

M.B. Nieto – Morone^{1,2*}, M.C. Alonso – García¹, F.G. Rosillo¹, M.A. Muñoz – García²

¹ Photovoltaic Solar Energy Unit – Energy Department – CIEMAT – SPAIN ² ETSIAAB, LPF-TAGRALIA, Universidad Politécnica de Madrid – SPAIN

OBJECTIVE

The objective of this research is to evaluate the performance of **repaired photovoltaic (PV) modules** under **real operating conditions**, providing critical insight into the effectiveness of repair interventions in restoring functionality and mitigating **power loss**. This study aims to contribute to the development of strategies aimed at increasing the **reuse** of PV modules, thereby reducing **electronic waste mass** and minimizing the **environmental impact** associated with their **lifecycle**.

METHODS

INITIAL CHARACTERIZATION

| | |
|---------------------|---|
| VISUAL INSPECTION | IV CURVE |
| DRY INSULATION TEST | LEAKAGE CURRENT TEST IN WET ENVIRONMENT |
| IR CHARACTERIZATION | ELECTROLUMINESCENCE CHARACTERIZATION |

Table 1: Electrical parameters Module type 1 measured in solar simulator

| Isc (A) | Voc (V) | Pmax (W) |
|---------|---------|----------|
| 5.23 | 43.24 | 152.40 |

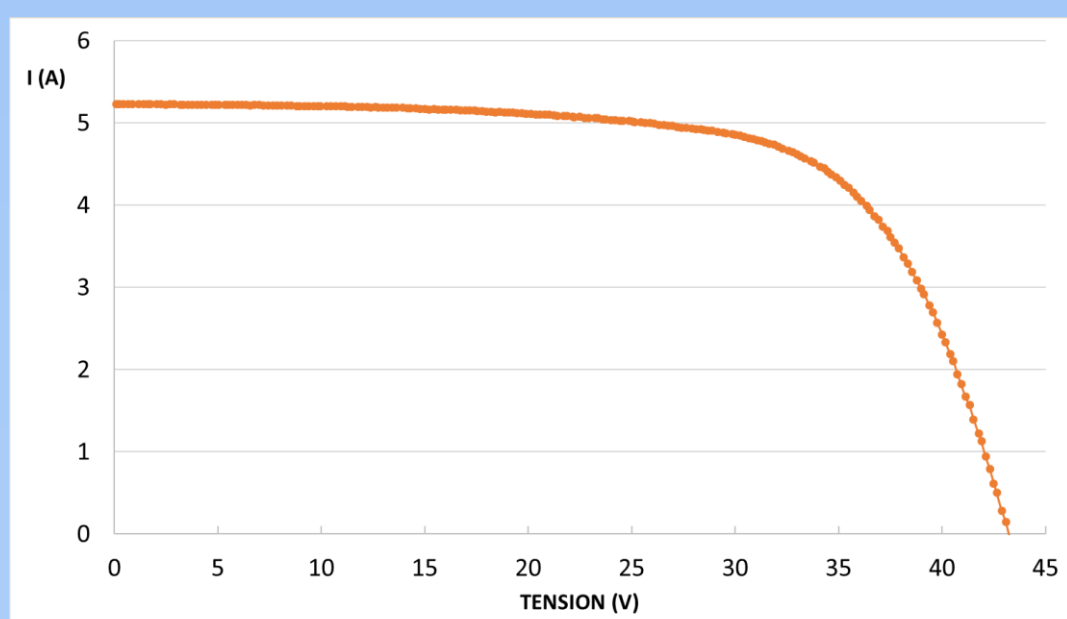


Fig. 1: IV Curve Module type 1

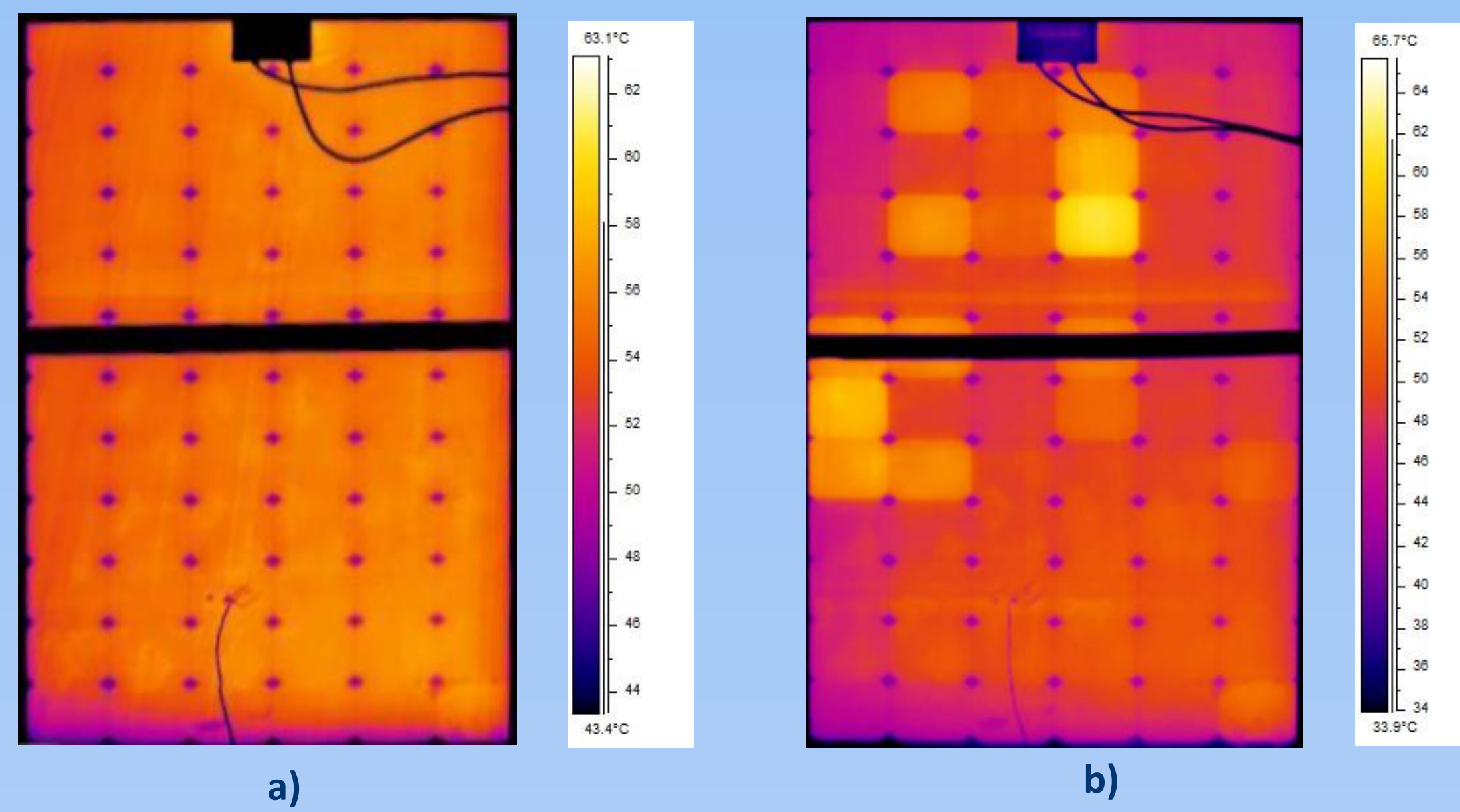


Fig. 2: IR thermography images of module type 1, a) in operation point and b) in short circuit

| | |
|---------------|---------|
| V (V) | 39.9 |
| I (A) | 8.2 |
| Exposure (μs) | 10788.4 |

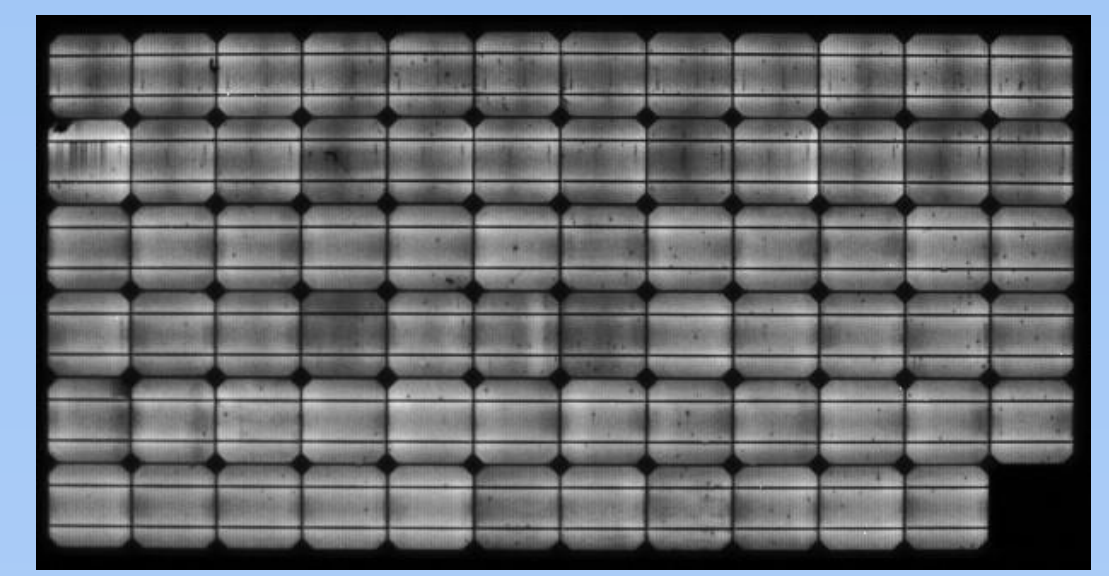


Fig. 3: Electroluminescence image of module type 1

MONITORING SYSTEM

- LOCATION: Madrid, Mediterranean continental climate
- GRID-CONNECTED PV SYSTEM
- MODULE TYPE 1: Pmax 152.4 W, initial in STC (Nominal: 170 W, Isc 5.25 A, Voc 43.9 V).
- MODULE TYPE 2: Pmax 259.8 W, initial in STC (Nominal: 280 W, Isc 8.36 A, Voc 46.9 V).
- IRRADIANCE SENSORS:
 - GLOBAL IRRADIANCE SENSOR (PYRANOMETER CMP11)
 - REFERENCE CELL SOLAR IRRADIANCE
- TEMPERATURE SENSORS:
 - AMBIENT TEMPERATURE
 - MODULE TEMPERATURE ATTACHED TO BACKSHEET

METHODOLOGY and CALCULATIONS

- Step 1: data collection, periodic thermography inspection
- Step 2: Modelling power production from:

$$P_2 = P_1 \cdot \frac{G_2}{G_1} (1 + \gamma(T_2 - T_1))$$

Running two simulations:

- P1 = nominal power.
- P1 = degraded power, from the initial measured IV curve at STC

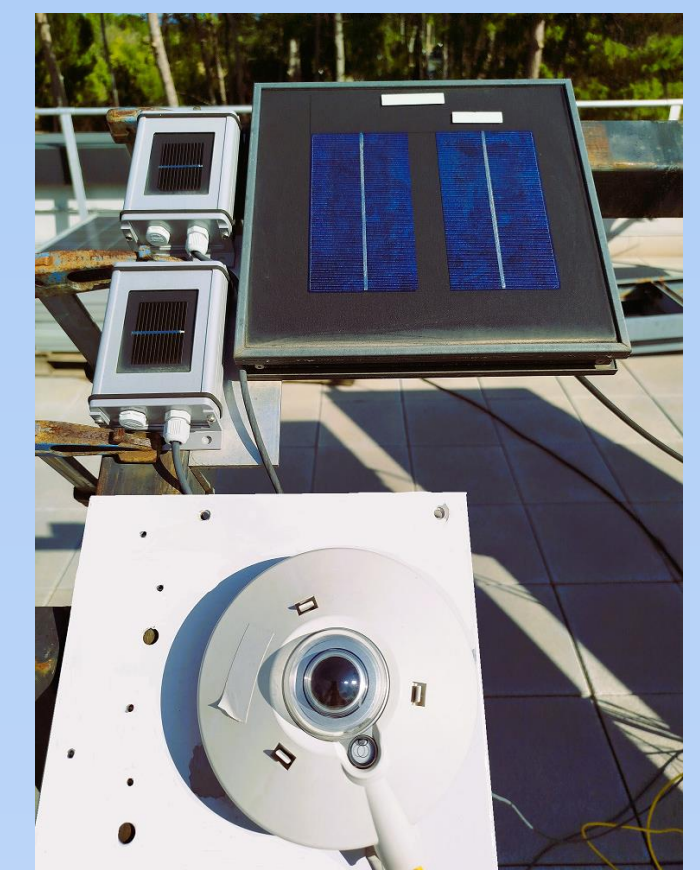


Fig. 4: Irradiance sensors in field monitoring system

Monitoring began in December 2023 and is still ongoing.

RESULTS

WINTER TYPICAL DAY JANUARY 2024

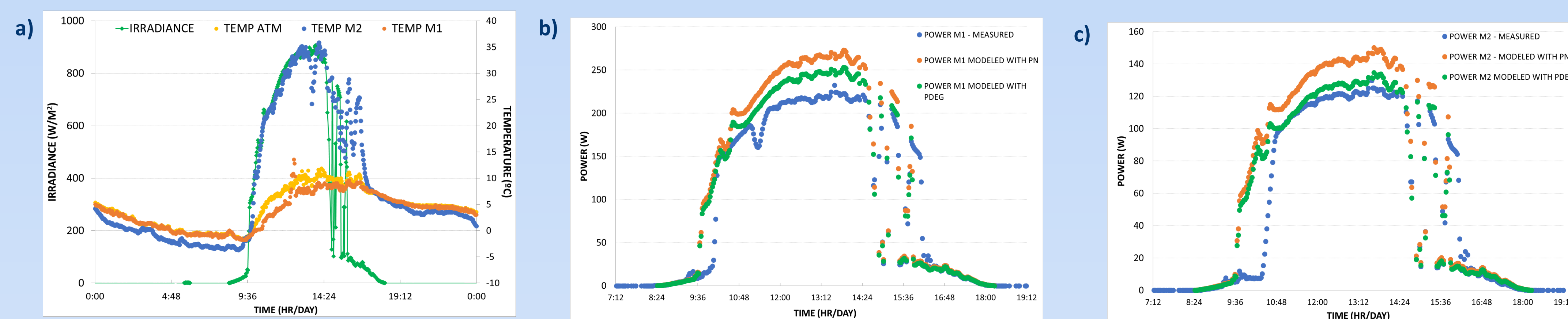


Fig. 5: a) Irradiance and temperature evolution during a typical winter day, 11th January 2024. b) and c) Module type 1 and Module type 2 Power evolution comparison between in-field measured data, modelled with nominal power and degraded power (from initial IV characterization).

SUMMER TYPICAL DAY AUGUST 2024

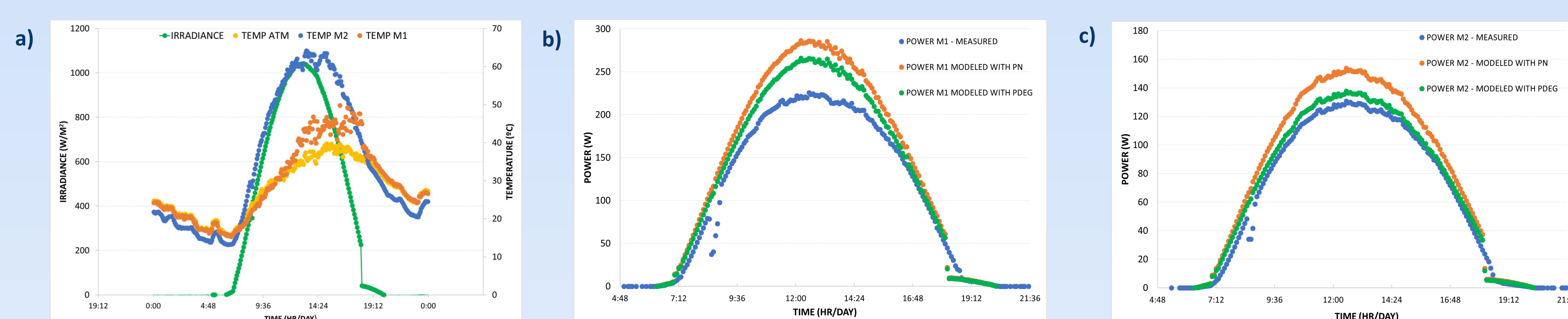
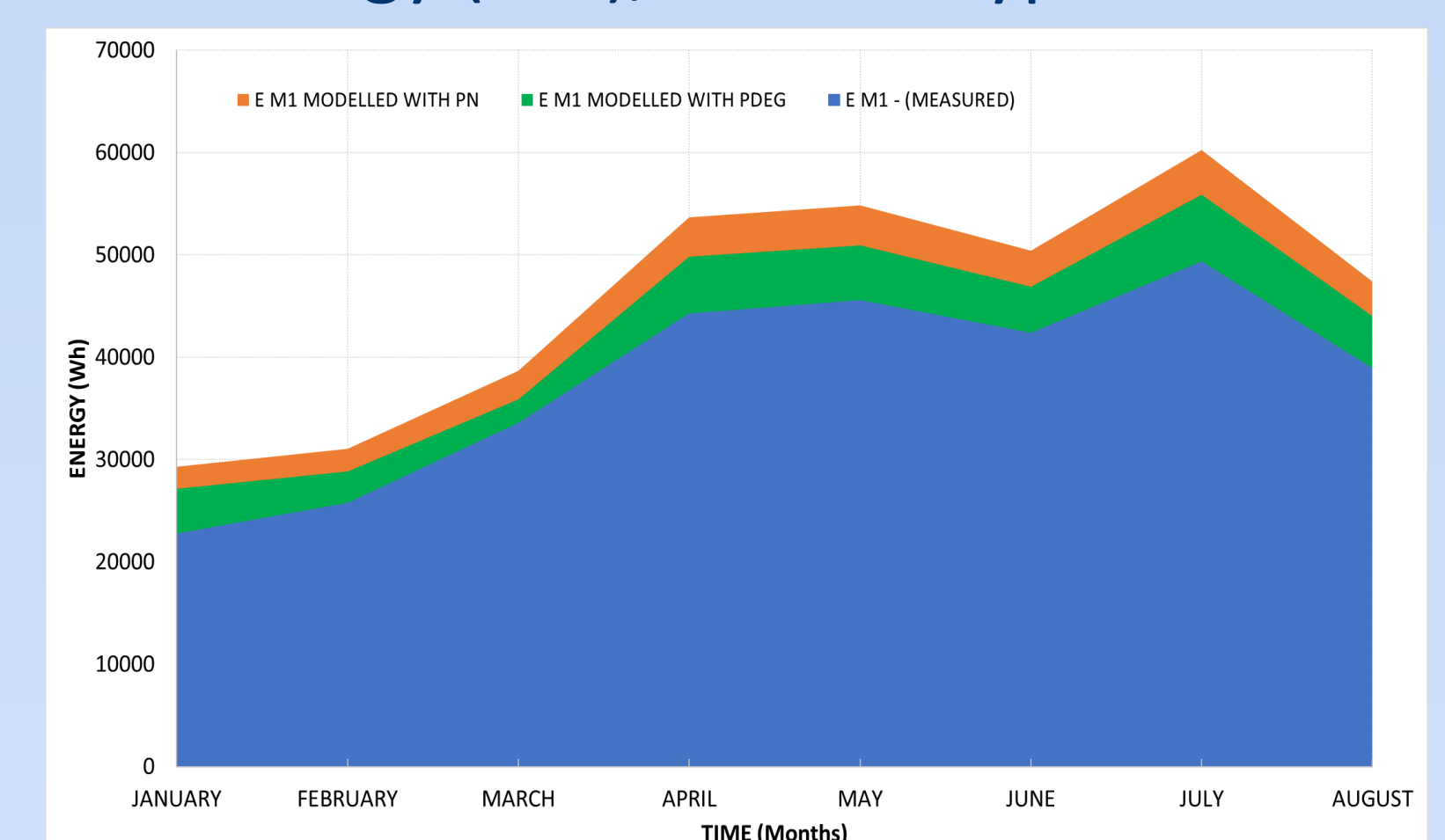


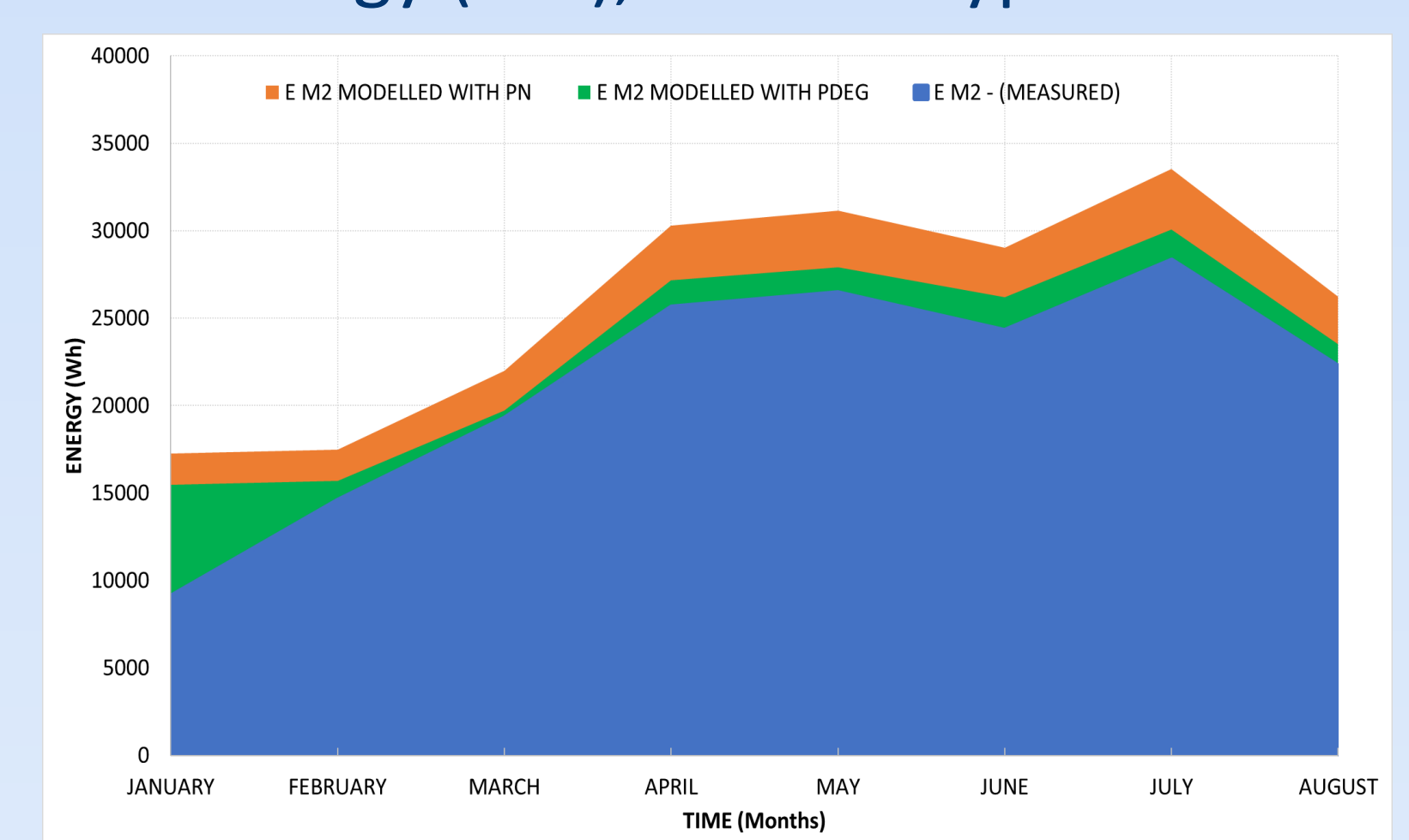
Fig. 6: a) Irradiance and temperature evolution during a typical summer day, 15th August 2024. b) and c) Module type 1 and Module type 2 Power evolution comparison between in-field measured data, modelled with nominal power and degraded power (from initial IV characterization).

Energy (Wh), Module type 1



a)

Energy (Wh), Module type 2



b)

Fig. 7: a) and b) Energy produced by the system during the study period for modules type 1 and type 2.

CONCLUSIONS AND OUTLOOK

The measured power is consistently lower than the simulated degraded power and significantly below the nominal power, which aligns with expectations for 12-year-old modules. The additional performance losses may be attributed to real operating conditions, including environmental stressors and system inefficiencies. However, module type M1 shows only a **7.21%** reduction from nominal power, while module type M2 presents a slightly larger reduction of **10.35%**. These results suggest that the repaired modules still perform within acceptable limits, meeting the manufacturer's warranty criteria, and supporting the feasibility of their **reuse**.