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DIAMOND

Ultra-stable, highly efficient, low-cost perovskite photovoltaics with minimised environmental impact

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Deliverable D5.2 – Report on the first operation of novel developed maximum power point tracker (MPPT) with 100 channels

No.		Participant organisation name	Type	Country
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1. Executive Summary

This report presents the development, functionality, and operation of a newly developed maximum power point tracker (MPPT) equipped with over 100 channels for simultaneous maximum power point (MPP) operation. This system is an important tool in WP 5, which focuses on the stability assessment of the perovskite solar cells. The MPPT system, consisting of custom-developed printed circuit boards and associated software, enables extensive aging and degradation studies under real-world stress conditions.

The system was realized and tested by ageing >100 perovskite solar cells for >100 h under simulated sunlight. By optimizing the choice of electronic component, the system could be realized at a cost below 10€ per channel, i.e., per measured solar cell.

Moreover, the protocol for outdoor ageing in T5.4 is defined in this report.

2. Introduction

The Diamond project has been established to address the critical challenges of stability and efficiency in perovskite solar cells. The focus on improving the longevity and performance of these cells through material innovation and advanced testing methodologies is crucial for their eventual market viability.

Within this context, WP 5 is dedicated to the stability assessment of perovskite solar cells. One shortcoming previously identified has been the lack of statistically significant data when it comes to ageing of perovskite solar cells. To overcome this problem, the deliverable D5.2 focuses on the development and deployment of a cost-effective maximum power point tracker (MPPT) system capable of MPP tracking over 100 channels, i.e., 100 solar cells, simultaneously. This system is instrumental in conducting large-scale, statistically significant aging studies under predefined stress conditions that mimic real-world environmental impacts as well as for large scale outdoor aging campaigns.

The hardware developed for this task includes the development of printed circuit boards (PCBs) with the capability to perform Source Measure Unit (SMUs) functions on eight cells at once. These are complemented by specially designed chucks that ensure compatibility with the cell layouts used in the Diamond project. The choice of hardware enabled a low-cost realization at a price of <10€/channel.

The software component enables the functionality of this setup, allowing scalable control through an I2C interface from low-cost devices such as Raspberry Pis or other single board computers (SBCs).

3. Design of Measurement Electronics

A source measure unit consists of a Digital-to-Analog Converter (DAC) to apply voltage and source current to the Device-under-Test (DUT) and an Analog-to-Digital Converter (ADC) to measure voltage and current flowing through the DUT with sufficient accuracy. Each here described MPP-channel consists of a DAC, ADC and a DUT.

The tailoring of the requirements is crucial to reduce cost per channel in the system, targeting costs of 10€/channel. The key reduction of requirements are as follows:

- Limit of the voltage to range between 0 and 5 V: This is in the voltage range for most commercial ICs required for the device. On the other hand, single-junction solar cells practically never exceed 2V in open-circuit voltage. This voltage range is a sweet-spot to directly interface with off-the shelve integrated circuits (ICs) while also covering the voltage range of typical single junction up to potentially triple-junction tandem devices.
- Limit of the source/sink current to a range from 100 µA to 50 mA: The order of magnitude of the current required to characterize solar cells is primarily a function of the irradiance and cell area. Typical laboratory scale perovskite solar cells have an active area in the range from 0.1 mm^2 to 1 cm^2. For the relevant irradiance of AM1.5 G this results in a current between 2 mA and 40mA (allowing for variations in the bandgap). The high end of the range is limited by the current source and sink capability of the setup, the lower range is limited by the measurement accuracy when using a shunt resistor for current measurement, parasitic leakage current through the analog multiplexers and the limited input impedance in the ADC during the conversion process.
- Limit data rate to below 1 sample-per-seconds (SPS): For practical application the stability of solar cells must be in the range of multiple years. Under constant illumination the data rate can be limited compared to typical current-voltage measurements which require multiple datapoints per second for fast measurements of the current-voltage-curve (JV-Curve) of a solar cell.

While reduction in cost is one challenge, the other challenge is scaling of the system. For the DUT to remain under the desired operating conditions (maximum power point), each channel must have at least one DAC so that voltages can be **continuously and individually** applied to each DUT, while the data acquisition can be multiplexed. This shows that control of the of the DACs is the limiting factor when it comes to scalability of the system, and the choice of this component is crucial in meeting the goal of the deliverable.

Between the market availability of the ICs, the cost of the ICs, the available software for interfacing with the ICs and the ability to scale, the MCP4728 from Microchip Technologies was chosen for this task. Each device has 4 individually controllable integrated DACs and the I2C address of each device can be changed to one out of 8 possible addresses. This allows to control up to 8 devices on a single I2C bus, providing 32 controllable outputs on a single I2C bus. This IC however does not have sufficient current handling capability for the requirement of ± 50 mA, therefor the output is buffered by the LMV234 from Onsemi, a unity-gain stable rail-to-rail quad operational amplifier.

From a cost perspective the DACs and ADCs are some of the most expensive items on the Bill of Materials (BOM). While the number of DACs cannot be reduced, due to the requirement of individual control, the ADCs input can be multiplexed to measure several DUTs sequentially. From a software and hardware availability perspective the ADS1115 from Texas Instruments was chosen as the ADC. The 4 available inputs and the extensive multiplexing setup capabilities also enables the system to perform 4-wire measurements. Two inputs are used for the current measurement through a measurement resistor and two inputs can be configured to measure the voltage at the DUT. The ADS1115 is also controlled through the I2C interface and can be configured to one of four addresses.

The ADC frontend multiplexing setup is realized through the 74HC4051 8-channel analog multiplexer/demultiplexer from Nexperia. One of the key characteristics is the low leakage current below 1 µA of each channel. This leakage is one fundamental factor limiting the low end of the current range and measurement accuracy.

Controlling the 8 states of the analog multiplexer requires three input pins, while these could be controlled from the main SBC, this would require more available pins and limits scaling. Thus, an I/O-Expander is used to control these pins via the I2C interface. Four of the remaining pins on the I/O-Expander are used as inputs to a voltage divider. The output from the voltage divider is buffered through the same operational amplifier LMV234 from Onsemi to provide a common ground for the DUTs that is neither 0V (Ground) or 5 V (VDD). This allows for cells of different polarity to be measured simultaneously and it can be used to measure IV-curves under reverse bias conditions, which can be scientifically relevant.

In the initial stages of the design, the scalability aspect was still not fully solved and two solutions were pursued. Many Single-Board-Computer (SBC) planned to control the devices on the I2C bus only expose a single I2C bus, thus necessitating multiple SBCs to scale efficiently, which then would have to be controlled on a network level (TCP/IP). The alternative solution considered was to use microcontroller boards with USB-connections, specifically the Raspberry Pi Pico (Pico Pi) to perform the multiplexing on the USB-Level, using of-the-shelve USB-hubs. Thus, the board was designed with the capability to plug in a Pico Pi directly on top, with a pin compatible header. This would have also allowed to compensate for problems with the I/O-Expander as each controlled pin is also exposed to the Pico Pi. While the solution featuring a Pico Pi has been proven unnecessary, the final design still features this connection. This would still enable this potential solution in case one wants to effectively control a single board, directly from a Personal Computer via USB through a Pico Pi.

The **final board layout of the measurement electronics unit is** depicted in Figure 2, top. As each board can address eight channels, for simplification these will be referred to as "octoboards" in the following.

Figure 1, bottom, shows the **topology of the complete MPPT system**:
- The system is controlled by a single board computer (Raspberry Pi 4B).
- Over four I2C busses, four bundles of 3-4 octoboards, each, are addressed by four parallel running python scripts.
- These electrical components can all be powered by a single power supply.
- Each octoboard is connected to one measurement-chuck unit (cf. Figure 2), allowing to contacts a total of eight solar cells.
- All substrates are mounted on a single sample holder plate which is placed inside a solar simulator.

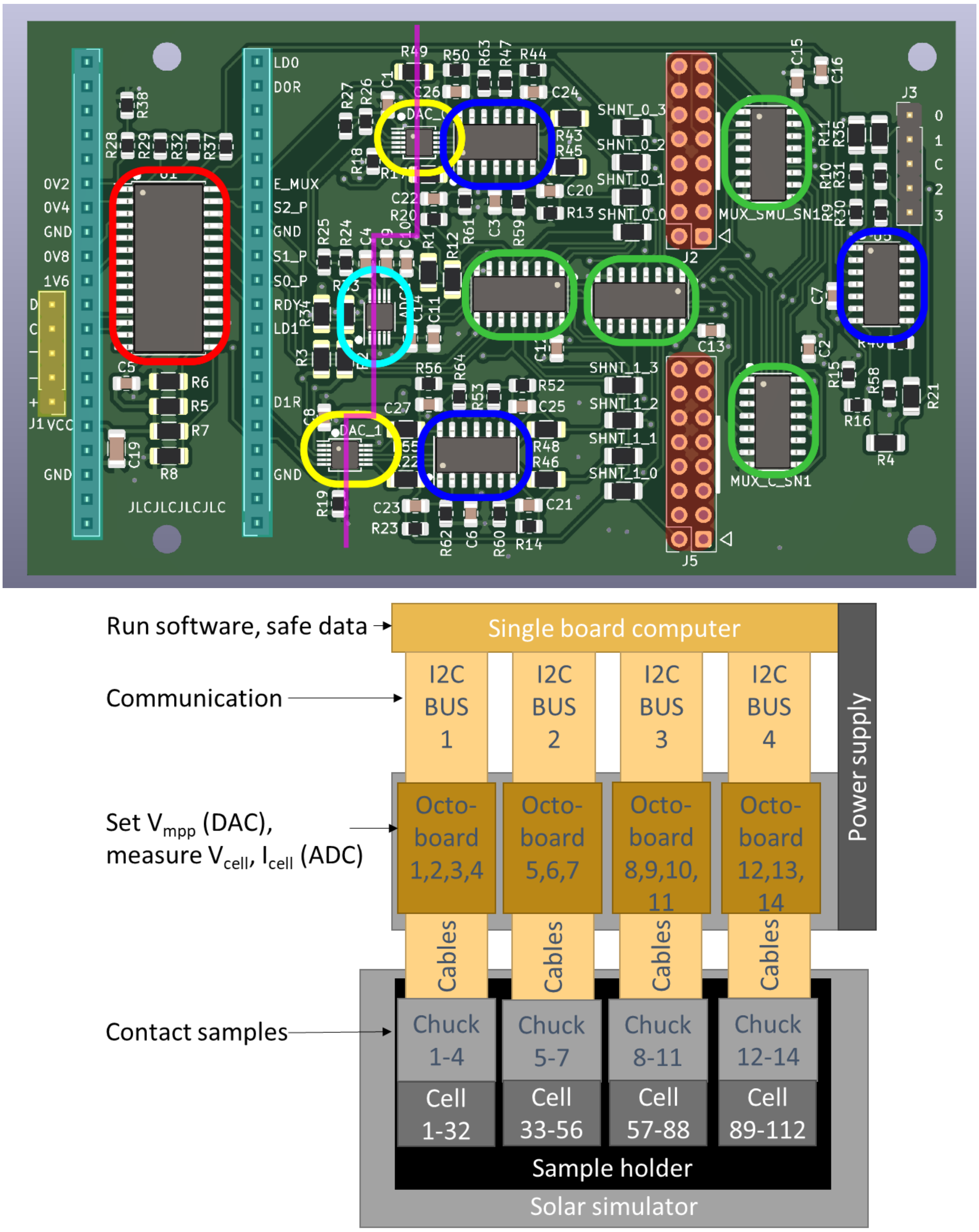

Figure 1*: Top: Final layout of a single eight-channel SMU. The 1x05 header for connection to an SBC is highlighted in yellow. Two 1x20 headers for connecting to a Pico Pi are highlighted in turquoise. The two 2x08 headers for connection to the DUTs are highlighted in orange. The I/O expander and analog multiplexers are circled in red and green, respectively, operational amplifiers in blue, the ADC in turquoise, and the two DACs in yellow. The magenta line separates the digital and the analog part of the board.*
Bottom: Topology of the MPPT system comprising the single board computer, octoboards and sample holder with mounted solar cells.

4. Construction of Sample Holder

To efficiently mount cells as DUTs a sample holder had also been developed. The holder consists of sample holder units that can provide the electrical connection of two substrates to the corresponding eight channel SMU octoboards via pogo-pins (cf. Figure 2). The holders are designed for the solar cell layout that has been agreed upon by the DIAMOND partners for ageing test, wherein four solar cells are embedded onto one 25x25mm² glass.

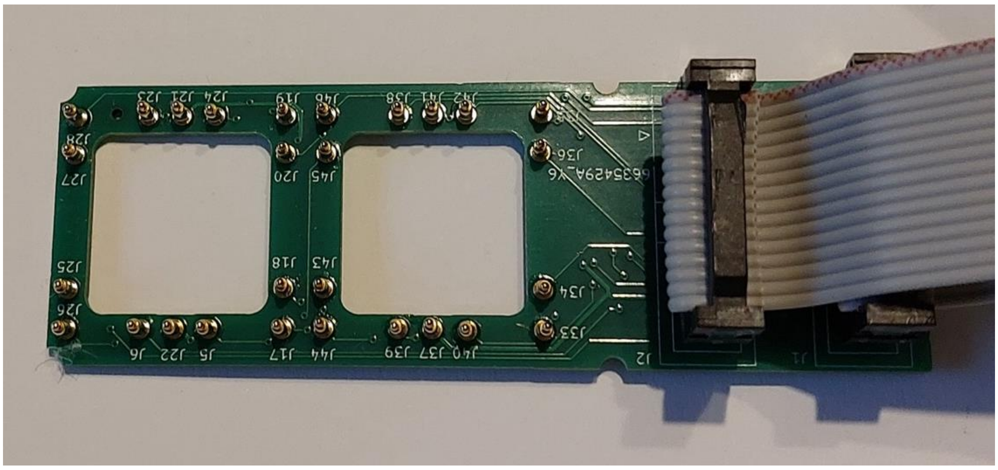

Figure 2*: Sample holder unit are designed for a minimal unit of two substrates to provide contact between the solar cells and the SMU boards. Two 2x08 headers on the right are used for connection to a single eight-channel SMU. Pogo pins on the left provide connecting two substrates. The hole in the PCB also allows for thermal connection of the substrates to a cooling unit.*

Figure 3 shows the design of the complete sample holder. The sample holder can hold to 28 substrates, i.e., 112 solar cells. Four to six substrates each can be individually mounted by pressing the samples onto the pogo-pins with a screw-mountable cover plate to provide electrical contact. The sample holder has a solid metal base plate with thermal connection to the substrates to allow good thermal coupling. This plate can be placed onto a thermally controlled chuck to enable active cooling. Electrical connection to the octoboards is provided via multipoint connectors. The frame between the samples (green in the CAD drawing of Figure 3) is made from electrically isolating PET to prevent shunting of the samples. The top side of the holder was designed to allow for optimal illumination of the sample while unwanted back reflection into the solar simulator is minimized. The plate can be placed under a solar simulator ageing station for indoor illumination or as well as outdoors.

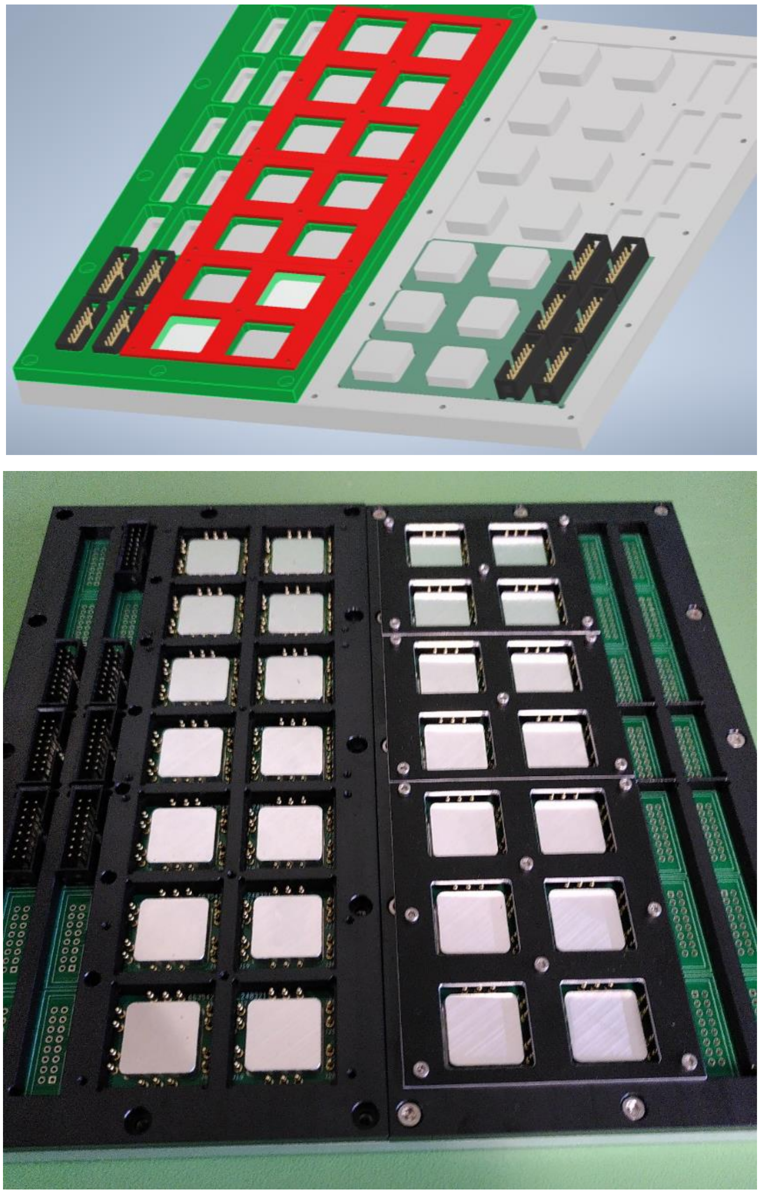

Figure 3*: Solar cell holder. Top: CAD drawing of the setup. 14 solar cells substrates of 4 cells each can be placed on the holder. Grey shows the metal baseplate that acts as a heatsink. The sample frame made of electrically non-conducting PET is shown in green. Samples are pressed onto the pogo-pins (not displayed here) with the front-plate displayed in red. This plate is designed for fast and flexible (de-) mounting of groups of 2 substrates. Electrical connection is provided by the multipoint connectors (black/ gold).*
Bottom: Photograph of the corresponding sample holder The photo shows the sample holder in a pre-finalized state to provider a better understanding of the assembly.

5. Software Design and Implementation of Data Logging

The software controlling the MPP tracker utilizes a Python-based system operated from a Raspberry Pi. The Raspberry Pi is also used for data logging and storage. This setup employs the Raspberry Pi's I2C interface to communicate with 4 octoboards on one I2C channel. The script has an Initialisation Process and an Operational Loop within which the MPP Algorithm is operated.

Initialisation Process:
The software begins by incrementally adjusting the common voltage and each individual DAC output to establish a stable common voltage level at around 2.5V. This careful adjustment is crucial to prevent any significant reverse biasing of the cells, yet the voltage allows MPP tracking irrespective of the individual cells' polarity. During this phase, the software also runs a preliminary operational loop for each channel, where it measures the short-circuit current (I_{sc}) at 0 V. If I_{sc} exceeds a predetermined threshold (I_{thresh}), the software methodically adjusts the voltage to find a good initial approximation of the maximum power point voltage (V_{mpp}) and current (I_{mpp}) for each cell, the sign of the inital I_{sc} is also used to determine the polarity of the cell at each respective channel. This part of the process is essential for setting a baseline for more precise power optimization in subsequent steps. If the short-circuit current is below the threshold, the channel is considered not to be connected and is excluded from the operational loop.

Operational Loop and Data Logging:
After the initial setting of V_{mpp}, the software enters the main operational loop, where the iterative MPP algorithm is executed. This algorithm operates through five steps on each channel where the initial I_{sc} was greater than the threshold. The final values are stored on the disk. This loop continues across all available channels, repeating indefinitely until the script is manually stopped. The key data points, time, voltage, and current are logged and saved to a CSV file. This file is systematically named using a convention that includes the I2C pins used, the I2C address offset of the specific SMU-Board (ranging from 1 to 4), and the channel number on the SMU-Board (ranging from 1 to 8). This approach to data management ensures that the recorded information is well-organized and easily retrievable for analysis, without the need to manually input parameters beforehand. With a simple CSV file as interface, it also allows for network-based storage or periodic cloud upload as a backup for the measured data.

MPPT algorithm:
The algorithm optimizes the voltage applied to the solar cell in each channel to maximize the power output. It starts by measuring the voltage (V_{cell}) and current (I_{cell}) from the solar cell to calculate its power output. This data is appended to the file corresponding to this specific channel. The power is then compared with that from the previous measurement. If the measured power after the last voltage adjustment has increased, the algorithm slightly increases the voltage adjustment step, continuing the adjustment of the applied voltage in the same direction to enhance power output further. If the power decreases or remains the same, the algorithm reduces the adjustment step and reverses the voltage adjustment direction, to allow for the possibility that the maximum power point is at a slightly lower voltage setting. The reduction of the voltage step is crucial to eventually modulate the applied voltage only a

minimal amount around a potentially stable maximum power point. The increase of the voltage steps in case the direction of voltage adjustment increases in delivered power by the solar cells allows for faster following of quick changes in the maximum power point. This process of adjusting, measuring, and refining continues is performed consecutively on each channel of the whole device.

5. Implementation and Testing

All PCBs have been designed with KiCad and manufactured by a commercial PCB manufacturer. Soldering of specific connectors and final cabling was carried out at University of Marburg. The cable management was optimized for ease of handling of the system for users while not compromising signal quality over the I2C data lines as well as measurement lines. The entire measurement electronics was stored in a custom-made housing unit that enables efficient handling and maintenance.

A demonstrator was designed for 14 octoboards, i.e., the system can measure 112 solar cells and has 112 channels. While this is a practicable size for a first MPPT system, our design is modular and easily scalable to larger numbers of channels.

Figure 4 shows the complete MPPT system. On the left, the 14 octoboards controlled by the Raspberry Pi single board computer are displayed. As shown on the right, these boards are connected to the 112 solar cells, mounted on the sample holder and placed inside the solar simulator ageing station.

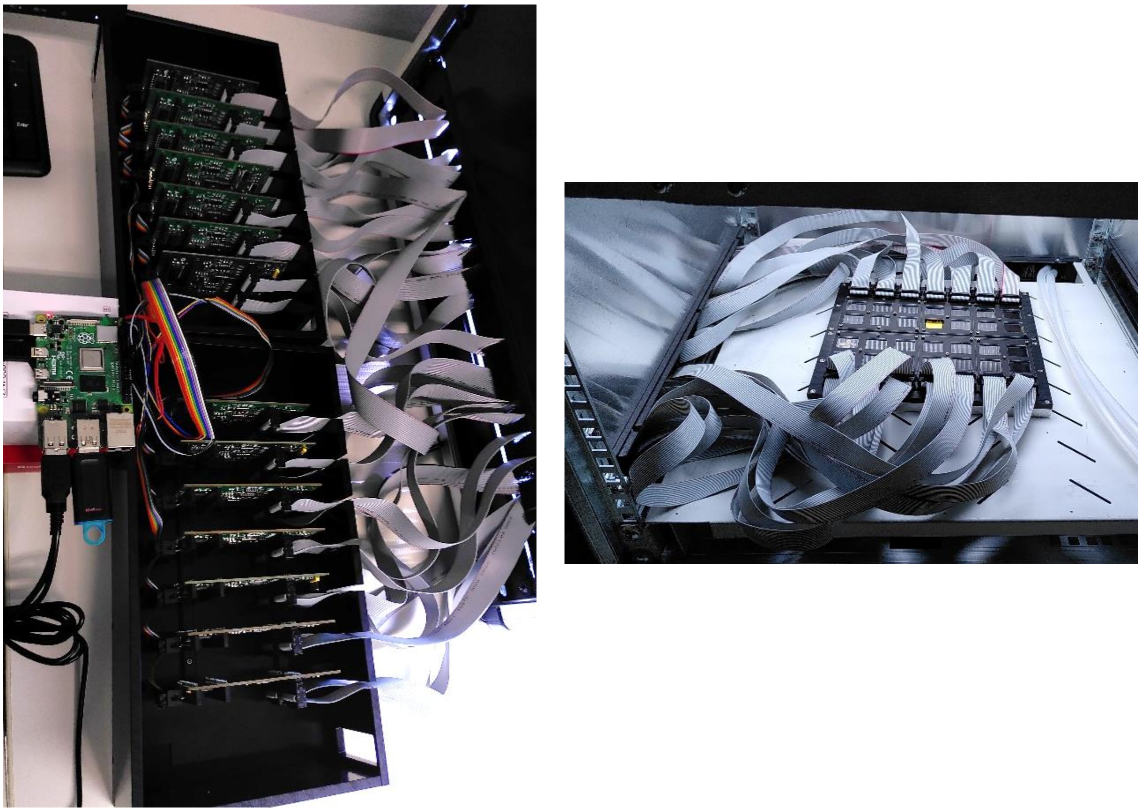

Figure 4: Photograph of the high throughput MPP tracking system that allows simultaneous MPP tracking of 112 solar cells. Left: array of 28 printed circuit boards comprising of the measurement electronics. All boards are controlled by a Raspberry Pi single board computer. Right: Sample holder to contact and hold 28 substrates comprising of a total of 112 solar cells. The sample holder is placed inside a class A solar simulator ageing station.

Figure 5 demonstrates the successful proof of concept: MPP tracking of perovskite solar cells under simulated solar light (Class A AM1.5g ageing station) has been demonstrated for >100 channels over >100 h.

Interpretation of the measured data: As one can see, the power at MPP of most devices degraded significantly within the first 20 h of measurement. We ascribe this to the fact that the samples were not encapsulated and hence exposed to air during the measurement, which is known to cause rapid degradation in most perovskite solar cells. Due to manufacturing issues in this batch of >100 solar cells, the power conversion efficiency of some samples was very low. Such low power samples are challenging to the system, but one can see that the MPPT system can also handles these cases. Some curves display a noisy signal, which is probably due to a high contact resistance between the tip of the pogo pins and the solar cell contact pads. In the following experiments, we will try to mitigate this by adding silver conductive paint to the samples to improve the contact resistance.

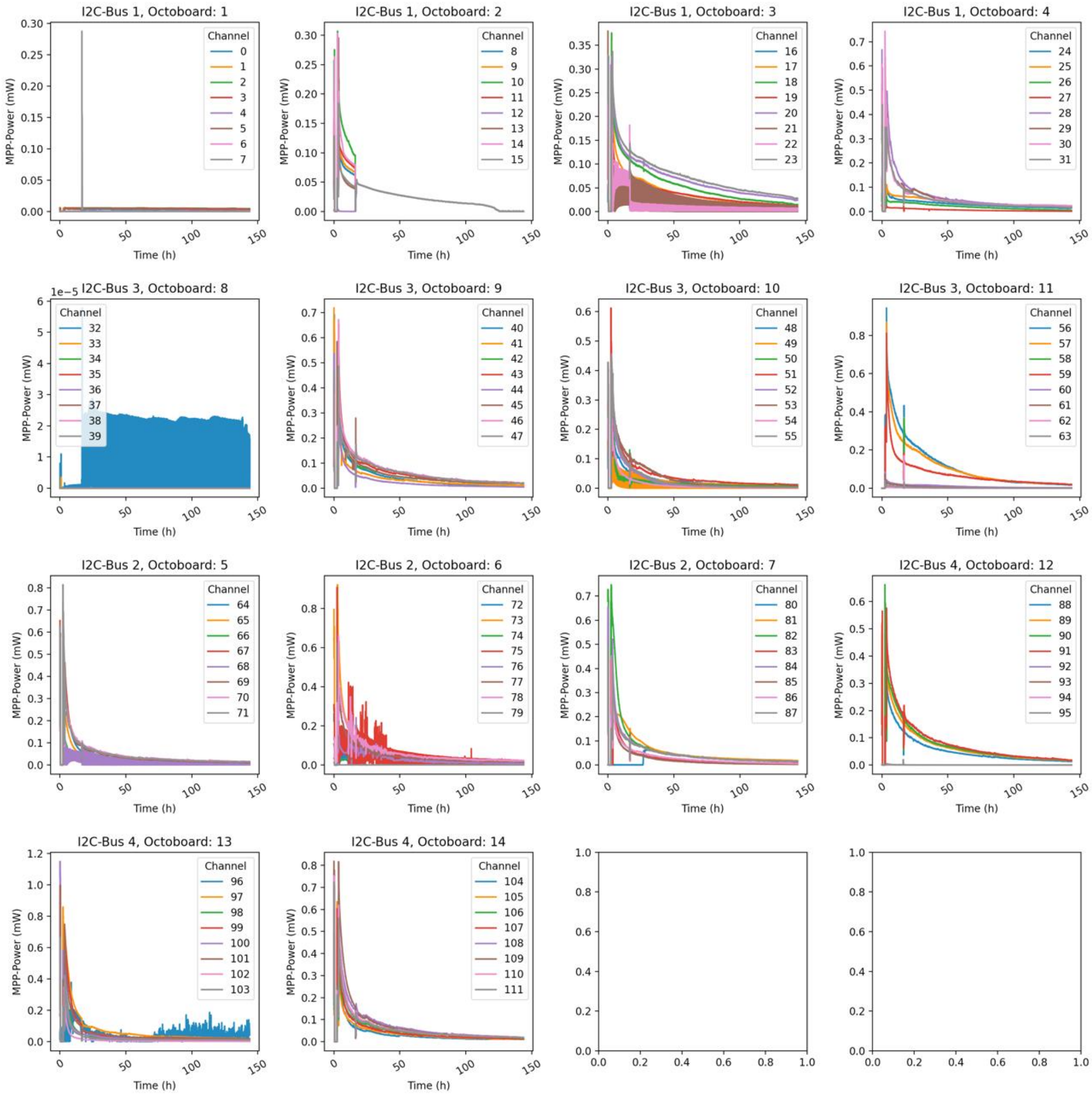

Figure 5*: Measured maximum power point values of 111 solar cells tracked with the MPPT system for > 100 h.*

7. Cost analysis

A key requirement of the low-cost laboratory MPP-tracker system is the comparatively very low cost per measurement channel, targeting a price as low as 10 €/channel.

The core technological component of the system is represented by the measurement electronics and computation units. By carefully designing the measurement electronics to fulfil the complete parameter space required for measuring laboratory type solar cells while on the other hand not unnecessarily overdesigning the measurement range, the price for electronic components could be significantly reduced. Likewise, for computational units, Raspberry Pi components offer a powerful and cost-efficient solution.

Besides the pure cost of hardware components, integration of electronics on a PCB represents a significant cost driver. German PCB-manufacturers have been considered but the cost estimate was about five times higher than the services from the Chinese manufacturer JLCPCB, which was finally chosen to assemble the parts.

In the following table and in Figure 6, the costs for the demonstrator system described in this report are listed. The cost of all electronic components adds up to 4.31 €/channel. One can clearly see that the octoboards account for approximately half of the cost, which is justified since this unit was custom designed and comprises many electronic components. It represents the core of the MPPT setup where all the measurement is carried out. The sample holders account for the second largest share of cost. This is especially due to the fact that the assembly of pogo-pins is associated with additional costs in PCB manufacturing due to their high aspect ratio. The other components, Raspberry Pi 4B, power supply, level shifter, and cables & connectors account in sum for less than ¼ of the cost.

Component	**Quantity used**	**Per piece price [EUR]**	**Price per channel [EUR]**
Octoboards	4	27.1	2.15
Sample holder unit	4		1.22
Raspberry Pi 4B	1	40.51	0.32
Power supply	1	10.51	0.08
Level shifter	4	1.45	0.05
Unit of cables & connectors	16	3.98	0.50
Total			**4.31**

All components cost include shipping, taxes and customs

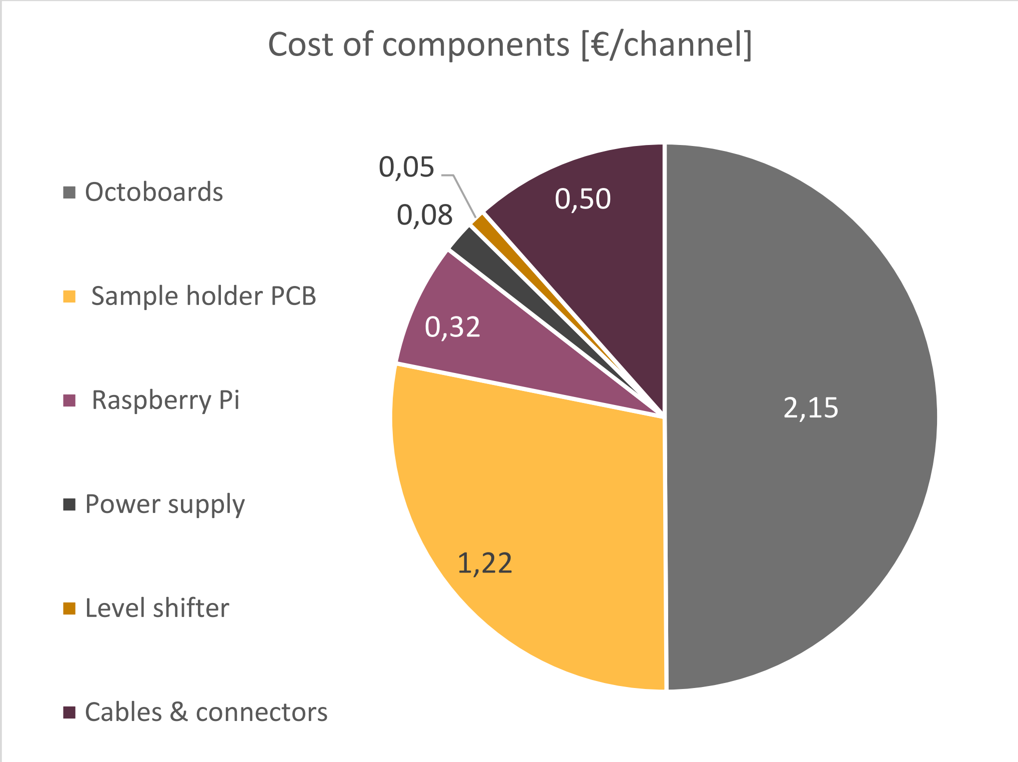

Figure 6. Proportionate cost of the price of each component of the MPPT system. The total cost is 4.31 €/channel.

It needs to be noted, that the material and manufacturing (tooling costs) for the mechanical parts of the sample holder and the box to hold the octoboards amounted to 1,511 EUR, i.e. 11.81 EUR/ channel. This design was not optimized for minimal cost and if costs need to be optimized, then a significantly cheaper sample holder can be constructed. Yet, such a cheaper holder may not be thermally coupled to a cooled chuck. In the above calculation, the personnel costs for the assembly of the cables and connecters were also not included. This process required several iterations and we are therefore not able to provide an accurate estimate of the required assembly time.

Overall, the assessment shows that the core component, namely the measurement and processing units, can be manufactured at very low costs well below 10 EUR per channel in a modular way that allows for straight forward scaling of the system. These components are universally deployable virtually in any laboratory environment. Peripherical components like the sample holder need to be individually adjusted to the specific laboratory or outdoor environment where the MPPT system is to be installed.

8. Definition of outdoor ageing conditions

As agreed in the grant agreement, in this deliverable report, the conditions for outdoor ageing in various partner laboratories within WP5 are also specified in D5.2 as follows:

Partner	**UP**	**UU**	**SNX**	**FhG**	**CEA**
Light source	Natural sunlight	Natural sunlight	Natural sunlight	Natural sunlight	Natural sunlight
Electrical load:	Open circuit Option of MPP tracking for one channel.	Open circuit, short circuit and MPP tracking are possible.	Open circuit. Option of MPP tracking for two channels.	MPP or open circuit	MPP or open circuit
Sample type (cell or module)	For simulated light up to 12x12 cm2, for natural light no limit.	Both cell or module.	Up to 20x20 cm (1 sample).	Small cell and module (µW to 25 W, 0-50V µA up to 1 A)	Both cell or module.
Periodic I-V measurements	Outdoor measurement for one module/panel.	Possible for natural light. Additional measurements can be added under simulated sunlight.	Possible for natural light. Additional measurements can be added under simulated sunlight.	Possible for natural light. Additional measurements can be added under simulated sunlight.	Possible for natural light. Additional measurements can be added under simulated sunlight.
Peripherical measurements:	Irradiance, temperature and humidity.	Irradiance and temperature.	Irradiance and temperature.	Irradiance and temperature.	Irradiance and temperature.
Orientation of the samples	Flexible adjustment of orientation and angle for optimal orientation.	True south, 42° elevation, can be adjusted with special fixtures.	South facing, optimal angle.	South-facing and fixed at the optimal angle (32°).	South-facing and at optimal angle.
Encapsulation	Small cells can be tested in air tight box (maximum illumination area of 15x15 cm2).	Encapsulation is needed. If an air-tight box is provided, it can be also mounted.	Encapsulation is needed. SNX can also build a transparent air tight box customized to desired sample sizes.	Samples have to be encapsulated, no air tight box available	Samples have to be encapsulated.

9. Conclusion

For this deliverable, an MPPT system was successfully designed, implemented, and tested, at a cost well below the already ambitiously targeted aim of 10 € per channel.

This was facilitated by the design and manufacturing of measurement electronics and sample holder. Software and corresponding data logging technologies have been successfully developed. The viability of the system was successfully tested by measuring >100 perovskite solar cells in the MPPT for a time >100 h.

This is an essential step forward for the goals of the DIAMOND project. In the next months, the system will be used to acquire statistically relevant ageing data of a larger numbers of solar cells.

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