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AMANDA

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Deliverable

D3.3 PV Energy Harvester proof-of-concept prototype

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List of definitions & abbreviations

Abbreviation	Definition
ASSC	Autonomous Smart Sensing Card
CAGR	Compound Annual Growth Rate
EH	Energy Harvesting
ESL	Electronic Shelf Labels
LED	Light-Emitting Diode
MOCVD	Metal-Organic Chemical Vapour Deposition
PV	Photovoltaic
SAM	Serviceable Addressable Market
SMT	Surface Mount Technology
TAM	Total Available Market

Executive Summary

This report is part of **WP3 – Energy Autonomy Booster**. The aim of WP3 is to provide and develop a power card that includes energy generation, regulation and storage. The Deliverable presents the energy generation (Energy Harvester) component fabrication and testing as part of **Sub-Task T3.1.2 PV cell growth, processing and characterization** and **Sub-Task T3.1.3 PV cell assembly and encapsulation, Sub-Task T3.1.5 Adapt fabrication process for compatibility with high temperature reflow process,** and **Sub-Task T3.1.6 Investigate / Optimize process flow for cost reduction.**

The Energy Harvester (EH) process flow, prototype testing and optimisation procedure for manufacturing are provided, together with a business case for the component.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Purpose, context and scope of this Deliverable

Lightricity has developed a new photovoltaic (PV) technology especially designed to harvest energy from indoor low-lighting environments. This innovative and ultra-high efficient technology will make possible for the AMANDA consortium to introduce a completely energy-autonomous device that can harvest indoor and outdoor energy to operate the ASSC in challenging environments. This Deliverable is part of **WP3 – Energy Autonomy Booster** and provides the required input for **Deliverable D5.1 - 1st Unconstrained Prototype** and **Deliverable D5.2 - Miniaturized PCB Prototype.** It covers the development of proof-of-concept EH prototypes, from fabrication to reliability testing and discusses optimisations in the process flow to achieve mass manufacturability at lower cost.

1.2 Purpose of the EH component within the AMANDA card

The purpose of the photovoltaic energy harvester is to provide continuous power to the AMANDA ASSC, in combination with the PMIC and the rechargeable energy storage. The EH is thus part of the energy block on the AMANDA card and relies on the conversion of ambient light, both indoor and outdoor, into useful electrical energy that can be delivered to the main microcontroller, sensors and other peripherals. The interaction between all the different elements within the energy block and the rest of the system has been fully described in **Deliverable D1.7 - Architecture design of the AMANDA system delivered (for both breadboard and integrated/miniaturized system).**

1.3 Overall technical objectives and challenges

This Deliverable is part of WP3 that focuses on the development of a power card that includes energy generation, regulation and storage. The main technical objectives are:

- To design and develop an ultra-high performance photovoltaic Energy Harvester based on Lightricity III-V energy harvesting technology. The project targets a 30-35% EH module efficiency under white LED and fluorescent spectrum
- To drastically reduce the thickness (<1mm) and footprint of the EH for integration with the ASSC card
- To design an EH component process-flow compatible with high temperature reflow process (250°C)
- To fabricate EH cells and modules prototypes using dedicated automated tools
- To investigate and implement technical strategy for cost reduction, with a target of cost parity (per µW) with competing small-scale PV energy harvesting technologies, such as amorphous silicon and dye-sensitized solar cells.

The main technical challenge for the Energy Harvester in the AMANDA project is to maintain the excellent performance while shrinking the device and increasing the maximum applied temperature.

1.4 Improvement over State-of-the-Art

Lightricity's indoor energy harvester will need to compete with the current and emerging technologies targeting indoor application. In **Deliverable D1.1 – SoA and gap analysis recommendations,** we have already shown examples of competing technologies that are available commercially and/or at an R&D level. It was demonstrated that existing, commercially available silicon-based technologies would not be able to meet the small size requirement of the ASSC card, due to their poor efficiency indoors. Other emerging technologies such as dye-sensitized or organic photovoltaics may exhibit slightly higher performance than Silicon indoors but suffer from stability issues that are unlikely to be solved in the short-to-medium term. Lightricity's world-class performance of their larger scale energy harvesting prototypes is a key enabling technology, providing the power requirements of the ASSC. The small form factor, thickness, high aesthetics (uniformly black) and robustness of the energy harvester will enable new wearable applications and fits perfectly into the sensing card concept. Compatibility with much higher temperatures will facilitate greatly the manufacturing of the ASSC since the PV component will be assembled with other electronic components during a standard reflow process. AMANDA follows a design-led approach wherein both design and performance aspects will operate in synergy to offer the best possible functionality of the ASSC. Figure 1 below summarises the improvement of performance of Lightricity technology for the macro-scale devices (few cm^2). The main technical challenge in the AMANDA project will be to maintain the excellent electrical performance while reducing the size of the photovoltaic devices (down to <1cm^2) and increasing the maximum applied temperature (up to 250°C).

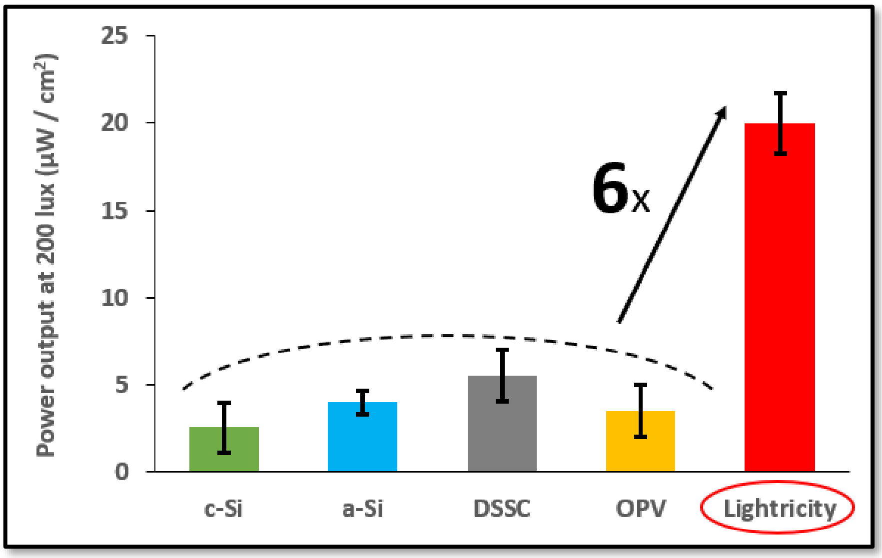


Figure 1 Comparison of performance of Lightricity vs. SoA technologies

2. Opto-electrical characterisation of the PV Energy Harvester

2.1 Testing of complete Energy Harvesting modules

The final encapsulated EH module (EXL-1V20-SM/EXL1) is shown in Figure 2. These modules were characterised in a custom luxbox, with current-voltage (IV) and power-voltage (PV) curves shown in Figure 3 and Figure 4 respectively.

Figure 2 Final EH module prototype (EXL-1V20-SM/EXL1)

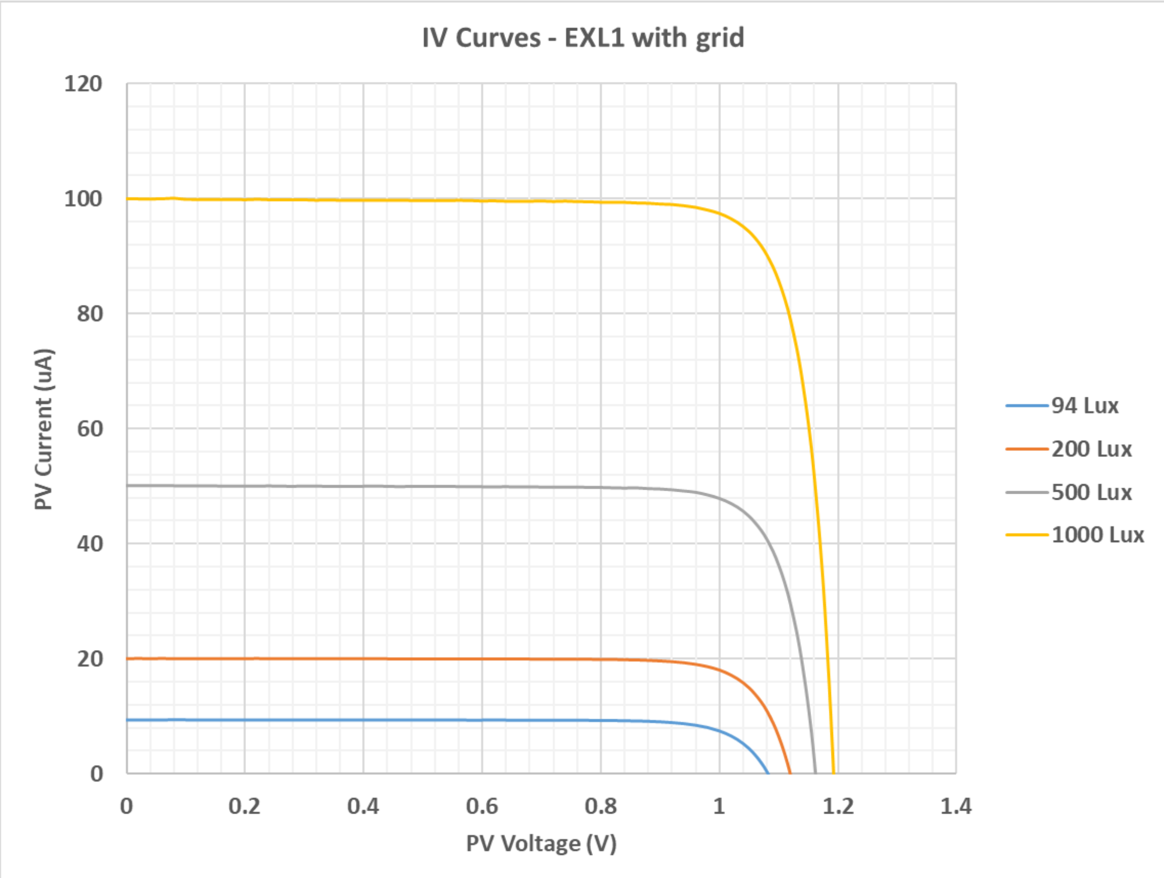


Figure 3 Current-Voltage curves for various illumination levels (EXL-1V20-SM/EXL1)

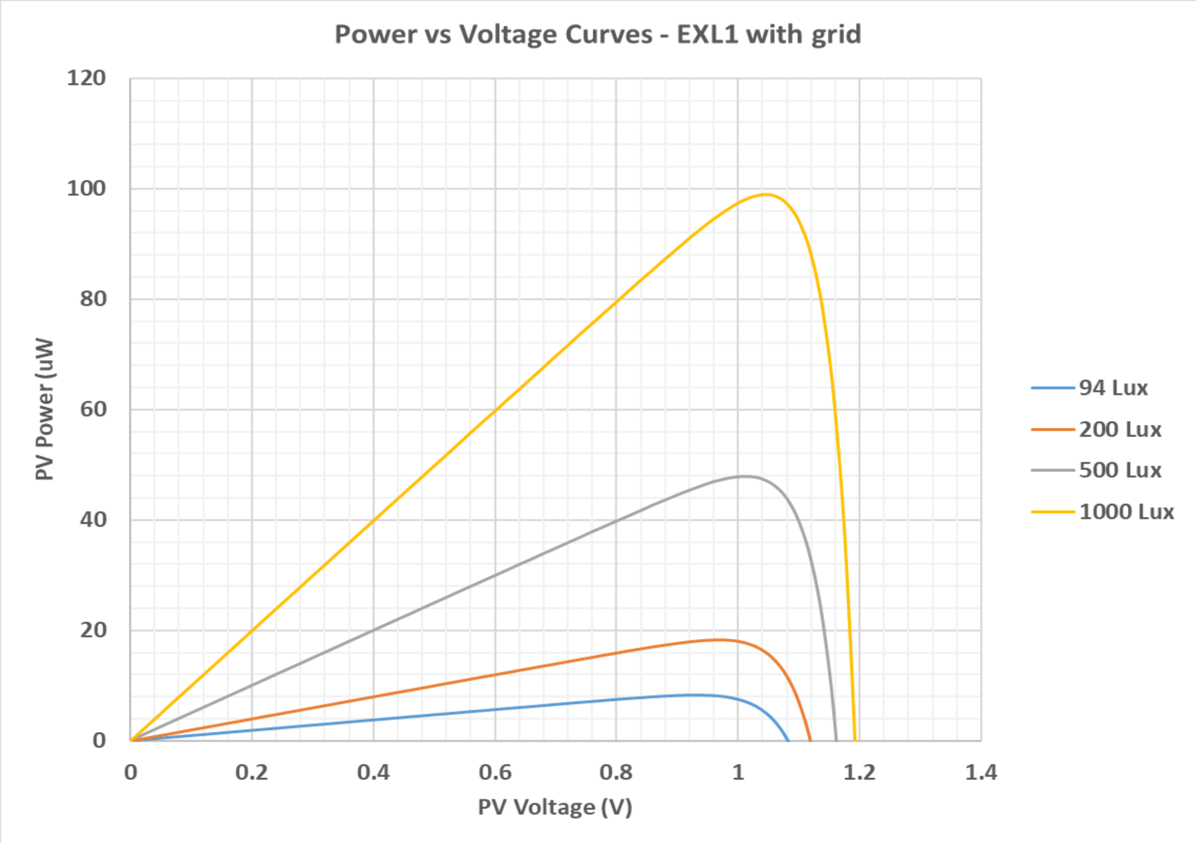


Figure 4 Power-Voltage curves for various illumination levels (EXL-1V20-SM/EXL1)

2.2 Performance against target specifications and AMANDA requirements

The specifications of the two EH component parts developed as part of the AMANDA project are summarised below in Table 1 and Table 2:

Parameter / Performance Module EXL-1V50-SM	Target 200 lux white LED spectrum	Measured 200 lux white LED spectrum
Size / Thickness	23.8 x 10.2mm / <1mm	Performance confirmed on the die level. Final encapsulation in progress (delayed due to Covid-19)
Active area	2.15cm^2	
Number of cell(s)	1	
Open circuit voltage	1.15V	
Short circuit current	49.8µA	
Operating voltage	1.0V	
Operating current	47.6µA	
Operating power	47.6µW	
Power density (active area)	>20µW/cm^2	
Cell efficiency	>30%	

Table 1 ExCellLight EXL-1V50-SM performance and functionality

Target performance Module EXL-1V20-SM	Target	Measured
	200 lux white LED spectrum	200 lux white LED spectrum
Size / Thickness	11.65 x 8.85mm / <1mm	11.65 x 8.85mm x 0.65 mm
Active area	0.98cm^2	0.98cm^2
Number of cell(s)	1	1
Open circuit voltage	1.15V	1.13V
Short circuit current	22.7µA	22.7µA
Operating voltage	1.0V	0.98V
Operating current	21.7µA	21.4µA
Operating power	21.7µW	21.0µW
Power density (active area)	>20µW/cm^2	>20µW/cm^2
Cell efficiency	>30%	>30%

Table 2 ExCellLight EXL-1V20-SM performance and functionality

As shown in Table 2, the EXL1 module exhibits a power density of >20µW/cm^2 under white LED spectrum, as targeted. The thickness of the module was ~0.65mm, meeting the AMANDA requirements.

3. Reliability testing of the PV Energy Harvester

3.1 Environmental testing (temperature/humidity)

The following tests will be carried out on the EXL-1V20 after Covid19 restrictions are lifted:

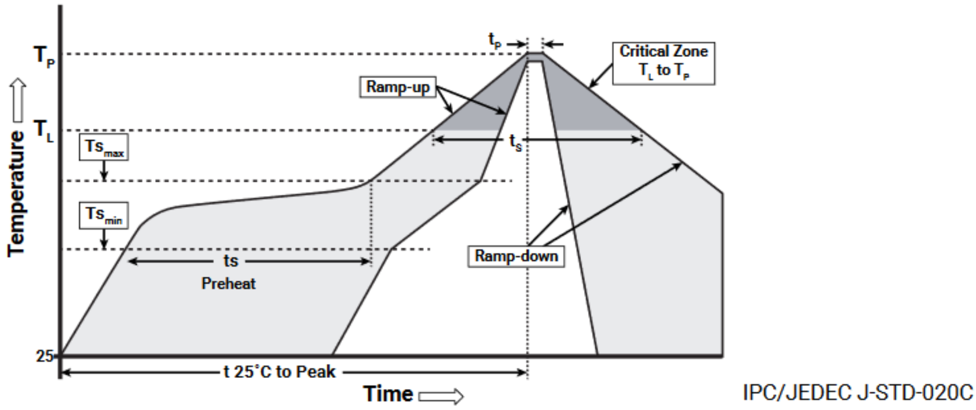
- 120°C and 85% RH for up to 96 hours
- Thermal shock test: -40°C to +125°C, up to 1000 cycles
- High temperature operating life: 125°C for up to 1000 hours
- High temperature intermittent: up to 250°C

3.2 Reflow temperature testing (SMT compatibility)

A dedicated IR heater equipment (Figure 5) for emulating a standard reflow process has been purchased and installed at the Lightricity labs.

Figure 5 IR-heater for reflow temperature testing

The following reflow tests will be carried out on the EXL-1V20 after Covid19 restrictions are lifted (Figure 6). These will assume worst-case scenario for the peak temperature and duration as shown in the table of Figure 6.



Profile Feature	Lead-Free Solder
Average Ramp-Up Rate (Ts_{max} to Tp)	1.2 °C/second
Preheat: Temperature Min (Ts_{min})	120 °C
Preheat: Temperature Max (Ts_{max})	170 °C
Preheat: Time (ts_{min} to ts_{max})	65-150 seconds
Time Maintained Above: Temperature (T_L)	217 °C
Time Maintained Above: Time (t_L)	45-90 seconds
Peak/Classification Temperature (Tp)	235 - 245 °C
Time Within 5 °C of Actual Peak Temperature (tp)	20-40 seconds
Ramp-Down Rate	1 - 6 °C/second
Time 25 °C to Peak Temperature	4 minutes max.

Figure 6 Experimental reflow profile

3.3 Performance with respect to AMANDA requirements

This Section will be updated after the Covid19 restrictions have been lifted. Reliability testing and reflow testing results will be provided.

4. Integration with the AMANDA ASSC

4.1 Physical integration with the AMANDA ASSC (thickness and SMT compatibility)

There are important aspects to consider in order to improve the integration of the Energy harvester with the AMANDA ASSC.

- **Form factor, size and thickness**. The EH component should be as small as possible while providing sufficient power for operation of the card, even under low light levels available indoors (from 100lux). We have thus focussed on ~2.4cm^2 and 1cm^2 rectangular packages that will only occupy less than 5% of the total area of the card. It should also be ultra-thin (<1mm) to be compatible with the ASSC
- **Assembly**. The EH component should be assembled onto the ASSC card PCB (see example on Figure 7) with a low-cost assembly technique to ensure that production of the ASSC card can be easily scaled-up. This will be ensured by the design of a surface mount technology (SMT) compatible device that can be picked and placed onto the board and assembled using standard reflow process at 250°C

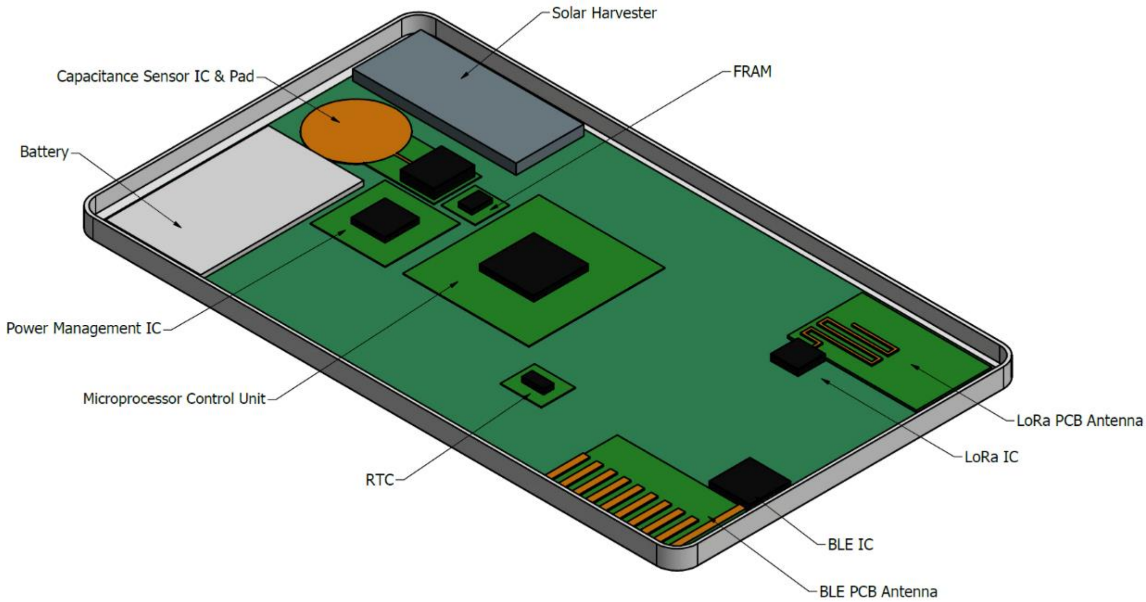


Figure 7 Integration of the Lightricity energy harvester (EXL-1V50-SM) within the ASSC

4.2 Testing of the AMANDA ASSC (indoor light simulator)

The indoor light simulator can be adapted to test the various functionalities of the ASSC under a wide range of illumination levels, covering all use cases (indoor, outdoor). Testing will be performed during the last phase of the project.

5. Conclusions

This Deliverable is part of **WP3 – Energy Autonomy Booster** and provide the basis for Deliverables **D5.1 - 1st Unconstrained Prototype** and **D5.2 - Miniaturized PCB Prototype.** The document fully describes the process flow, characterisation procedure and results for the energy generation as part of **Sub-Task T3.1.2 PV cell growth, processing and characterization** and **Sub-Task T3.1.3 PV cell assembly and encapsulation, Sub-Task T3.1.5 Adapt fabrication process for compatibility with high temperature reflow process,** and **Sub-Task T3.1.6 Investigate / Optimize process flow for cost reduction.**