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Raspberry Pi based photovoltaic I-V curve tracer

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ABSTRACT

This paper details the design and implementation of a photovoltaic current – voltage (I-V) tracer. The I-V tracer employs a capacitive load controlled by a raspberry pi model 4B. The complete measurement system includes protections, capacitor charging/discharging power electronics and current, voltage, irradiance and temperature sensors. Results, which include maximum power point, open circuit voltage, short circuit current and module efficiency, are displayed on an LCD touch display. Detailed description of the required software and the graphical user interface is also presented. This measurement system is very useful for testing photovoltaic installations, allowing an immediate verification whether the panels fulfill with the specifications and detection of possible failures.

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Introduction

Specifications table

Hardware name	PV IV curve tracer
Subject area	• Engineering and Material Science
Hardware type	• Field measurements and sensors
Closest commercial analog	No commercial analog is available
Open source license	GNU Lesser General Public License (LGPL) 3.0
Cost of Hardware	1151.85 €
Source file repository	https://osf.io/g8w2q/
OSHWA certification UID	ES000026

Hardware in context

In photovoltaic (*PV*) installations it is very important to know the characteristics of the solar panels used. This information is provided in the *PV* panels manufacturers datasheets, where some specific working points of the panel are detailed (open circuit, short circuit, and maximum power). This information is valid under standard test conditions (usually constant irradiance = 1000 W/m^2, temperature = 25 °C and air mass = 1.5) and extrapolations to other working conditions must be

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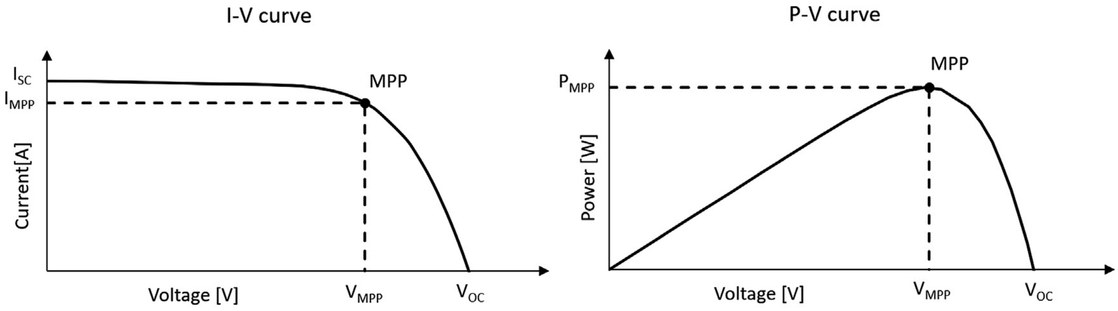

Fig. 1. *I-V* and *P-V* curves of a photovoltaic panel.

done with different formulas provided by the manufacturer or found in the technical literature. Besides, other useful information provided in the datasheet is the current versus voltage (*I-V*) curve and the power versus voltage (*P-V*) curve of the photovoltaic panel, these curves give a full-picture of the solar panel behaviour and how the working voltage affects the extracted current or power. Fig. 1 illustrates a typical *I-V* and *P-V* curve and the key points.

These curves change with the temperature, irradiance, ageing and many other external conditions during the panel's life. That is the main reason why photovoltaic engineers use curve tracers to validate and test photovoltaic installations. The *I-V* / *P-V* curves can be measured periodically, given a detailed analysis of the behaviour when compared with the presented in the datasheets, and being a very useful tool to detect any problem in the *PV* installation (dirt, breaks, failures, shadows, ...) and to verify if the module meets with the efficiency parameters declared by the manufacturer.

To measure photovoltaic curves different methods have been proposed in the literature, the principle of operation of all of them is the same, they are based on a controlled sweep of the current provided by the panel, from the short circuit point to the open circuit point [1]. In [2] it is presented the development of a low-cost *I–V* curve tracer acquisition system based on TivaC Series LaunchPad, although the estimated material cost is less than 200 euros, it is not a stand-alone system, it needs a computer and also Labview software, which increments the total costs of the system and compromises its portability. In [3] it is also presented a low-cost *PV I-V* curve tracer, based on the variable load method, implemented with a MSP430 microcontroller, nevertheless this system also needs a computer to visualize the data and it is only valid for low power measurements. Finally, in [4] it is introduced a I-V curve tracer for PV research and teaching, this tracer is based on the capacitance method [5] and it is controlled by STM32F334R8 microcontroller, the user interface is developed in Visual Basic so an external computer is needed to run it.

The aim of this work it to develop a portable stand-alone *PV* I-V curve tracer with all functions and the user interfaces included so there is no need of an external computer. The system is based on the capacitive load method. This measurement method is based on connecting the *PV* module to a high-capacity discharged capacitor, the capacitor will charge from zero volts up to the open circuit voltage of the panel, sweeping the entire characteristic curve [5]. During the charge of the capacitor the *PV* module current and voltage are sensed, and the temperature and irradiance measured. A raspberry pi model 4B is used for generating all the control signals needed, acquire the data, process the information, and present the output in a touch LCD screen. Besides, periodically measurements can be programmed, and the curves can be saved locally, or automatically exported to an USB stick or to a shared drive connected via ethernet or wi-fi.

Hardware description.

The measuring device presented in this work consists of a portable solar panel *I-V* / *P-V* curve tracer that has a graphical interface for an easy interaction with it. It has been designed to be able of measuring the *I-V* curve generated by a photovoltaic generator with a maximum voltage of 200 V and a maximum current of 20 A. As has been mentioned, the system is based on the capacitive load method. During the capacitor charge process, pairs of voltage and current values are acquired at the output of the solar panel, which will correspond to those of the *I-V* characteristic curve of the panel. The hardware comprises three main parts:

- Measurement circuit, which will safely connect and disconnect the panel to the capacitor and sense the current and the voltage of the panel during the measurement.
- Control circuit, based on a Raspberry Pi computer, is responsible to control the measurement circuit, acquire the *I-V* data points, display the results, and interact with the user.
- Power supply, that powers the device from the main grid through AC/DC converter.

Measurement circuit

The measurement circuit presented in Fig. 2 is composed by two power relays (K1 and K2), a capacitor (C), a resistance to discharge the capacitor (RL), an IGBT (IGBT1), a voltage sensor (V) and a current sensor (A). An electrolytic capacitor with

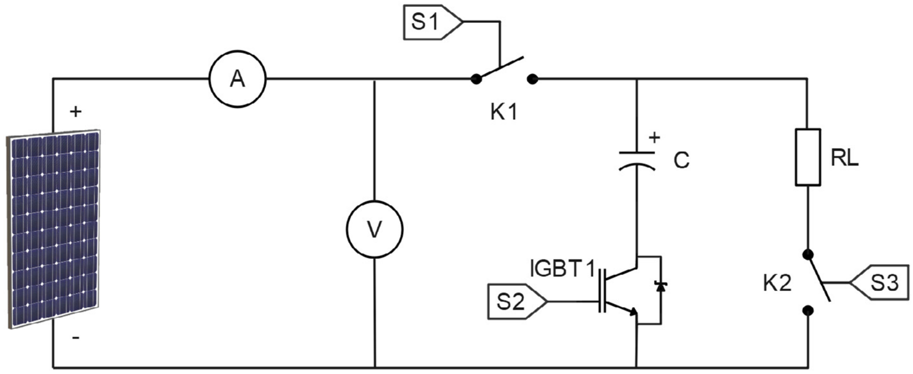

Fig. 2. Measurement circuit diagram.

capacitance of 2200 μF has been selected (Nichicon LNX2G222MSEG), the discharge resistance value is 120 Ω (ARCOL HS50 120R), power relays (G7L-2A-X-L of OMRON) have been used to control the connection and disconnection of the capacitor with the discharge resistance and the solar panel. An IGBT Infineon IHW20N120R5 is used to start the capacitor charging, without the rebounds and delays associated to the relays. Finally for the acquisition of the voltage and current, two transducers have been used. On the one hand, the LEM LV-25P for voltage measurement, and, on the other hand, the LEM LA 100-P for current measurement, both with galvanic isolation between the primary circuit (solar panel output) and the secondary circuit (acquired voltage signal). For the current measurement, four turns of the solar output cable are used to increase the precision and use all the sensor measurement range. As can be seen in Fig. 2, the voltage is measured directly at the solar panel output, and not at the capacitor terminals. Therefore, the measurement carried out by this device is a true reflection of the behaviour of the panel.

As can be seen in Fig. 2 there are three different control signals in the measurement circuit: S1, which manages K1 relay; S2, which controls the IGBT and S3, which manages K2 relay. These signals are isolated via opto-couplers from the control circuit for safety reasons. Table 1 shows the controlled sequence to perform a measurement, and Table 2 describes the purpose of each step in the sequence.

Table 1
States of each control signal at each step.

	S1	S2	S3
STEP 1	OFF	ON	ON
STEP 2	ON	OFF	OFF
STEP 3	ON	ON	OFF
STEP 4	OFF	ON	OFF
STEP 5	OFF	ON	ON

Table 2
Description of each step.

STEP 1	Capacitor discharge before measurement
STEP 2	Solar panel connection to the measurement system.
STEP 3	Data acquisition. The IGBT is activated, and the sweep is performed
STEP 4	After the sweep, the panel is disconnected from the circuit.
STEP 5	Capacitor discharges after measurement

Control circuit

Fig. 3 represents a diagram of the control circuit, and its most significant parts are: the single board computer (Raspberry Pi 4 Model B (8 GB)); the USB oscilloscope (Analog Discovery 2); the AC/DC converter (Adafruit ADS1115); and the touchscreen (Raspberry Pi 7″ Touch Display).

A Raspberry Pi 4 Model B has been chosen as a single board computer to make the device completely portable. Moreover, it manages all the control signals via the 40-pin GPIO (General Purpose Input/Output) header.

A Digilent Analog Discovery 2 (AD2) USB oscilloscope has been chosen to acquire the voltage signals generated by the voltage (Oscilloscope channel 1) and current (Oscilloscope channel 2) sensors. This device is powerful enough to carry

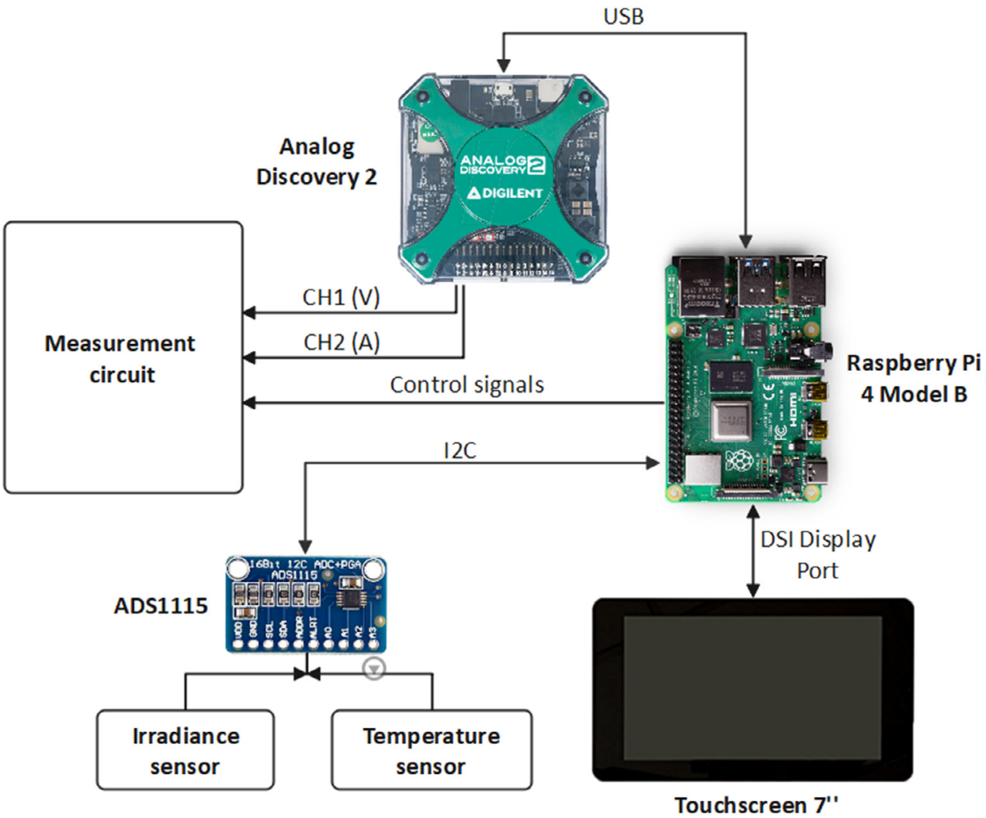

Fig. 3. Control circuit diagram.

out this task, and small enough to be included within the measurement device. Regarding its configuration, it has been programmed so that it measures with a resolution of 0.32 mV and with a sampling frequency of 320 kHz.

Irradiance and temperature analog sensors are conditioned by the Adafruit ADS1115, a 16-bit analog-to-digital converter with I^2C interface. The sensor 7821 from DAVIS has been selected for the irradiance measurement, and the LM35 for temperature measurement.

Power supply

The power circuitry (Fig. 4) begins at the IEC C13 connector, which is connected to an AC / DC converter (TRACO POWER TMP 30452C) that converts 85–264 VAC to isolated 5 VDC and 12 VDC. The 5 VDC output is used by the control circuit

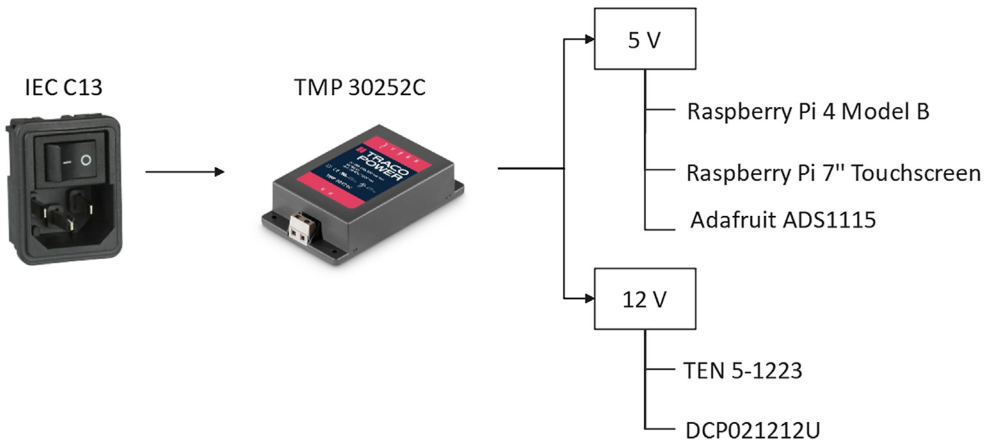

Fig. 4. Power supply diagram.

(Raspberry Pi, touch screen and ADS1115 AC / DC converter), and the 12 VDC output is used by two DC / DC converters, which supply the measurement circuit. The converter TEN 5–1223 is responsible for supplying ± 15 V to the current and voltage sensors and the DCP021212U is used to provide isolated control signals.

Design files summary

Bill of materials

Build instructions

A two layers Printed Circuit Board (PCB) has been designed to implement the measurement circuit, the control circuit, and the power supply circuit. Its fabrication is the first step of the assembly, and it may be outsourced to a PCB service provider using the provided Gerber files (iv_tracer_Gerbers.zip) (Table 3). Fig. 5 shows a render of the final PCB designed.

The second step is to populate the fabricated PCB (Fig. 6). Files iv_tracer.sch and iv_tracer.brd (Table 4) indicate the location of each component (Table 5) and the values of the resistors and capacitors. The time required to complete this step is about 6 h, and the necessary tools for soldering PCB are: a soldering iron, tin, flux, and isopropyl alcohol for PCB cleaner.

External connections to PCB is the third step. Table 6 shows the PCB connections with the other components of the device, and a diagram of the complete system assembled can be visualized in Fig. 7.

Next, enclosure machining can be done using the Blueprints.pdf file, which contains the blueprints of all the holes in the box where the different connectors and the screen will be placed. Finally, Fig. 8 shows how the components are positioned inside the box. The time required to complete this final step is about 8 h. Fully assembled device is illustrated in Fig. 9.

Table 3
Design Files Summary.

Design file name	File type	Open source license	Location of the file
iv_tracer_EG_program.py	Software	GNU Lesser General Public License (LGPL) 3.0	https://osf.io/zrs5f/
iv_tracer_library.py	Software	GNU Lesser General Public License (LGPL) 3.0	https://osf.io/htkbv/
iv_tracer_Gerbers.zip	CAM files – PCB	GNU Lesser General Public License (LGPL) 3.0	https://osf.io/qm7se/
iv_tracer.brd	CAD file - PCB	GNU Lesser General Public License (LGPL) 3.0	https://osf.io/vpwre/
iv_tracer.sch	CAD file - Schematic	GNU Lesser General Public License (LGPL) 3.0	https://osf.io/hujwn/
Blueprints.pdf	PDF	GNU Lesser General Public License (LGPL) 3.0	https://osf.io/yqukd/

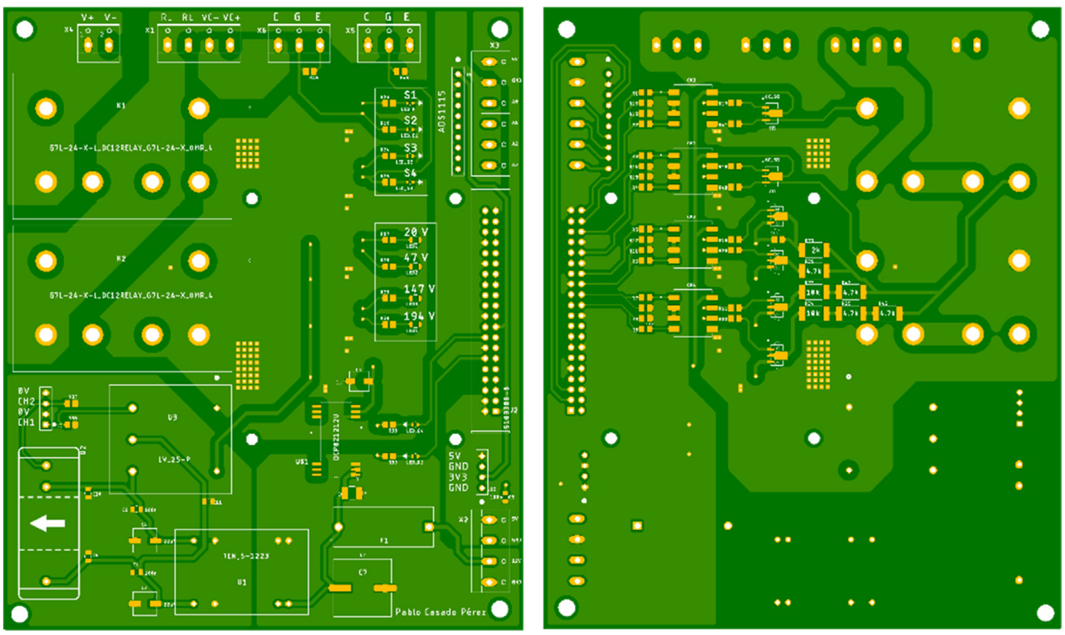

Fig. 5. 2 layers PCB render.

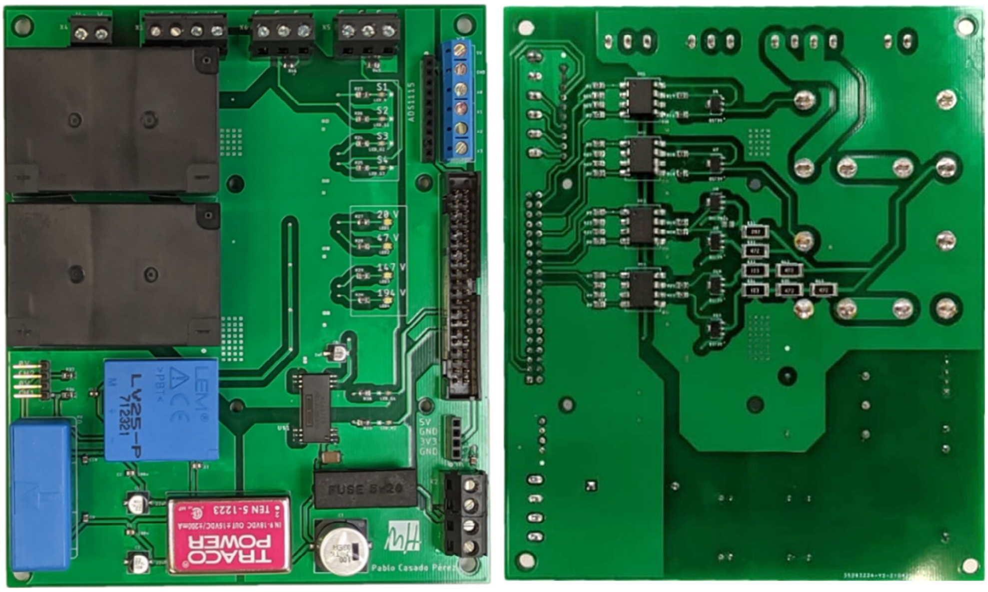

Fig. 6. PCB with all components soldered.

Table 4
Design Files Description.

Design file name	Description
iv_tracer_EG_program.py	Python script for the Graphic User Interfaces.
iv_tracer_library.py	Python script. Requires installation of Python 3 or higher.
iv_tracer_Gerbers.zip	Collated Gerber and drill files for PCB manufacture. An external manufacturer will likely require these files, packaged within the .zip archive.
iv_tracer.brd	BRD (Autodesk Eagle) format design files for the printedcircuit board.
iv_tracer.sch	SCH (Autodesk Eagle) format design files for the design of thecircuit board.
Blueprints.pdf	PDF with the blueprints of all the holes in the box.

Table 5
Bill of Materials.

Designator	Component	Number	Cost per unit -EUR	Total cost -EUR	Source of materials	Material type
Raspberry pi 4 8 GB	RASPBERRY PI 4 MODEL B 8G	*1*	*62.82 €*	*62.82 €*	Digikey	*Other*
Heatsink RPi case	4341	*1*	*20.90 €*	*20.90 €*	Digikey	*Other*
Raspberry Pi 7″ Touch Display	8,997,466	*1*	*50.26 €*	*50.26 €*	Digikey	*Other*
Analog Discovery 2	410–321	*1*	*334.20 €*	*334.20 €*	Digikey	*Other*
Voltage Transducer	LV 25-P	*1*	*22.81 €*	*22.81 €*	Digikey	*Other*
Current Transducer	LA 100-P	*1*	*51.31 €*	*51.31 €*	Digikey	*Other*
Optoisolator	HCPL-2231-500E	*4*	*5.77 €*	*23.08 €*	Digikey	*Other*
DC DC Converter 12 V	DCP021212U	*1*	*8.04 €*	*8.04 €*	Digikey	*Other*
AC/DC Converter 5 V 12 V	TMP 30252C	*1*	*65.67 €*	*65.67 €*	Digikey	*Other*
DC/DC Converter +/-15 V	TEN 5–1223	*1*	*21.70 €*	*21.70 €*	Digikey	*Other*
Relay 20A 12 V	G7L-2A-X-L DC12	*2*	*72.94 €*	*145.88 €*	Digikey	*Other*
BJT Transistor NPN 350 V	BST39TA	*2*	*0.33 €*	*0.66 €*	Digikey	*Semiconductor*
MOSFET N 240 V	BSS87H6327FTSA1	*4*	*0.38 €*	*1.51 €*	Digikey	*Semiconductor*
IGBT Transistor 1200 V	IHW20N120R5XKSA1	*1*	*2.78 €*	*2.78 €*	Digikey	*Semiconductor*
Fuseholder	4527	*1*	*0.57 €*	*0.57 €*	Digikey	*Other*
Fuseholder cover	4527C	*1*	*0.27 €*	*0.27 €*	Digikey	*Other*
Fuse	5SF 1-R	*1*	*0.20 €*	*0.20 €*	Digikey	*Other*

Table 5 (*continued*)

Designator	Component	Number	Cost per unit -EUR	Total cost -EUR	Source of materials	Material type
C	LNX2G222MSEG	*1*	*43.56 €*	*43.56 €*	Digikey	*Other*
C3, C4	EEE-FK1E220R	*2*	*0.35 €*	*0.70 €*	Digikey	*Other*
C7	EEE-TK1J101AQ	*1*	*1.59 €*	*1.59 €*	Digikey	*Other*
C8	EEE-HD1H1R0R	*1*	*0.30 €*	*0.30 €*	Digikey	*Other*
C6	CL21B473KCFNNNE	*1*	*0.08 €*	*0.08 €*	Digikey	*Other*
C1, C2, C5, C9, C10, C11, C12	CL21B104KCFNNNE	*6*	*0.08 €*	*0.48 €*	Digikey	*Other*
R31	RMCF2512JT2K00	*1*	*0.25 €*	*0.25 €*	Digikey	*Other*
R33, R34	RMCF2512JT10K0	*1*	*0.25 €*	*0.25 €*	Digikey	*Other*
R32, R35, R42, R43	RMCF2512JT4K70	*4*	*0.25 €*	*1.00 €*	Digikey	*Other*
LED1, LED2, LED3, LED4	EAST2012WA1	*4*	*0.21 €*	*0.85 €*	Digikey	*Semiconductor*
LED_R, LED_R2	SML-D12U1WT86	*2*	*0.10 €*	*0.19 €*	Digikey	*Semiconductor*
LED_G1, LED_G2, LED_G3, LED_G4	SML-D12M1WT86	*4*	*0.10 €*	*0.38 €*	Digikey	*Semiconductor*
Connector Header	5103308–8	*1*	*2.27 €*	*2.27 €*	Digikey	*Other*
RPi Conector	1988	*1*	*2.47 €*	*2.47 €*	Digikey	*Other*
HDMI 2.0 Cable	BC-HH003F	*1*	*5.85 €*	*5.85 €*	Digikey	*Other*
USB 3.0 Cable	A-USB30AM-30AM-050	*2*	*4.63 €*	*9.26 €*	Digikey	*Other*
RJ45 Cable	AMJG0808-0050-BKB-26	*1*	*2.06 €*	*2.06 €*	Digikey	*Other*
Aluminium box 250x250	1550WNBK	*1*	*41.92 €*	*41.92 €*	Digikey	*Other*
RJ45 Connector	EHRJ45P5ES	*1*	*10.20 €*	*10.20 €*	Digikey	*Other*
USB 3.0 Connector	AC-USB3-AAB	*2*	*12.25 €*	*24.50 €*	Digikey	*Other*
HDMI Connector	AC-HDMI-RRB	*1*	*10.26 €*	*10.26 €*	Digikey	*Other*
IEC320-C14 Connector	1–1609112-3	*1*	*9.62 €*	*9.62 €*	Digikey	*Other*
Temperature sensor	LM335Z/NOPB	*2*	*1.43 €*	*2.86 €*	Digikey	*Other*
Davis irradiance sensor	6450	*1*	*168.29 €*	*168.29 €*	Davis instruments	*Other*
			TOTAL	*1151.85 €*		

Table 6
PCB connections.

Connector	Connected to
X1-1	Discharge resistor
X1-2	Discharge resistor
X1-3	Negative terminal capacitor
X1-4	Positive terminal capacitor
X2-1	+Vout1 TMP 30252C
X2-2	-Vout1 TMP 30252C
X2-3	+Vout2 TMP 30252C
X2-4	-Vout2 TMP 30252C
X3-1	5 V to sensors
X3-2	GND to sensors
X3-3	Irradiance sensor data
X3-4	Temperature sensor 1 data
X3-5	Temperature sensor 2 data
X4-1	Solar panel positive connector
X4-2	Solar panel negative connector
X6-1	IGBT 1 Collector
X6-2	IGBT 1 Gate
X6-3	IGBT 1 Emitter

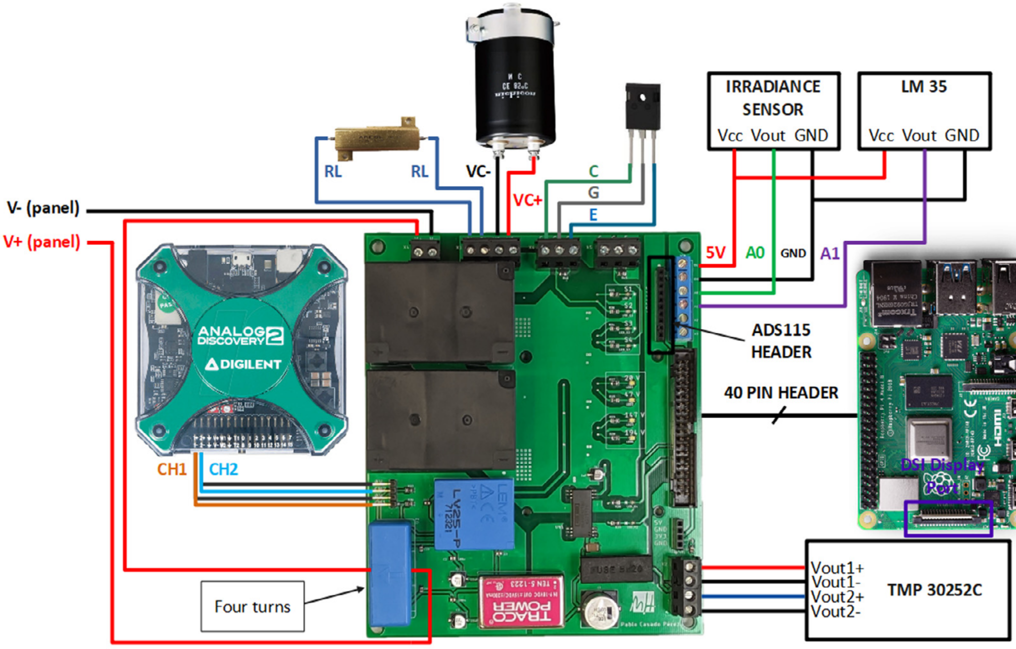

Fig. 7. Diagram of the PCB connections.

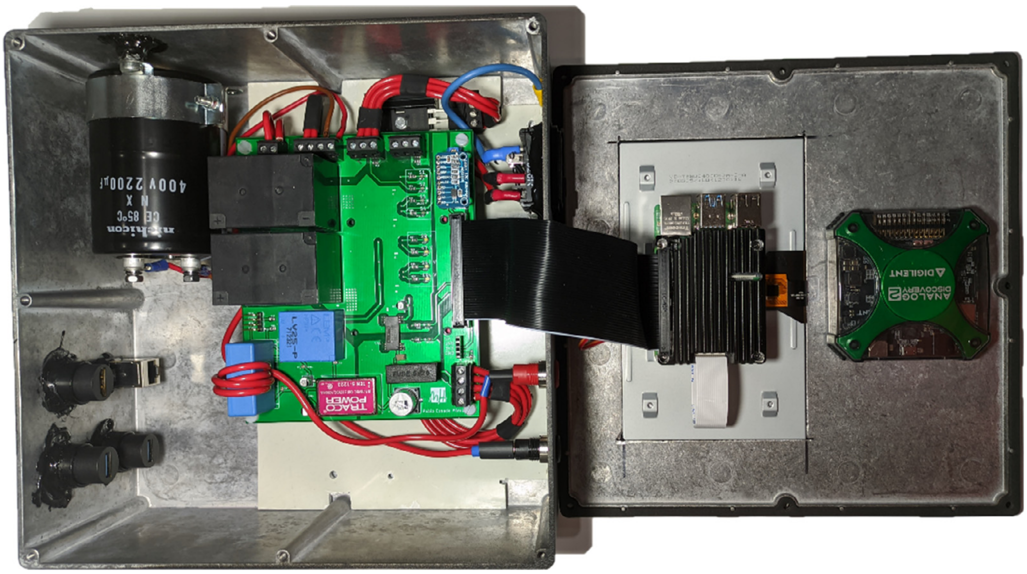

Fig. 8. Inside view of the device. In this image are not the USB, HDMI, and Ethernet cables that connect the Raspberry Pi to the connectors on the case. The USB cable that connects the Raspberry Pi with the Analog Discovery 2 is also not connected. The TMP 30252C converter is under the PCB.

Fig. 9. View of the rear face (I), where there are the positive and negative connectors for the solar panels, and the connector for the electrical network; the front face (II), where are the USB, HDMI, and Ethernet Raspberry Pi connectors of the; and the upper cover (III), which only contains the touch screen.

Operation instructions

First, the I-V tracer should be powered through the IEC C13 switch. Second, open a terminal window and execute the Python script ''iv_tracer_EG_program.py''. Then, the graphical user interface is shown on the screen. In Figs. 10 – 13 are explained all the buttons and their purpose to perform a measurement. As can be seen in Figs. 14 – 15, there is a section devoted to display the results, where a preview of the last measure can be consulted. Also, the parameters and I-V and P-V curves of a specific measurement can be checked.

Fig. 10. Starting screen. At the bottom there is a button for each section: Home (Section for starting new measures); Results (Section to consult previous measures); Settings (Section to configure measurement parameters); Exit (Button to close the program).

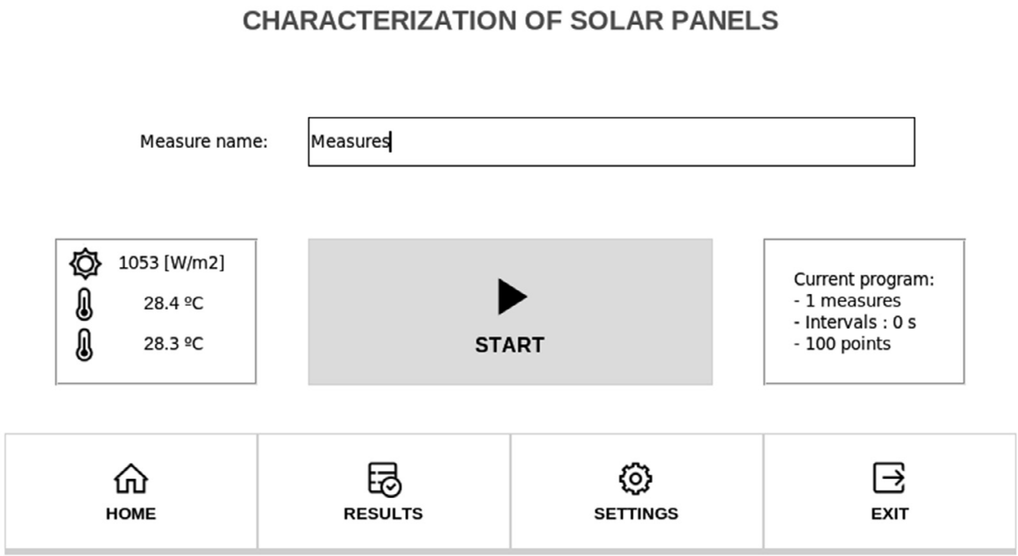

Fig. 11. Home screen. At the top there is a text field to write the name of the folder where the measurements will be saved. On the left is the current irradiance and temperature data. On the right is the current program settings. In the centre is the button to start the measurement.

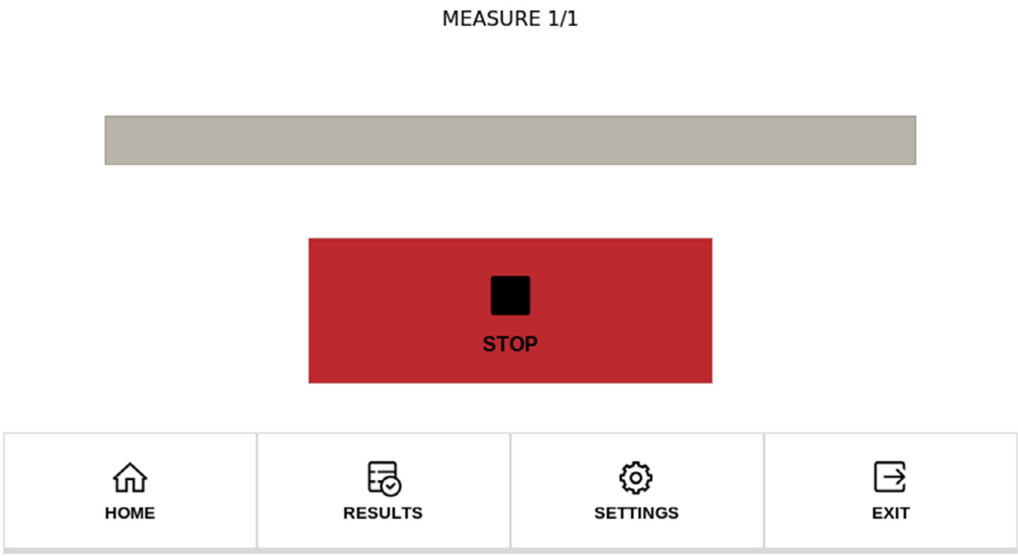

Fig. 12. Measurement screen. It is generated by pressing the start button. To stop press the red button. In the centre there is a progress bar of the measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

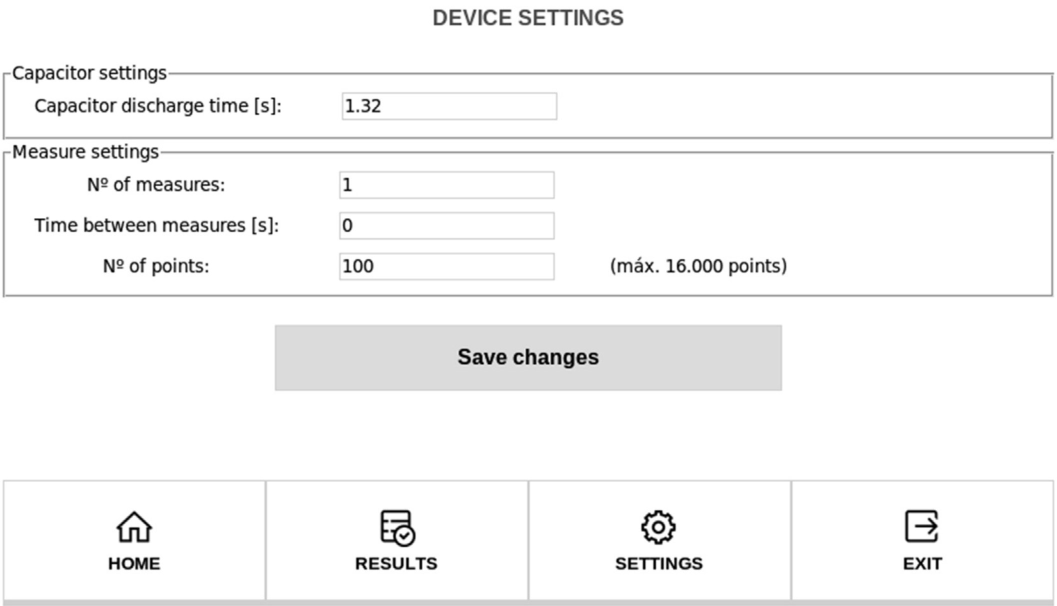

Fig. 13. Device settings screen. The capacitor discharge time is 1.32 s by default. If the capacitor is changed, it will have to be modified. In addition, the number of measurements in a series, the time between measurements, and the number of points in each measurement (It is limited to 16000) can be modified.

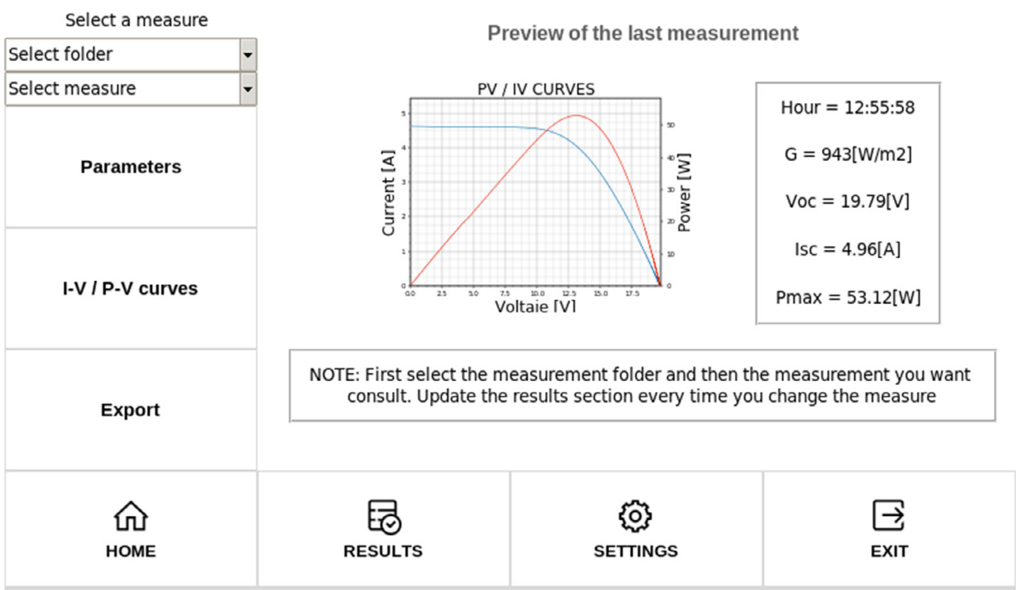

Fig. 14. Results screen. First, a preview of the last measurement appears on the screen. To see a specific measure, select the folder and the measure that you want to consult. Then select parameters, *I-V* / *P-V* curves, or export (Measurements can be exported to a USB stick).

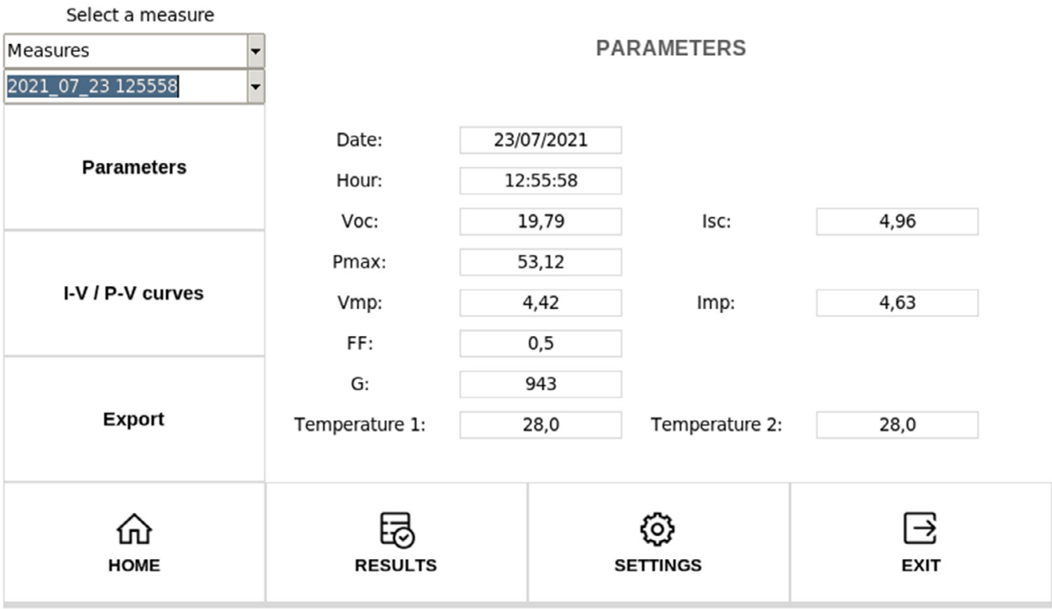

Fig. 15. Parameters screen.

Validation and characterization

To test the device's operation, tests have been carried out with the SR-P660255 panels of Sunrise. Table 7 shows its characteristics under Standard Test Conditions (STC) according to its manufacturer:

Table 7
Manufacturer information with STC (Standard Test Conditions): 1000 W/m^2; AM = 1.5; 25 °C.

	1000 W/ m^2 (STC1)
Maximum power (Pmax)	255 W
Voltage at MPP (Vmpp)	30.24 V
Current at MPP (Impp)	8.44A
Short circuit current (Isc)	9.11A
Open circuit voltage (Voc)	37.49 V

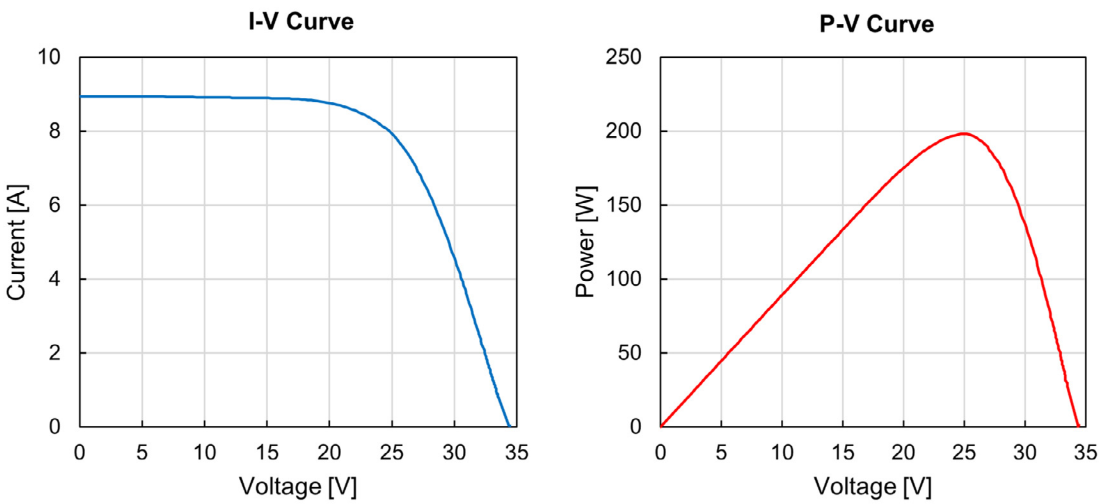

Fig. 16. *I-V* and *P-V* curves of the measurement.

On the one hand, a measurement has been made without shadows. Fig. 16 shows the *I-V* and *P-V* curves of the measurement, and Table 8 shows the measurement parameters where FF is the Fill Factor, G the irradiance and T_1 and T_2 the ambient temperature.

On the other hand, another measurement has been made with shadows on the panel. Fig. 17 shows the *I-V* and *P-V* curves of the measurement, and Table 9 shows the measurement parameters.

As shown in Figs. 16 and 17, the I-V curve tracer measures in different conditions and provides the relevant information to discern between nominal and abnormal (shadowing) conditions. This information reveals very useful to photovoltaic installations.

Table 8
Measurement parameters.

V_{OC} [V]	I_{SC} [A]	P_{MPP} [W]	V_{MPP} [V]	I_{MPP} [A]	FF	G [W/m2]	T_1 [°C]	T_2 [°C]
34.49	8.95	198.30	24.98	7.94	0.64	945	28.1	28

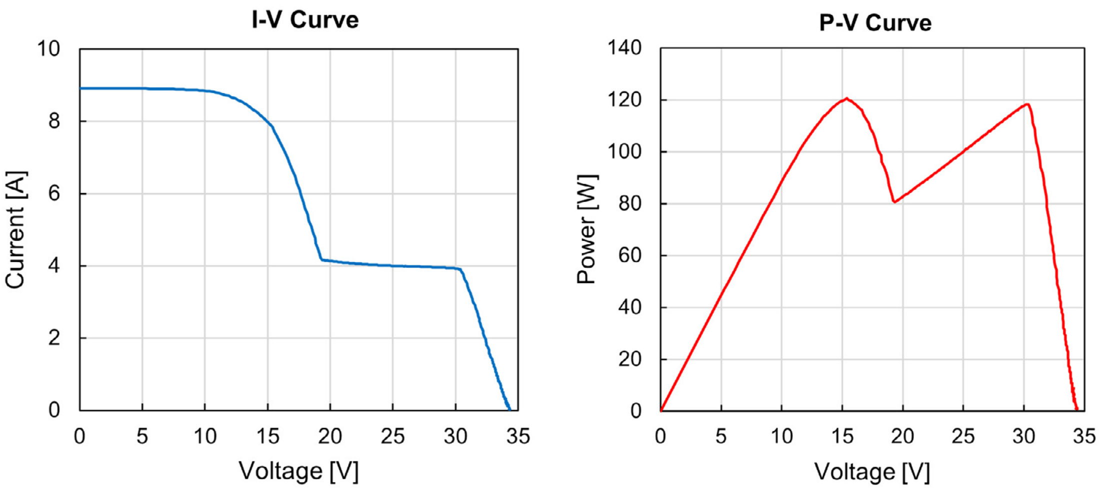

Fig. 17. *I-V* and *P-V* curves of the measurement.

Table 9
Measurement parameters.

V_{OC} [V]	I_{SC} [A]	P_{MPP} [W]	V_{MPP} [V]	I_{MPP} [A]	FF	G[W/m2]	T_1 [°C]	T_2 [°C]
34.42	8.91	120.60	15.39	7.84	0.39	950	28	28.2

Conclusions

Previous tests show that the design implemented in this article verifies the immediacy and precision that can be obtained with the capacitive charge method. All the tests can be performed in real time and the data is processed instantly. In addition, the graphical interface allows the user to control the device without the knowledge of Python for its operation. Some of the possible applications where this curve tracer would be useful would be:

- Detect shadow losses.
- Check the correct operation of a photovoltaic installation.
- Characterize photovoltaic panels.

However, the device presented in this document has some limitations, such as:

- No battery for use in areas without electrical network.
- Low rated voltage (200 V) compared to commercial devices (more than 1000 V).

Table 10
Comparative with some commercial devices.

	Proposed PV IV curve tracer	SOLAR I-Ve	IV TRACER FTV200
V_{OC} max. [V]	200	1500	1000
I_{SC} max. [A]	20	15	10
Advantages	• Programmable periodical measurements • Full user interface integrated • Open Source Development	• Battery powered • Internal module database • PC Interface with software for windows	• Integrated library of panels • Battery powered • Bluetooth communication
Disadvantages	• Low rated voltage • No battery	• Monochrome screen • Tablet or computer needed for advanced analysis • No programmable periodical measurements • Irradiance sensor not included	• Tablet or computer needed for advanced analysis • No programmable periodical measurements
Cost	1151.85 €	4507.30 €	3650.00 €

Various alternatives to the proposed curve tracer are available on the market, two examples are SOLAR I-Ve from HT Instruments, and IV TRACER FTV200 from Chauvin Arnoux. Table 10 benchmarks the proposed device against these commercial devices. As can be seen from this data, commercial systems have higher rated voltage (more than 1000 V) compared to PV IV curve tracer (200 V). Nevertheless, they are quite more expensive.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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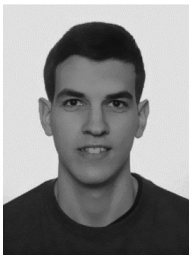
References

[1] Y. Zhu, W. Xiao, A comprehensive review of topologies for photovoltaic I-V curve tracer, Solar Energy 196 (2020) 346–357, https://doi.org/10.1016/j.solener.2019.12.020.
[2] M. Cáceres, A. Firman, J. Montes-Romero, A.R. González Mayans, L.H. Vera, E. F. Fernández, J. de la Casa Higueras, Low-Cost I-V Tracer for PV Modules under Real Operating Conditions, Energies 13 (17) (Aug. 2020) 4320, https://doi.org/10.3390/en13174320.
[3] P. Papageorgas, D. Piromalis, T. Valavanis, S. Kambasis, T. Iliopoulou, G. Vokas, A low-cost and fast PV I-V curve tracer based on an open source platform with M2M communication capabilities for preventive monitoring, Energy Procedia 74 (2015) 423–438, https://doi.org/10.1016/j.egypro.2015.07.641.
[4] C. Abe, J. Dias, G. Notton, and B. Pillot, "Construction of an I-V curve tracer for a photovoltaic research and teaching platform" vol. 05, pp. 1757–1765, Jan. 2018, doi: 10.21090/IJAERD.21106.
[5] F. Spertino, J. Ahmad, A. Ciocia, P. di Leo, A.F. Murtaza, M. Chiaberge, Capacitor charging method for I-V curve tracer and MPPT in photovoltaic systems, Solar Energy 119 (2015) 461–473, https://doi.org/10.1016/j.solener.2015.06.032.



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