical specifications of a PTC test facility installed at the authors’ lab, a requirement profile was developed. Some of the desired properties included:

- Easy transportability / installation
- Fast scan (no need for solar tracking)
- Sufficient spatial resolution at low cost
- Automatic plot of flux distribution
- Low Cost (< 10,000 Euro)
- Measurement under changing conditions possible
- Easy data analyses and interpretation

2.1 Evaluation of possible measurement principles

While the state of the art analysis provides a clear indication of which sensor systems have already been used more or less successfully, there are several other measurement principles that may in theory serve as potential alternatives. Hence, different feasible technological approaches were assessed using development methods such as morphological boxes and value-benefit-analyses. Table 2 provides a brief summary of the key findings relevant to each measurement principle by stating advantages and disadvantages.

Table 2. Comparison of different measurement principles for optical assessment of PTCs.

	Advantages	Disadvantages
Laser Survey	Single segments of the collector can be investigated. Independent from collector-tracking errors. Simple proof of concept possible [10].	External laser support structure necessary. Measured values do not correspond directly to flux distribution at absorber. External influences (gravity, wind, etc.) cannot be investigated.
PV Cell or Photodiode Based Scan	Measured values are directly corresponding to the flux distribution. No external support structure required. Measurement while tracking possible. Variation of external factors possible.	Absorber tube must be replaced with scanner. Tracking errors influence the measurement. Potential inaccuracies due to shading of the scanner.
CCD-Camera	Simple principle and low engineering effort. Quick and easy proof of concept possible. Fast results, no complex data analysis required.	No direct assessment of collector geometry possible. External influences (gravity, wind, etc.) cannot be investigated. Measured values do not correspond directly to the flux intensity at the absorber.
Optical 3D-Scanner	Quantifiable geometrical error of the collector. Direct knowledge about the geometry of the collector. Off-the-shelf 3D scanners available. Portable solution, allowing easy in-the-field measurements.	Surface treatment of mirror necessary (reflective surfaces cannot be scanned). Even slight scanning errors have profound effect on subsequently calculated irradiance distribution. External influences (gravity, wind, etc.) cannot be investigated.

According to the value-benefit-analysis, which was conducted within this project, a scanner system based on CPV cells fulfills the above listed requirements best as it offers an output signal directly proportional to the incoming flux. Hence, no conversion of pure geometry data to flux distribution (i.e. optical calculations) are required. Furthermore, CPV cells can cover a wide dynamic range, fast sensor response offer excellent signal to noise ratio (SNR) and have successfully been used and characterized by the authors [16].

2.2 Component selection and assembly

In order to keep system costs, complexity and engineering effort low, the goal was to resort to as many off-the-shelf components as possible. While the sensor unit itself required some custom engineering, most of the mechanical components and power electronics for the actuator systems could be sourced from industrial vendors. All components were selected with the goal in mind to create a low-cost design, which still meets the needs. The development of the device, which was called **ALFA Scan**, (**A**utomated **L**ight **F**lux **A**ssessment) is described below.

2.2.1 Electrical sensor and control unit

The actual sensor consists of a 10x10 mm Azurspace 3C44 triple-junction solar cell mounted on a water-cooled heat sink, which in turn is attached to a dual axis linear actuator system. The sensor unit (and the entire actuating system for that matter) was developed aiming for maximum compactness to reduce shadowing. As opposed to thermal flux sensors (such as the Hukseflux SBG01), CPV cells instantly detect changes in flux intensity and enable quick measurements, hence avoiding the effect of changes in the sun's position during the scanning process.

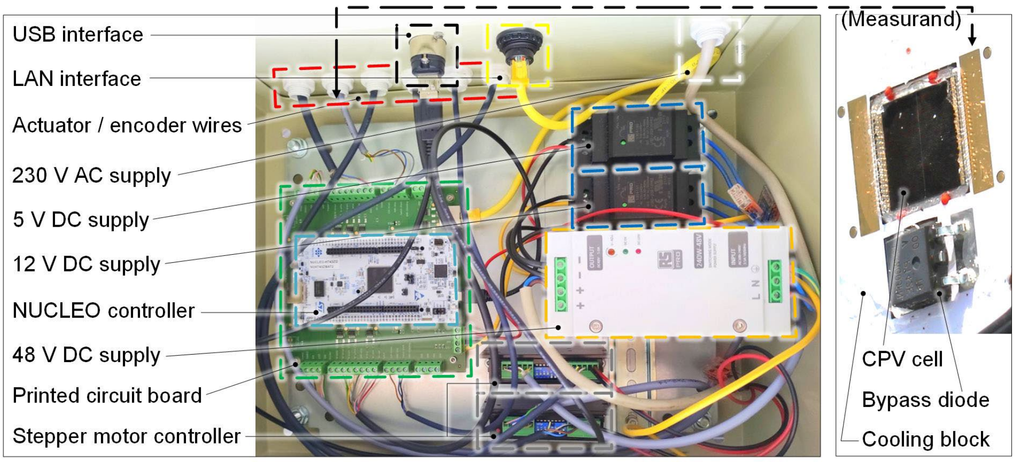

Figure 2. Electrical cabinet of the ALFA Scan flux mapper.

The short circuit current of the cell is recorded using a Keithley DMM7510 digital multi-meter (DMM), as it offers high accuracy and, more importantly, fast enough data acquisition (~4.3 kHz) to allow high spatial resolution as the sensor moves at speeds of approximately up to 0.7 m/s. It is of critical importance, that the cell's current signal is in sync with the sensor's position. For this reason, a NUCLEO-H743ZI2 development board was chosen as the main board controlling the two stepper motors, which are each powered by a stepper motor output stage. The exact position of the cell is calculated using the signal of an angular encoder with 500 increments, attached to each stepper motor. A pitch of 5 mm per turn results in a spatial resolution of 0.01 mm. The DC voltage for the components is supplied by 5V, 12V and 48V DC power supplies. The development board is connected to a PC via USB connection, allowing automated signal processing. The setup, installed in a control cabinet is shown in Figure 2.

2.2.2 Mechanical components and cooling system

The main task of the mechanical components is to move the above described sensor unit along two directions, namely in absorber tube direction (in x direction according to Figure 1) and along the focal distance (in z direction according to Figure 1). The width of the flux distribution (or lateral offset of the absorber tube o as shown in Figure1) can be accounted for by switching the single cell of the sensor unit to an array consisting of many small CPV cells, as described in the Summary and outlook. The main requirements for selecting the actuator system are:

- **Speed:** Being able to scan the flux distribution fast enough, so the change in the sun's position during the scanning process can be neglected.
- **Accuracy:** Both, positioning / position measurement as well as play of the moving parts must be sufficiently accurate for the envisioned task.
- **Temperature resistance:** The system must be able to withstand high solar radiation of up to several hundred suns, resulting in the avoidance of plastic / polymer parts.

There are numerous other design requirements such as weight / center of gravity to avoid excessive deformation of the PTC due to gravity sag, or heat shielding of cables, easy integration of the cooling circuit, to name but a few. Figure 3 shows a CAD model of the flux mapper's mechanical setup as well as a photograph taken during the installation process.

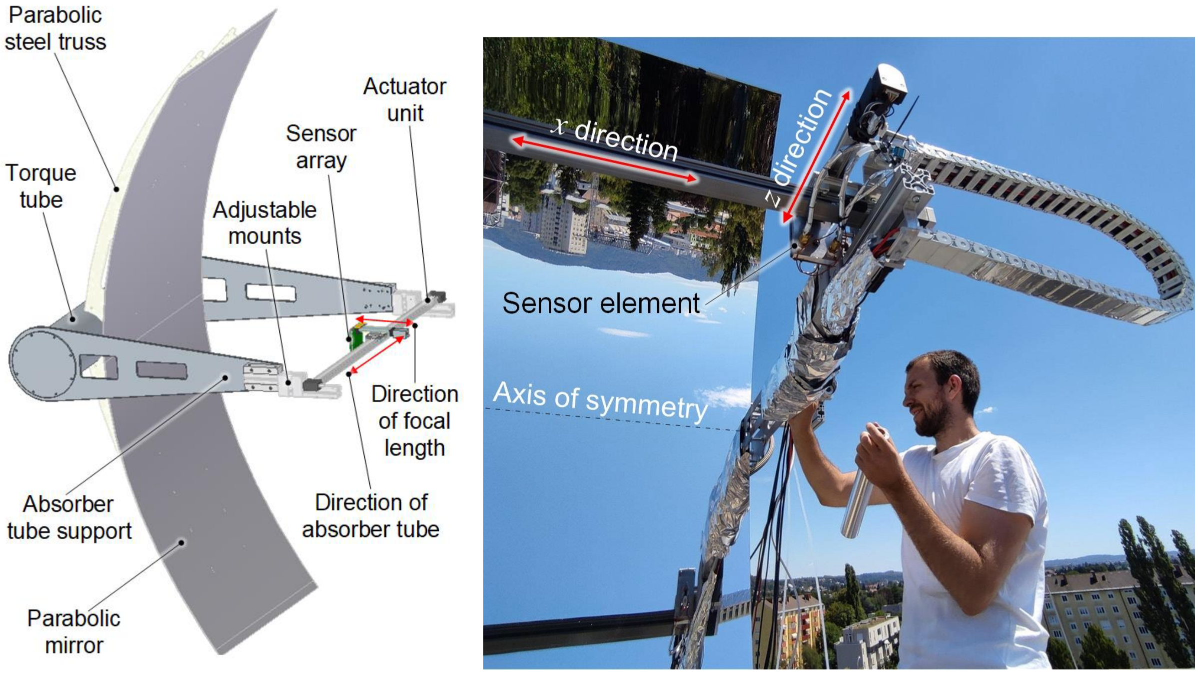

Figure 3. CAD model of the ALFA Scan flux mapper (left) and final installation (right).

The high solar flux density requires water cooling of all the electrical components exposed to the concentrated radiation, in particular the CPV cell. Since the sensor part is moving, highly flexible heat transfer fluid (HTF) hoses, which were routed in parallel with the electrical wires in a cable chain, were used. The HTF (in this case simply deionized water) is stored in a 10 l open expansion tank and fed through a water-air heat exchanger with two 120 mm fans. A diaphragm pump was deployed to cope with the pressure drop and the flowrate adjusted using a variable voltage power supply. A summary of the components including cost and source information is given in Table 3. Figure 4 shows the sensor unit including linear actuators after installation in the PTC.

Table 3. Components used in the ALFA Scan flux mapper.

	Component / Module	Manufacturer	Cost in €
Mechanic	X linear actuator (ZLW -0630S-toothed belt axis)	IGUS	1000
	Z linear actuator (SLNV-27B-mini linear module)	IGUS	370
	Electrical cabinet	Rittal	100
	Diaphragm pump	Seaflow	35
	Water-air heat exchanger with fans (H100x)	Corsair	90
	Hoses, clamps, connectors	ESSKA	50
	Various custom-made parts (heat sink, adapters etc.)	-	80
	Struts for support structure	ITEM	40
Electric	NUCLEO-H743ZI2 development board	NUCLEO	30
	Rail-mountable 240W / 48V DC power supply	RS PRO	100
	1904190, 5V and 12V supplies	RS PRO	44
	2xIGUS drylin® D7 stepper motor output stage	IGUS	140
	3C44 10x10 mm triple-junction solar cell	Azurspace	10[a]
		Subtotal	**2089**

[a]… minimum order is EUR 4,000 when acquiring directly through manufacturer.

3 Field testing and measurement results

3.1 Experimental setup

The ALFA Scan system was assembled and first tested in a lab environment and is currently deployed on a PTC test facility at Graz University of Technology, Austria (see figure 4), where a PTC with a 2.2 m aperture, based on a steel truss design with a 2 mm silvered float glass mirror for CPV-T hybrid applications was investigated. (Model SMT-8 by the Austrian manufacturer IMK Solarmirrortec; see [2] for more detailed PTC specs.)

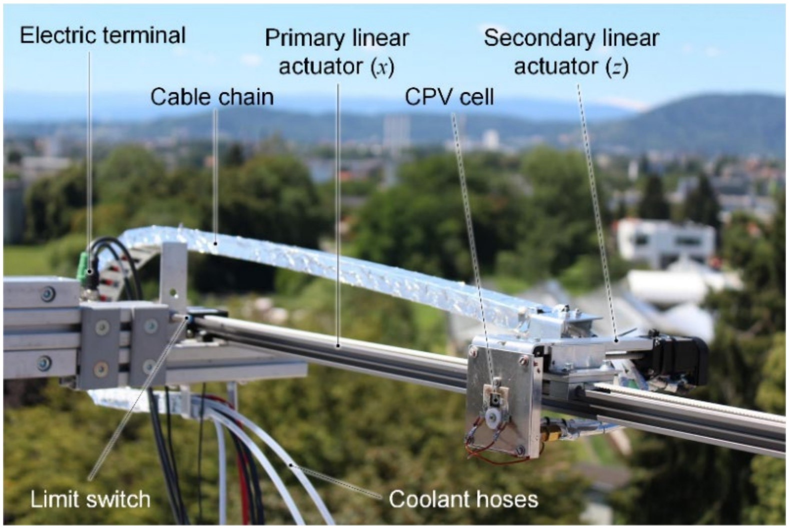

Figure 4. ALFA Scan's sensor unit and actuator system as seen from the mirror.

As can be seen in figure 5, the weather was ideal since there were no clouds in the sky. The flux mapper was mounted and the PTC was directed towards the sun (active tracking was deactivated during the measurement). The flux mapper's sensor unit was then moved in one direction along the length of the absorber tube (x direction), then the focal distance (z direction) was changed by 2 mm during each pass. The process was subsequently repeated about 25 times, lasting ~30 sec. in total and resulting an "serpentine like" motion of the sensor, which can also be seen clearly in the video provided in the "Underlying and related material" section.

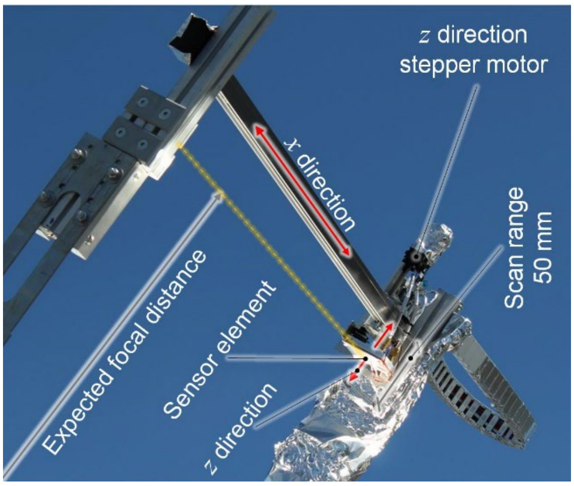

Figure 5. Operation of the ALFA Scan flux mapper.

3.2 Results and discussion

As the focus of this work is to discuss the possibilities of mapping flux distributions in parabolic trough collectors, as well as to describe the design process of a flux scanning device, only a small selection of exemplary data is shown in Figure 6 to demonstrate the capabilities of the developed technology. A variability of the irradiance along the absorber tube length can clearly be seen. This effect can be explained by the specific design of the PTC's support structure, incorporating a design based on 2 laser-cut parabolic support elements, placed at 150 and 650 mm according to the diagrams shown in Figure 6. The initially flat float glass mirror is forced into the parabolic shape of these elements by using bolt-down brackets, which introduce their clamping force from the aperture length side, or u coordinate according to Figure 1 (left). This punctual introduction of force results in distortions of the mirror, visible in the graph. Furthermore, as can be seen in Figure 6 on the right, precise adjustment of the focal length is essential, as an offset of only 20 mm may result in a reduction of irradiance on the 10 x 10 mm CPV cell of nearly 50 %.

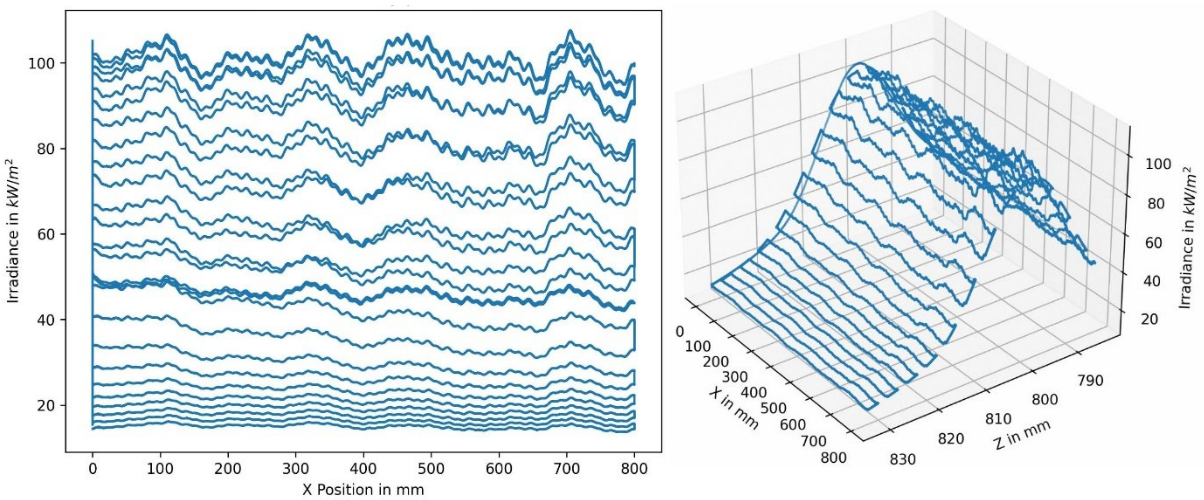

Figure 6. 2D and 3D plots of the flux distribution of the SMT-8 parabolic trough collector.

3.2.1 Shortcomings of the current setup

The ALFA Scan in its current form has proven to be a useful and versatile tool to determine the true focal length of PTCs. However, some modification is required to determine lateral offset, i.e. the O coordinate according to Figure 1 (left) as the sensor unit only uses a single cell with a size of 10 x 10 mm and hence records an average flux intensity across the width of the line focus. However, the sensor unit is currently being modified to allow for lateral (y or O coordinate) flux distribution measurements, by introducing an array of 3 x 3 mm CPV cells instead of a single 10 x 10 mm one, as shown in Figure 7. Results of these measurements will be published separately and can be provided upon request.

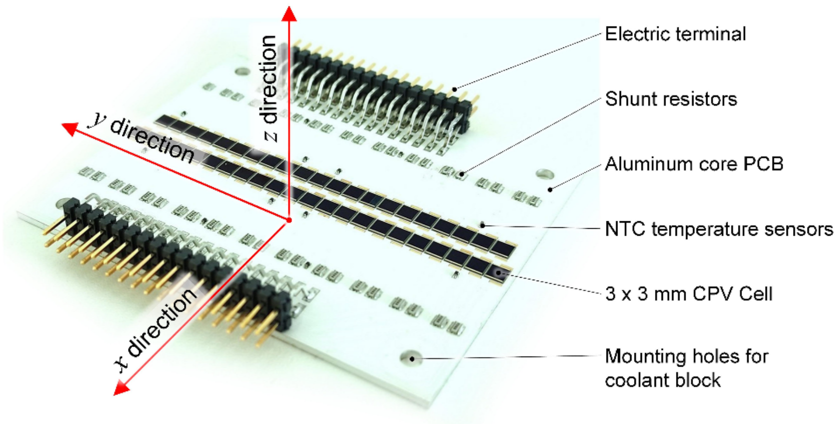

Figure 7. Upgraded sensor unit for future deployment in the ALFA-Scanner

With respect to resolution in x direction, i.e. along the absorber tube, it is also true that the irradiance is “averaged” by the cell’s size, but due to the properties mentioned in section 2.2.1 a theoretical spatial resolution of 0.01 mm can be achieved.

It must also be noted that the installation of the ALFA-Scan system currently requires replacing the absorber tube with the scanner’s linear actuator and is hence not suitable for quick in the field measurements of existing industrial PTC plants, but must be seen rather as a development tool in R & D. However, future research may incorporate certain design alterations and enable installing the scanner in parallel with mounted absorber tubes.

More detailed results including a comparison of different PTC architectures and an analyses of effects such as soiling, partial shading etc. will be published separately as these experiments are ongoing at the time of writing. However, more recorded data, as well as a video of the flux mapper during operation can be accessed by using the information listed in the “Underlying and related material” section.

4 Summary and outlook

This paper discusses tools and methods to assess the optical performance of parabolic trough solar collector (PTCs) by providing a state of the art analysis as well as an evaluation of theoretical measurement principles. Based on these findings, a flux mapper system called **ALFA Scan** (**A**utomated **L**ight **F**lux **A**ssessment) was developed and tested. The system is based on a CPV cell mounted on a dual actuator system, providing valuable results for PTC development and operation. However, due to time constraints in the project and supply chain issues only a single-cell setup instead was used as sensor unit instead of the initially planned CPV array, which will allow finer spatial resolution regarding the width of the flux distribution. Further testing is currently ongoing and includes:

- Effect of mechanical and tracking errors, as well as unwanted deformation and (wind and gravitational) loads.
- Comparative assessment of low-cost injection molded PTCs (as described in [17] and also shown in Figure 8.)

- Effect of systematic partial shading of the mirror, to assess which areas have the highest contribution to the energy yield. (Compare [10], Fig. 11 on page 47.)
- Effect of mirror composition (silvered glass vs anodized aluminum vs reflective foil etc.), which has been shown to have a significant impact not only on thermal efficiency of CSP in general, but especially on electricity yield of CPV systems in particular [16].
- Long term measurements to assess effects such as soiling and degradation.

Future research will also look into possible adaptations of the flux mapper to provide a tool for real-time assessment of production quality of PTCs during manufacturing and/or installation.

Figure 8. Setup for comparative flux mapping study of a novel injection-molded PTC and a conventional steel truss design with thin glass mirror.

Data availability statement

This publication is not based on (third party) data. However, some supplementary material can be accessed as described in the subsequent section.

Underlying and related material

A video of the *ALFA Scan* system in operation and an animated 3D-plot of the results can be found here: https://doi.org/10.13140/RG.2.2.31515.13601

Author contributions

A. Buchroithner: Funding acquisition, project administration, conceptualization, supervision and writing – original draft. R. Felsberger: methodology, data curation and visualization. T. Mitter: Methodology and Investigation. R. Preßmair: Validation, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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