HORIZON-CL5-2023-D3-02-12
Large area perovskite solar cells and modules

LUMINOSITY

Large area uniform industry compatible perovskite solar cell technology

Starting date of the project: 01/06/2024
Duration: 48 months

= Deliverable D5.1 =

Large Area Perovskite Films

Dissemination level		
PU	Public	x
SE	Sensitive, limited under the conditions of the Grant Agreement	
Classified R-UE/EU-R	EU RESTRICTED under the Commission Decision No2015/444	
Classified C-UE/EU-C	EU CONFIDENTIAL under the Commission Decision No2015/444	
Classified S-UE/EU-S	EU SECRET under the Commission Decision No2015/444	

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Executive Summary

This deliverable requires a demonstration of a R2R coated semi-fabricate perovskite stack with a surface area of 6000 cm^2. The deliverable aims to show the state of the art of the consortium on scaling up the perovskite solar cell layers. As state of the art, HyET has the capability of R2R deposition of the FTO electrode, and TNO has the capability to deposit all of the layers that can be potentially R2R slot-die coated. The other layers, that are requiring a scaling-up research, are sputtered transport layers and electrodes. These layers will be R2R processed by FEP after developing and optimizing them at S2S scale by scaling up partners at a later time in the project according to the GANTT chart.

This report will provide images of the coating process, encapsulation, and the end product, and characterization results. The outcome of the deliverable is an encapsulated perovskite semi-fabricate, with a total coated area of 7500 cm^2, with a length of 2.5 meters long foil.

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List of Abbreviations

APCVD: Atmospheric Pressure Chemical Vapor Deposition

CTL: Charge Transport Layer (refers to ETL and HTL in general)

ES: Edge Seal

ETL: Electron Transport Layer

FTO: Fluorinated Tin Oxide

HTL: Hole Transport Layer

PSC: Perovskite Solar Cell

PV: Photovoltaic

R2R: Roll-to-roll

sALD: spatial Atomic Layer Deposition

SEM: Scanning Electron Microscopy

SD: Slot-Die coating

Sp: Sputtering

S2S: Sheet-to-sheet

TCO: Transparent Conductive Oxide

TF-Si: Thin film Silicon

TRL: Technology Readiness Level

XRD: X-Ray Diffraction

1. Introduction

LUMINOSITY will promote flexible perovskite solar cell (PSC) technology to commercially relevant production scales using industrially proven roll-to-roll (R2R) processing methods, targeting photovoltaic (PV) module power conversion efficiency (PCE) of >20% at an area of >900 cm^2, by closing the efficiency gap between lab-scale and fab-scale processed devices, and by bringing TRL up to 7. Four critical challenges are standing between the current state-of-the-art and commercial-scale production of PSCs. These are: (1) integration of perovskite processing in TRL7 mass-production equipment (2) without a loss of efficiency during upscaling, (3) achieving operational stability similar to the lifetime of existing commercial TF-Si PV technologies, i.e. >20 yrs, and (4) reaching an economically and environmentally feasible maturity.

This deliverable is a demonstration of a R2R coated semi-fabricate perovskite stack with a surface area of 6000 cm^2. This deliverable aims to address the first challenge mentioned above by showing the state of the art of the consortium on scaling up the perovskite solar cell processing. As state of the art, TNO has the capability to deposit all of the layers that can be potentially R2R slot-die coated. The other layers, that are requiring a scaling-up research, are sputtered transport layers and electrodes. These layers will be R2R processed by FEP after developing and optimizing them at S2S scale by scaling up partners.

This report will provide images of the coating process, encapsulation, and the end product, and characterization results.

2. Results and Discussion

2.1. R2R Slot-Die Coating of Perovskite Solar Cell Layers

A simple perovskite solar cell stack consists of a number of layers with different functionalities that are deposited on a substrate carrier. The perovskite absorber is enveloped by two selective charge extraction layers, that specifically extracts electrons and holes, respectively; and two electrodes that collects these charges to generate photocurrent. ***Error! Reference source not found.*** demonstrates the s olar cell stack, and a breakdown of the layers that are R2R coatable according to the *workflow* at M6 of

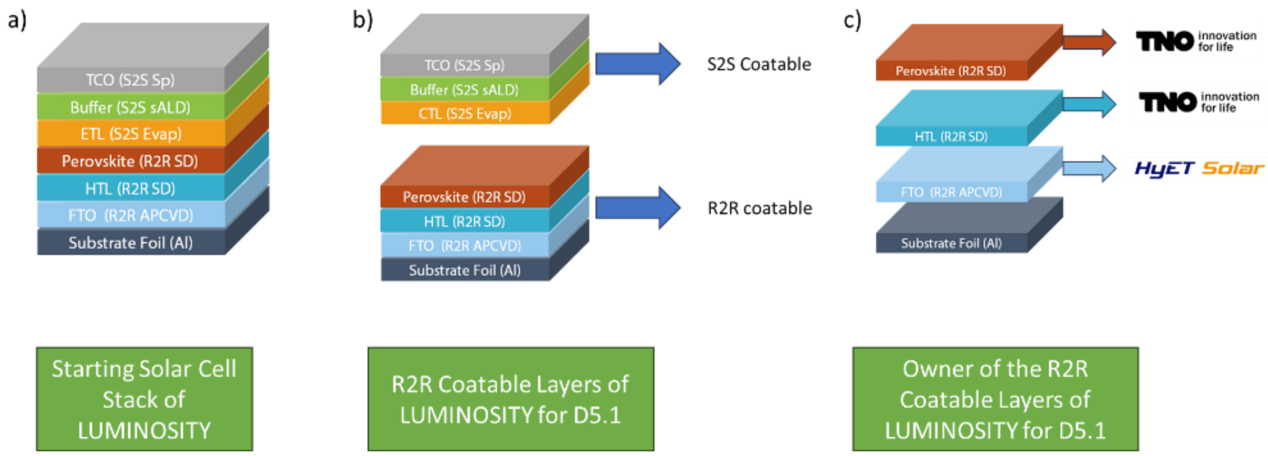


Figure 1 a) Starting solar cell stack at M6 of LUMINOSITY. b) Visualization of R2R and S2S coatable layers at the start of the deliverable. c)the owner of the R2R processed layers for the demo that is prepared for this deliverable.

LUMINOSITY project, as well as the owners of the layers, who processed the R2R coatable stacks. FTO is R2R APCV deposited by HyET, HTL and Perovskite absorber are deposited by TNO via R2R SD coating under ambient conditions. As in this form, the stack is a semi-fabricate, which needs to be cut down into relevant sizes and the remaining layers are processed in S2S tools (ETL via evaporation, buffer layer via sALD, and TCO is via sputtering). This makes a complete solar cell stack which can be electrically characterized for its PCE. As this deliverable focuses only on the production and demonstration of R2R coatable layers, the device efficiencies will be reported later according to the GANTT chart. Figure 2 and

Figure 3 demonstrates the coating of HTL and Perovskite absorber via R2R SD technique. Coating takes place in cleanroom conditions, under ambient conditions. It is possible to use a white light, yellow light and combinations of them in the cleanroom environment depending on the sensitivity of the ink to light conditions. While the HTL ink is not sensitive to light, Perovskite ink is sensitive to light before it is being deposited and crystallized. Thus, the perovskite coating is done under yellow light conditions. A schematic of the R2R line is shown in Annex 1. The coating for all of the layers were done at a speed of 3 m/min. The R2R furnaces shown in Annex 1 have 20 different heating zones, which enables us to control heating profile at different times of the annealing. The heating profile for the HTL deposition was flat and fixed at 100°C, while the perovskite deposition had a variable profile ranging between 100°C and 140°C.

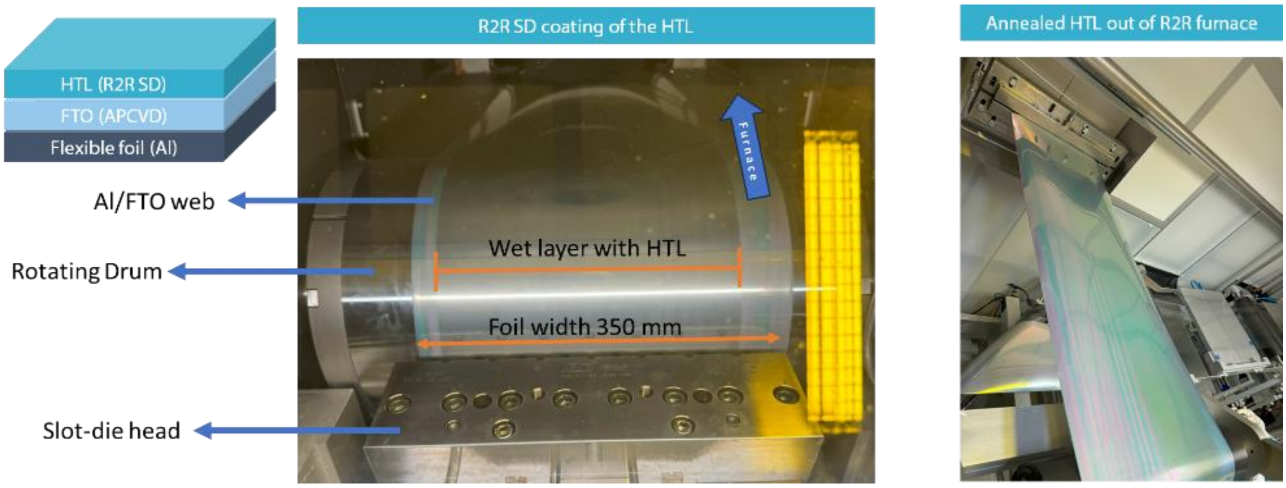


Figure 2 Ambient coating of the HTL via R2R-SD technique in the cleanroom environment

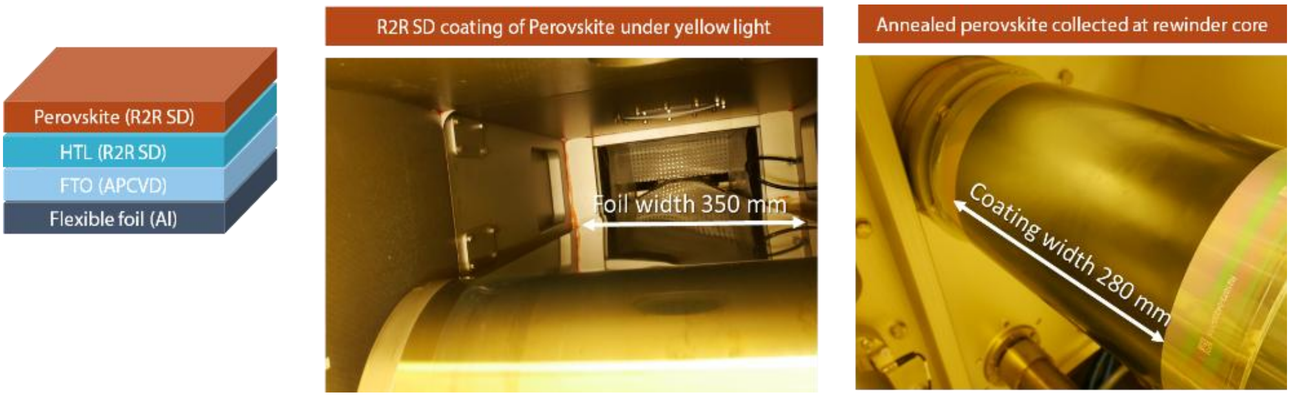


Figure 3 Ambient coating of Perovskite via R2R-SD technique. Coating is done under yellow light conditions in the clean room environment.

2.2. R2R Encapsulation of Perovskite Semi-Fabricate Foil Demonstrator

Conventional module encapsulation combines heat and vacuum followed by heat and pressure applied to the module in a total process time of 20 to 30 minutes. During this process air is removed between the interfaces and materials are allowed to melt and flow and to be pressed together. The materials in the module that require this lamination profile are mainly the encapsulant and the edge seal. The edge seal is a rubber strip at the edges of the lamination that creates a frame around the coated foil to prevent any side ingress from the outside. The encapsulant needs to melt to create a good optical contact between the encapsulant and the front sheet and to the solar cell and the encapsulant. Next to this it needs to melt to create a good mechanical contact on these interfaces; good adhesion to not lead to delamination during use in life or during accelerated lifetime testing. Also, the edge seal needs this combination of heat and pressure to allow for a good mechanical contact between edge seal and front and back sheet. This proper seal prevents side ingress from occurring, that in its turn would lead to a fast module degradation.

The demonstrator was made on a roll-to-roll laminator. The used process for the demonstrator consists of three steps. To reach good optical and mechanical contact between encapsulant and front sheet, in the first step the encapsulant is molten (pre-laminated) onto the front sheet. Two of these pre-laminated foils are produced (one for the front side and one for the back side). On one of the foils, the edge seal is applied. In the second step, the PV-foil is placed between the two pre-laminated foils and roll-laminated on the R2R laminator. In the third step, the edges are post-sealed with a hot clamp only at the location of the edge seal. In this last step, there is no heat applied to the encapsulant or the PV foil anymore. The result of the 3-step process is a proper packaged PV module, with good optical appearance. Tests need to confirm that this method also allows for passing all the required acerated lifetime tests. Figure 4 demonstrates a visual of encapsulated perovskite semi-fabricate. The encapsulation process is shown in Figure 5. The completed demonstrator is shown by the R2R coating operators in comparison of their size in Figure 6. The R2R coated foil is 2.5 meters long, and the coating area is approximately 7500 cm². The total length of the encapsulated demonstrator is 3 meters. There is 25 cm empty space at the beginning and at the end of the laminate.

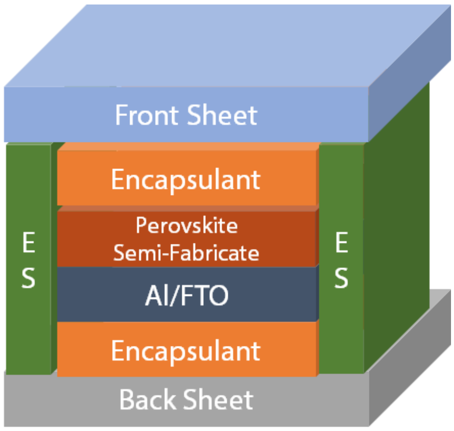


Figure 4 Illustration of encapsulated perovskite foil. Al/FTO/Perovskite Semi-fabricate is demonstrated in Figure 1C.

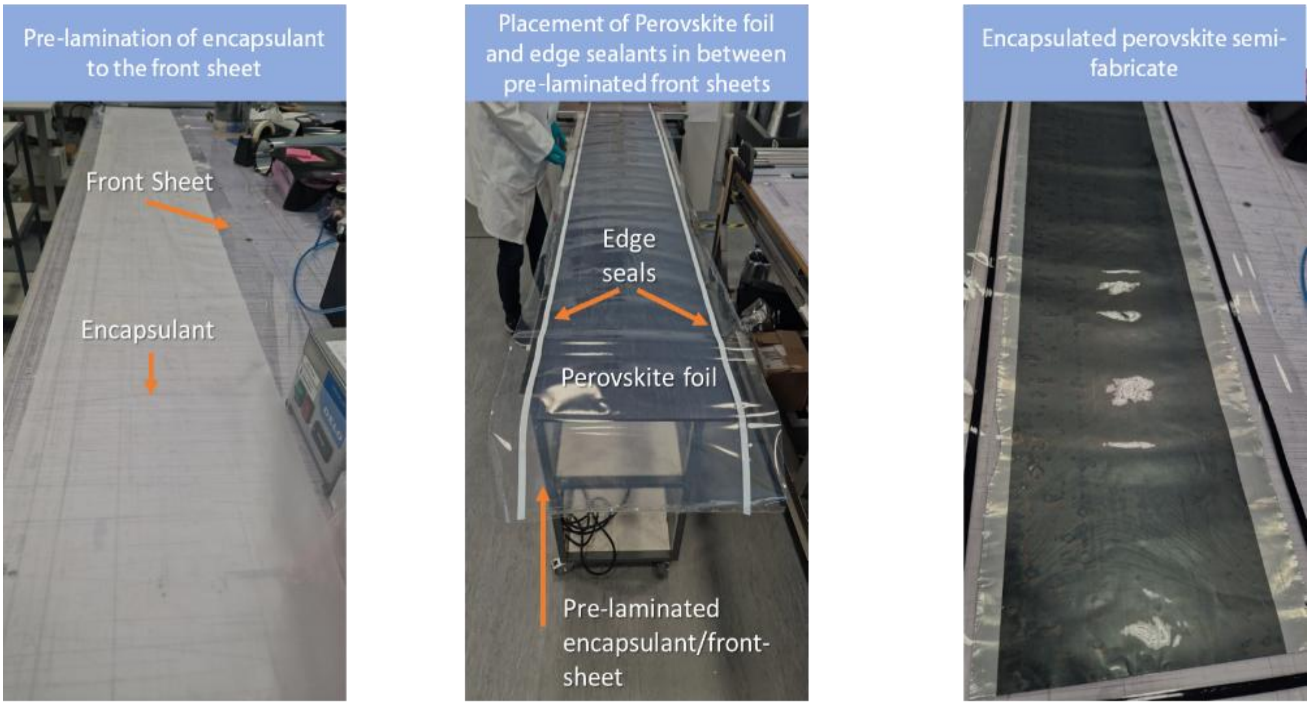


Figure 5 Selected steps in the R2R encapsulation process of perovskite semi-fabricate demonstrator

Figure 6 Demonstrator of an encapsulated perovskite semi-fabricate foil, produced by R2R techniques (R2R APCVD at HyET, R2R SD at TNO, R2R encapsulation at TNO). The total length of the coated foil is 2.5 meters, the coating area is 7500 cm2, the total length of the encapsulated demonstrator is 3 meters.

2.3. Characterization of R2R processed Perovskite Semi-Fabricates

Perovskite layers are characterized using SEM and XRD spectroscopy. SEM images in Figure 7 show clear island formation during perovskite conversion and growth. Most of the island structures are in touch with each other, indicating the formation of a closed film. However, there are some areas that forms rather open structures, which indicates relatively less coverage of the coated surface in these regions. The identified reasons of relatively lower coverage in some regions are i) deformation of Al foil during handling, which affects the coating gap, and eventually wet layer thickness, and perovskite conversion kinetics, ii) some local non-uniform appearance of FTO layer that potentially affecting the wettability of the deposited inks, iii) further requirement of optimization in R2R drier settings, iv) further improvement required in perovskite formulation in terms of functional additives and interface layers that improves wettability, conversion, and crystallization kinetics.

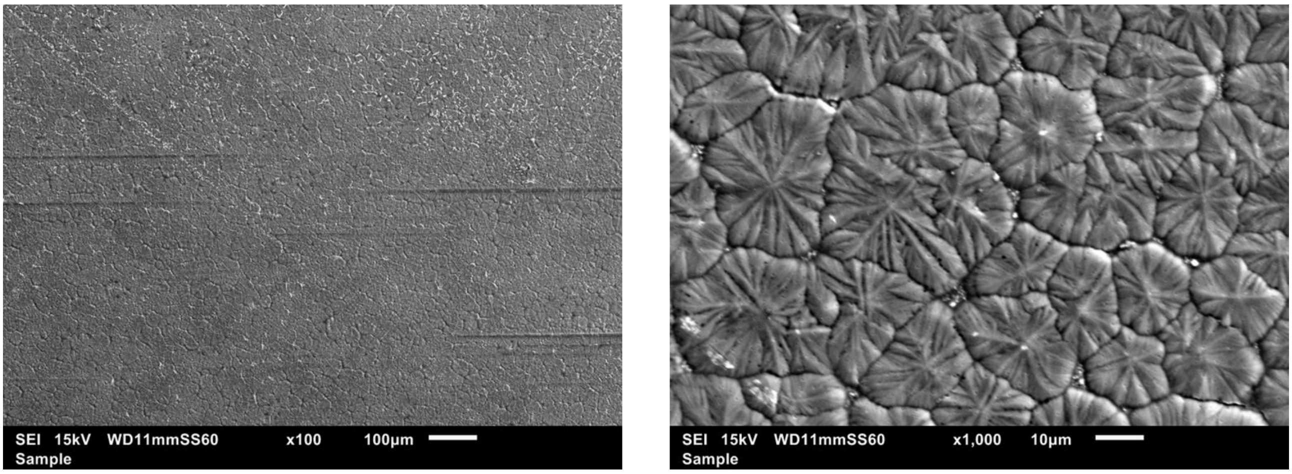


Figure 7 SEM images of R2R coated perovskite layer under 100 µm and 10 µm magnification, respectively.

XRD is done on different parts of the coated perovskite roll to analyze the crystallite phases of perovskite. Perovskite has several phases, among which, the alpha-phase is known as photoactive. The crystallographic diffraction angle of alpha-Perovskite phase is located around $2\Theta=14°$. Any disproportionation of the perovskite phase, or decomposition products, most likely PbI_2 and $CsPbI_2$ usually appears as a peak around $2\Theta=10°$. XRD graph in Figure 8 shows the prominent alpha-phase perovskite formation and missing peaks at lower angles indicates the complete conversion of the perovskite precursors into the correct crystallite phase. Other peaks labelled as “B” are satellite peaks observed at different diffraction angles. The peaks labelled as “A” are the fingerprints of Al foil, while the peaks labelled as “S” are the sign of SnO_2 (F-doped SnO_2, FTO electrode).

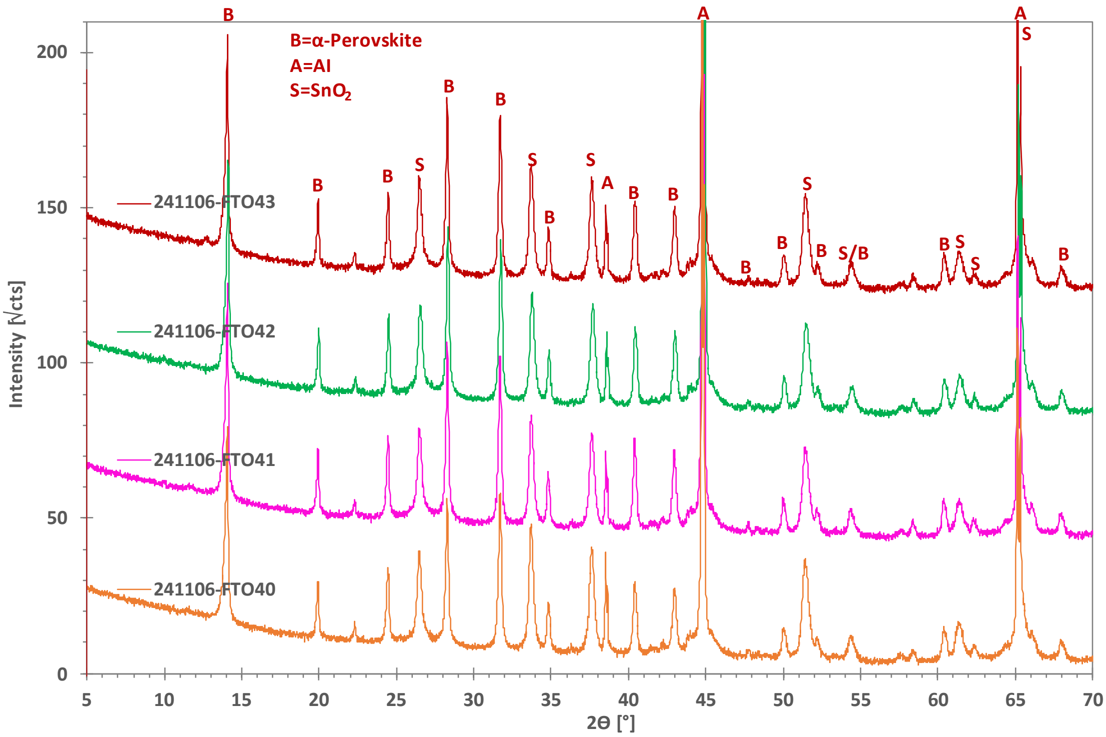


Figure 8 XRD data of R2R coated perovskite layers made from different parts of the coated rolls.

3. Conclusions

In conclusion, first R2R processing of perovskite semi-fabricate has been done in LUMINOSITY. In this deliverable, R2R SD coating of HTL, and R2R SD coating of Perovskite is demonstrated on Al/FTO foils in the form of a semi-fabricate with a surface area of 7500 cm^2. The perovskite foil is further packaged via R2R encapsulation and the demo is obtained. The morphologic and crystallographic properties were analysed via SEM and XRD, indicating the formation of closed grain boundaries with alpha-phase perovskite.

4. Degree of Progress

The progress is 100% achieved, the deliverable is reached.

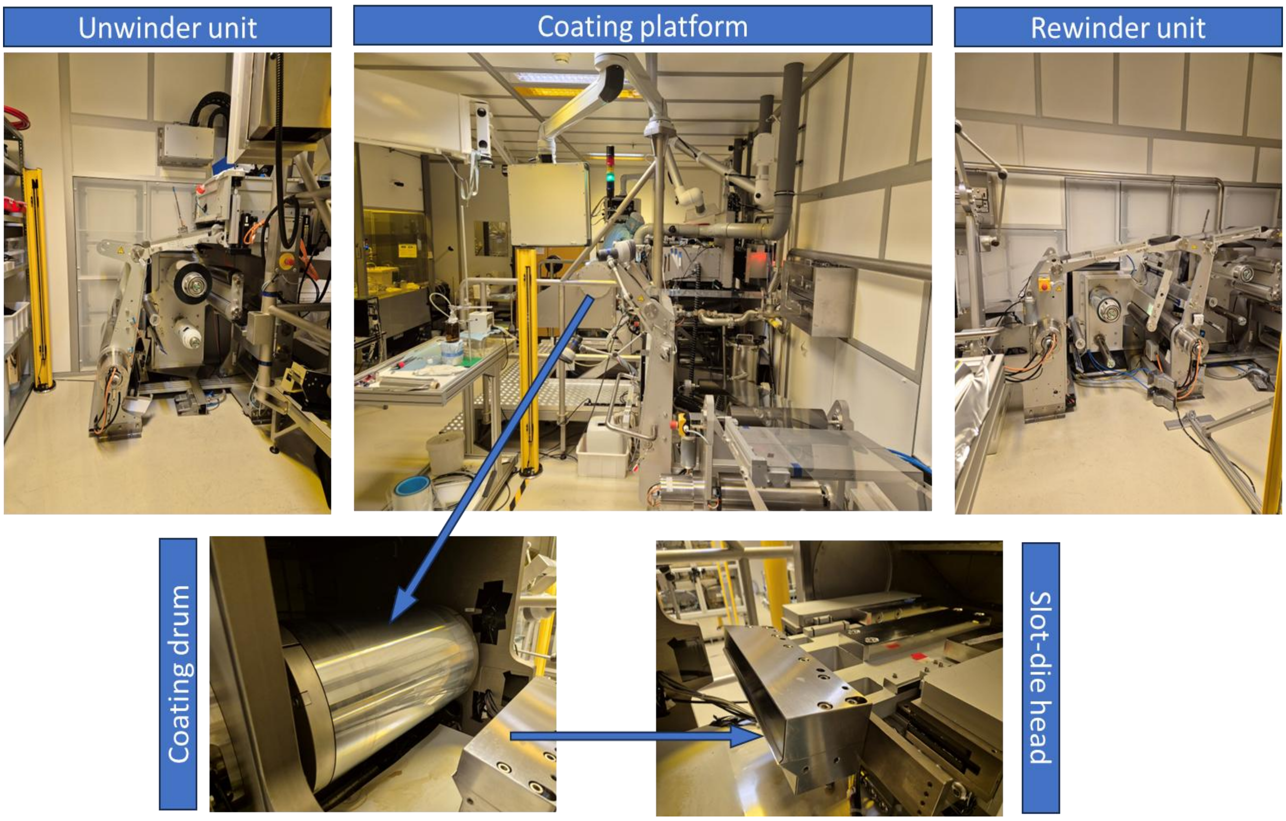
5. Dissemination level

Public.

6. Annexes

6.1. Schematics of the R2R slot-die coating line at TNO

General view of the TNO R2R line parts that are located in cleanroom



Overview of the R2R line. The coating hood, unwinder and rewinder units are located in the cleanroom, whereas the furnaces are located at the outside of the cleanroom to save space and operation costs. The furnace is air tight, and the air inside the furnace is cleanroom air. The coating platforms are available which are equipped with driers with a total length of 10 meters (the left side in the sketch below) and 20 meters (the right side in the sketch below), respectively. Several companies have partnered to build the R2R line, more than a decade ago.