

## Article

# High-Rate Roll-to-Roll Vacuum Metallisation for Flexible Packaging Materials: A Life Cycle Assessment Study

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## Abstract

Barrier layers are an essential component of flexible packaging for products susceptible to degradation or spoiling through ingress of water vapour or oxygen, which can readily penetrate conventional polymeric films. Vacuum metallisation of thin films for polymer packaging is widely employed to provide these barrier properties and hence extend the shelf life of the product. However, the environmental impacts associated with producing this metallised layer for packaging solutions are yet to be fully investigated or reported in the literature in the form of a Life Cycle Assessment (LCA). Using 87% primary data derived directly from industry, this study considers in detail all inputs, consumables, and outputs necessary to commercially produce a vacuum-metallised layer onto a high-area roll-to-roll polymer film substrate. A rating of “excellent quality” as per the industry-recognised pedigree matrix, along with validation of the data and acquisition procedures by relevant industrial experts throughout the production chain and adherence to (ISO)14040:2006 and (ISO) 14044:2006, ensures the highest standards of quality assurance and rigour. The Life Cycle Impact Assessment (LCIA) was performed for impact categories of climate change, freshwater consumption, and energy consumption, using the ReCiPe 2016 midpoint (H) methodology. Whilst the metalliser operation contributed the greatest energy use in the process, half of the climate change emissions and the majority of freshwater consumption were attributed to the raw materials and transportation. It should be noted that other converting processes experience a higher energy consumption (more than double) due to additional drying steps. A comparative LCA study was conducted, employing only secondary data found from publicly available literature and databases. The findings from this comparative study highlight significant overestimation of environmental impact, hence emphasising the importance of using up-to-date primary data wherever possible to reduce uncertainty in environmental impact from LCA.

**Keywords:** Life Cycle Assessment (LCA); flexible packaging; vacuum metallisation; vacuum coating; sustainability

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## 1. Introduction

Food packaging is an essential element to the preservation, transport, handling, and saleability of edible products. The main substrate used within the packaging can vary, with polymeric web (thin polymer film) most commonly used in manufacturing (76.8%), followed by paper substrates (11.4%) and finally aluminium foil (9.8%) [1]. Flexible plastic

is a fast-growing packaging category [2], with these materials increasingly being used as replacements for traditional packaging materials. To enhance these polymer films, barrier layers have been developed to reduce water vapour and oxygen ingress that occurs through most commercially relevant polymers.

Flexible packaging often incorporates a multi-layer structure where films are laminated together with the use of adhesives [3]. A typical flexible packaging structure consisting of several layers, commonly starting with a film, print layer, metallisation layer, adhesive, and sealant film. However, these structures are unsuitable for current recycling processes and result in large amounts of plastic waste. Alternate structures make use of a “mono-material” which is primarily (>90%) made of a single type of material, for example, polyethylene (PE). These may also require additional functional layers, such as an adhesive, barrier layer, and primer, but in such small quantities as to permit recycling of the packaging material. It is found that mono-material polymer packaging film consumption is forecast to grow exponentially with a rate of 4.5% annually [4].

Increasing demands in functionality and shelf life for polymer packaging have led to the development of coatings applied of additional material to improve shelf life by improving the oxygen and water vapour barrier. Barrier properties can be achieved in a variety of ways, such as a co-extruded specialist polymeric film with a thickness of 2–3  $\mu\text{m}$ , ethylene vinyl alcohol (EVOH) polymer skin layer ranging in several  $\mu\text{m}$  thickness, aluminium foil ranging from 7 to 9  $\mu\text{m}$  [5], and finally a vacuum coated layer of metals or metal oxides with less than 100 nm thickness which is advantageous for mono-material structures, and hence recyclability which requires at least 90% single polymeric film material. This study concerns the deposition process aspects of large-area roll-to-roll vacuum metallisation; the data acquisition and validation process for primary industry data is a significant effort. Further product conversion and end-of-life impacts are not considered here, as they are substantially diverse across the industry. The provision of focused LCA for this metallisation process enables the outcomes to then be incorporated as a common feature into a wide range of individual studies for specific packaging applications. Related studies published on metallisation and other PVD techniques lack direct relevance to flexible packaging, as both the economic and environmental benefits of roll-to-roll metallisation of polymeric web packaging film are predicated on economies of scale, with high-rate, high-volume, low-material-usage production, which is quite distinct from technologies using apparently similar processes.

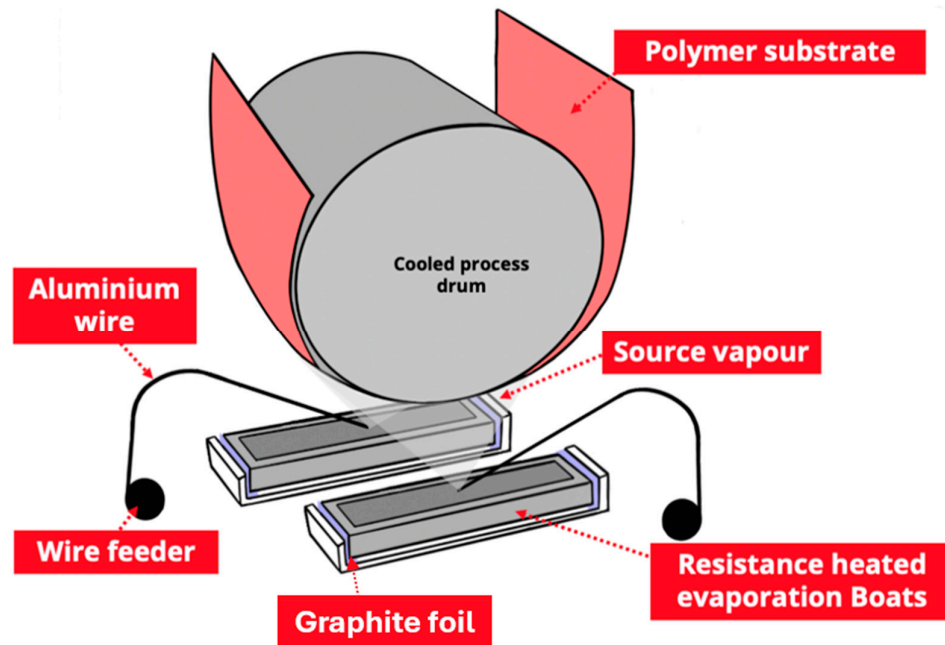
### 1.1. Coating Process

Vacuum metallisation is a commercially mature and widely used approach to improve barrier properties in flexible polymer packaging. Several technologies have been developed to deposit thin films onto the substrate in roll-to-roll processing, including physical vapour deposition (PVD) processes. One of the main variants of PVD techniques is thermal evaporation deposition (TED), which dominates the polymeric web coating market. This study will focus on a variant using resistance heating in which an electrical current is passed through a ceramic crucible/boat (commonly known as an evaporation boat). During processing, these resistively heated evaporation boats are at a temperature of approximately 1500 to 1650  $^{\circ}\text{C}$ . Aluminium wire (for this study a 2 mm diameter at 99.8% purity Al wire is used) is consistently fed onto the evaporation boat, where it melts, forms a pool, and is evaporated and then deposited onto the packaging substrate, which passes over a cooled drum. A vacuum level of  $5 \times 10^{-4}$  mbar in the evaporation zone and  $5 \times 10^{-2}$  mbar in the winding zone can be achieved.

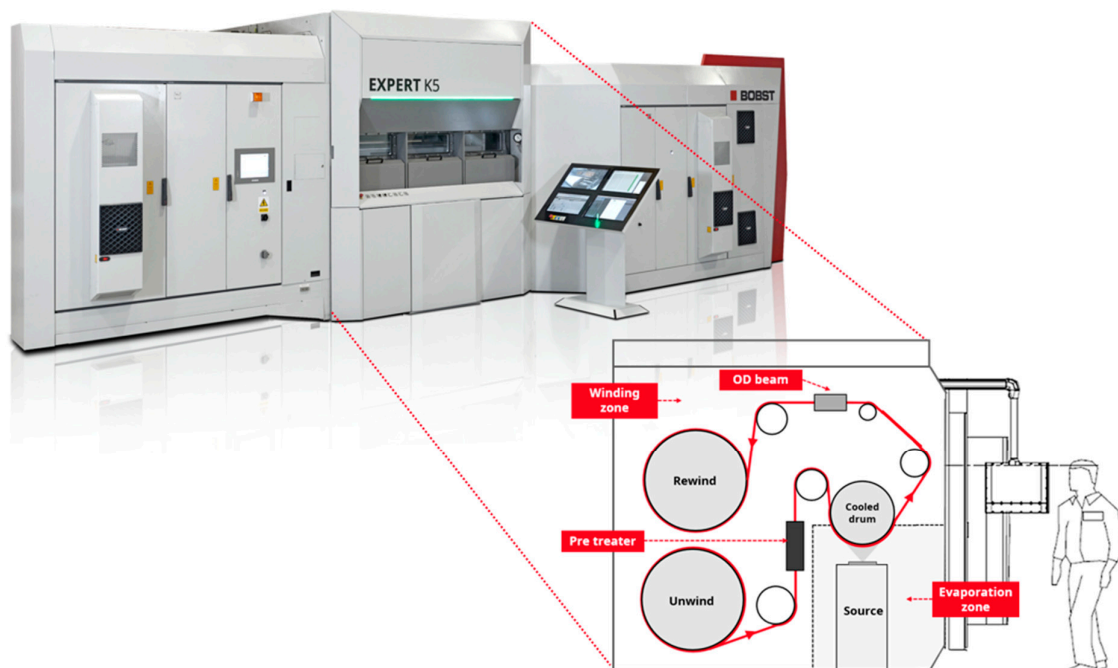
The cooled drum can be cooled down to  $-20$   $^{\circ}\text{C}$  to manage the heat load on the substrate. This is an industrial high-speed process that can take place at speeds of up to 1000 m/min with a polymer web width ranging from 1.35 to 4.85 m. A typical roll length can

range from 20,000 m to 70,000 m depending on the type and thickness of the substrate processed. Specific to this study, the BOBST EXPERT K5 1350metalliser with a 700 mm diameter and a large coating aperture is used to cover a broad range of packaging applications, producing aluminium thicknesses from 2.0 to 3.5 OD (Optical Density).

Figure 1 highlights a schematic representation of resistively heated boats for vacuum metallisation whilst Figure 2 highlights a cross-sectional image of the BOBST EXPERT K5 1350 metalliser detailing the processing zones present.



**Figure 1.** Schematic representation of resistance-heated boats in vacuum metallisation.



**Figure 2.** Cross-sectional layout of BOBST EXPERT K5 1350 metalliser.

The introduction of oxygen gas into the deposition zone can be used to oxidise the deposition flux, hence forming a partially oxidised  $\text{AlO}_x$  layer as opposed to an aluminium metal film, which can be required for transparency, microwave use, and to enable metal detection of foreign objects.

The polyethylene (PE) film used in this study has been coated using the EXPERT K5 Roll-to-Roll vacuum metalliser at Bobst Manchester Ltd, Manchester, UK. [6]. The EXPERT K5 1350 currently has the largest coating drum within the industry at 700 mm in diameter with a 20% wider coating window. Collection efficiency has been improved by 15% more aluminium deposited on the substrate, with a reduction in aluminium use achieved without compromising the metallised layer thickness or functionality [6]. Within the industry, BOBST has produced over four hundred metallisers in operation, and so a significant global benefit can be recognised with this study.

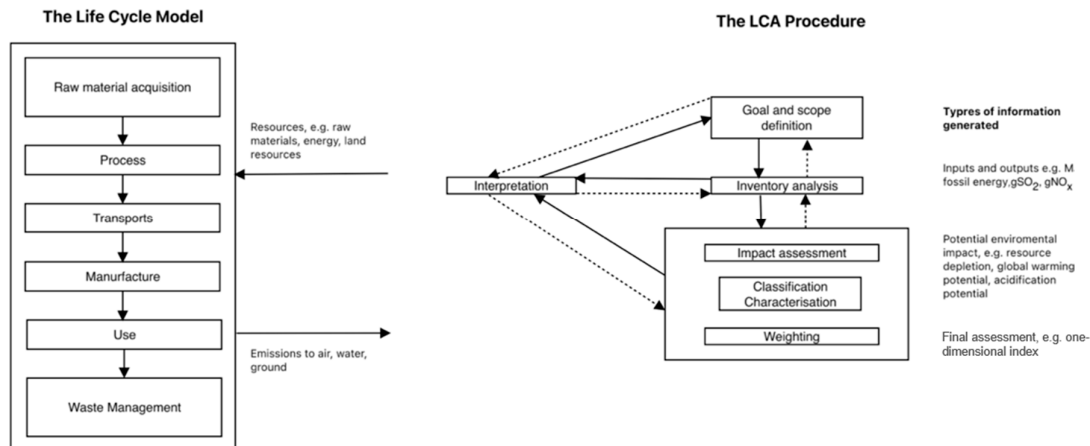
### 1.2. Plasma Treatment

Due to the low surface energy of many polymers, they often undergo a pre-treatment to enhance surface energy and hence promote adhesion of coated layers. One approach is the use of a technological plasma, created by electrical ionisation of a low-pressure gas. Plasma treatment, both pre- and post-deposition, is commonly used on polymer films to modify and enhance surface properties of the materials to improve the wettability, printability, and adhesion of coatings [7]. The gas may be inert, such as argon, to treat the surface without chemical change or may use the reactivity of oxygen for chemical modification. In this study oxygen plasma pre-treatment is used to enhance coating adhesion. It is generated via alternating current (AC) electrical power input, taken directly from the UK national grid.

### 1.3. Introduction to Life Cycle Assessment (LCA)

Life Cycle Assessment can be defined as a systematic analysis of the potential environmental effect that a product or service has over the product life cycle (PLC) [8]. It can consider all aspects from the acquisition of raw materials, manufacturing, transportation, use of the product or service, and finally the end-of-life processes (EOL). A full LCA would consider a product or service from “cradle to grave”, i.e., the extraction of raw materials from natural resources, such as mining of aluminium ores, to disposal of the product or service [9]. Shorter LCA scopes may be employed to specifically assess individual processes or groups of processes that may fit within multiple product life cycles highlighted from a cradle to gate methodology.

Various methodologies may be employed; therefore, it is necessary to define the goal and scope of a study and the impact categories to be investigated. The process can identify an inventory analysis, known as the Life Cycle Inventory (LCI) of a product, including all the raw materials required, along with identifying any emissions associated with their production. From assessing the inventory and materials, these inputs can be transformed into a Life Cycle Impact Assessment (LCIA), in which they can be calculated and equated into characteristics such as carbon emissions, freshwater consumption, ecotoxicity, eutrophication, and global warming potential [9]. These impact categories can then be interpreted and compared against a functional unit to allow a comparison between processes used in a PLC or allow a comparison between products that a company wants to introduce to the market. LCA can therefore be a valuable tool for identifying areas to improve in a product life cycle and to conduct internal business decisions supported by evidence of product or process sustainability. A simple model of the LCA and the LCA procedure is shown in Figure 3.



**Figure 3.** The life cycle model and the LCA procedure. Within this diagram on the life cycle model (left), the boxes indicate physical processes and arrows show the flow of energy. In the LCA procedure, the boxes represent procedural steps, and the arrows are the order in which they are performed. Dotted arrows represent possible iterations [9].

## 2. Methods and Materials

LCA SimaPro 9.5 2.0 software (PhD) (UK) (Sustainability insights for informed changemakers—SimaPro) [10] with the ecoinvent 3.9.1 database was used for the modeling in this LCA.

### 2.1. Requirements of Standards

The LCA conducted within this study adheres to the following International Standards:

- ISO 14040:2006—Environmental management—Life cycle assessment Principles and framework (ISO, 2006a) [11];
- ISO 14044:2006—Environmental management—Life cycle assessment Requirements and guidelines (ISO, 2006b) [12].

These standards can be broken down into the following phases:

- Goal and scope definition: this includes the purpose of the study, the description of the expected product of the study, system boundaries, and the functional unit (FU).
- Life Cycle Inventory (LCI) assessment: this section involves the collection of both input and output flows and the collection of the data associated with this study.
- Life Cycle Impact Assessment (LCIA): within this phase the environmental impacts associated with this product's life cycle can be identified.
- Life Cycle Interpretation: Once the results are identified, they can be interpreted, and the motivation of this study and target audience can be highlighted.

### 2.2. Goal and Scope Definition

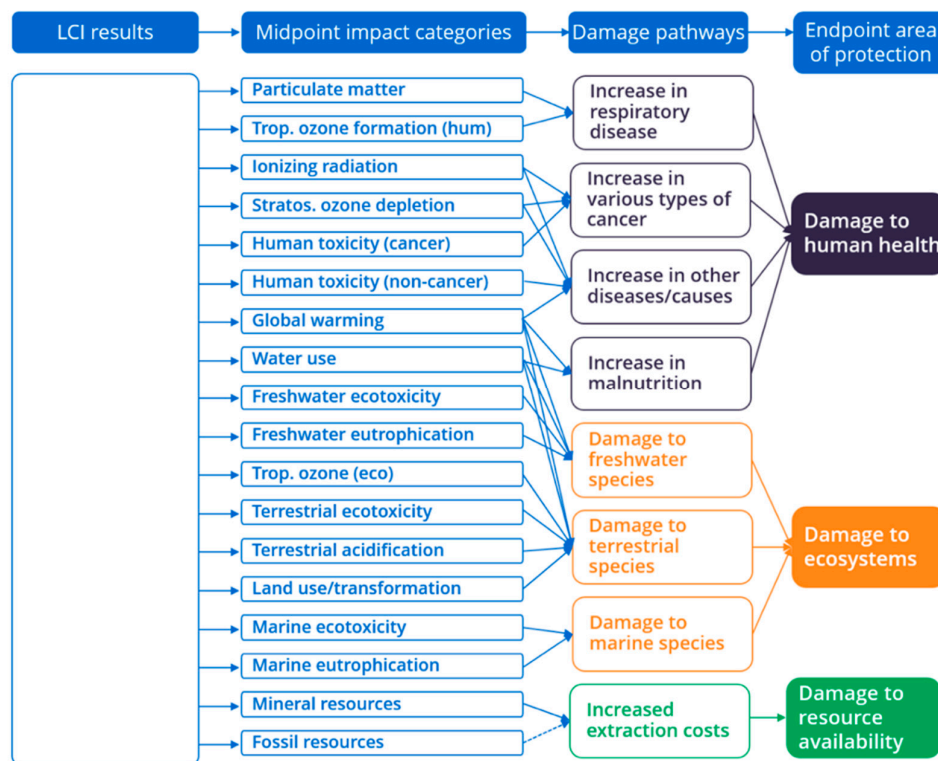
The environmental impacts arising from the deposition of a 50–60 nm thin aluminium layer onto a polymeric web via vacuum metallisation were analysed. Due to the commercial sensitivity of the exact thickness, only a range may be highlighted.

A functional unit of 1000 m<sup>2</sup> of coated film was selected due to its commercial relevance within the sector. Functional units within the packaging sector are typically identified as a weight or area of product, for example, 1000 kg of LDPE plastic packaging [13] or one tonne of AL-PE composite packaging material waste [14].

Functional units based upon area can be particularly advantageous to LCAs within flexible packaging, for which weight has much less relevance than area; 1 m<sup>2</sup> of plastic film was chosen by both [15] and [16].

The inventory developed for analysis makes extensive use of primary data for the metallisation process, courtesy of Bobst Manchester Ltd., along with further primary data provided by international partners along the value chain to inform over 80% of the inputs to the LCA, including all raw materials, energy inputs, and machine consumables associated with the process. All primary data collected for this LCA was inputted to SimaPro 9.5 2.0 software [10] with the ecoinvent 3.9.1 database.

LCIA phase methodology can either be selected at a midpoint or endpoint, with midpoint indicators focusing on single environmental impacts such as climate change, acidification, and ecotoxicity. Endpoint indicators show the impacts over three higher levels: damage to human health, damage to ecosystems, and damage to resource availability. Evaluation of literature sources, database methodology, and shared best practices within the packaging industry led to the selection of ReCiPe midpoint (H) for this assessment, where the (H) highlights a hierarchist perspective [17]. This is based on the most common policy principles with regards to timeframe and other issues. For example, ref. [18] evaluated the LCA results at a midpoint level, much like [19], who evaluated the results using ReCiPe midpoint (H), and ref. [20] used ReCiPe midpoint (H) within the LCA study. Within those three published studies, each used SimaPro as the software to conduct the LCA. Figure 4 highlights the midpoint impact categories investigated in this work, with particular emphasis on carbon emissions, freshwater consumption, and energy consumption. These three categories have been selected based upon specific demand within the industry; other impacts highlighted in the figure have been found to be marginal due to the nature of vacuum metallisation production, which has no chemical byproduct, etc.



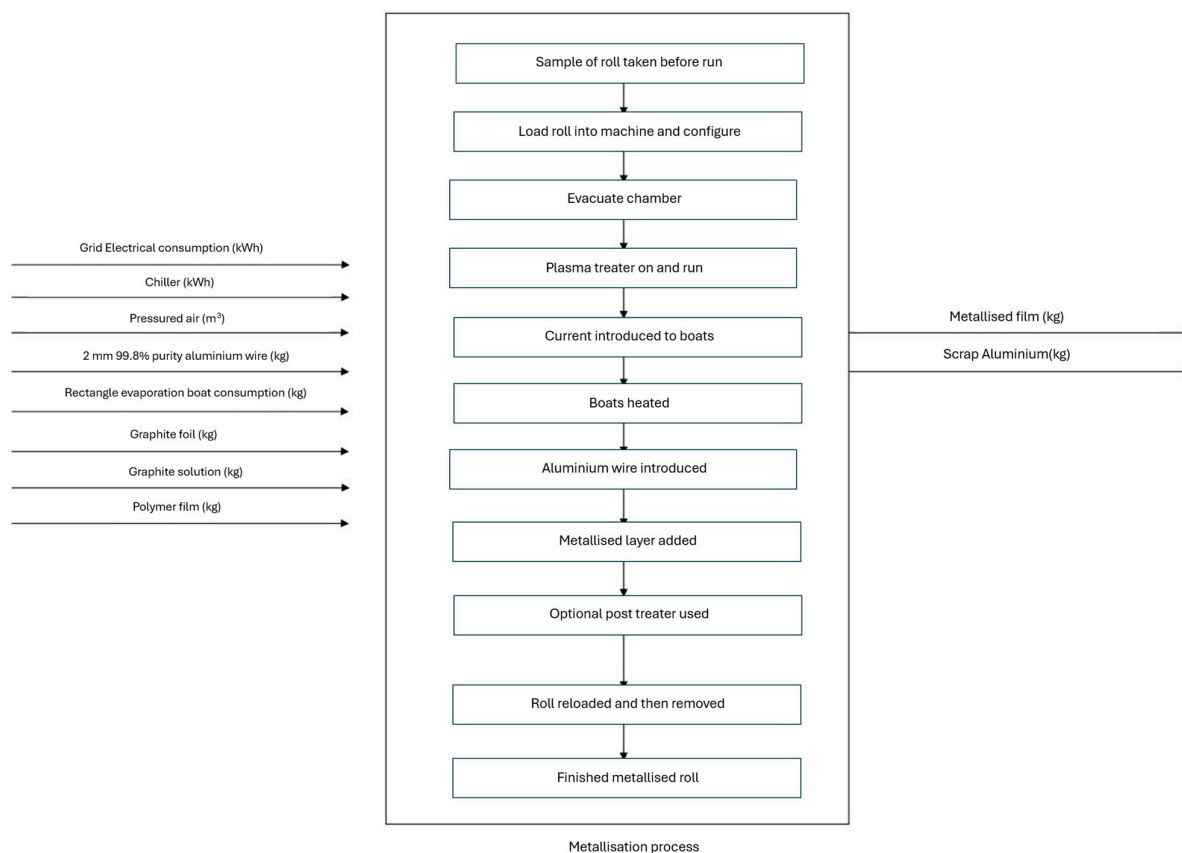
**Figure 4.** Representation of the relations between the midpoint impact categories and the areas of production (endpoint) in ReCiPe 2016 [17].

### 2.3. System Boundary and Functional Unit (FU)

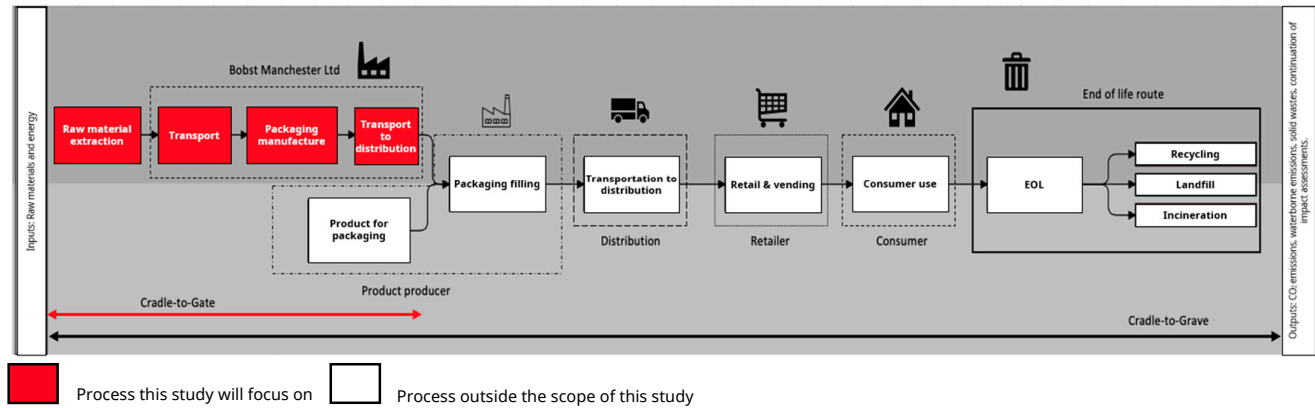
LCA relates environmental impact to the function of a product or system. Thus, there is a need to express the function in quantitative or qualitative terms as a functional unit [9]; this is a requirement of ISO 14040:2006 and 14044:2006.

Functional units within the packaging sector are typically identified as a weight or area of product, for example, 1000 kg of LDPE plastic packaging [13] or one tonne of AL-PE composite packaging material waste [14]. Functional units based upon area can be particularly advantageous to LCA's within flexible packaging. 1 m<sup>2</sup> of plastic film was chosen by both [15] and [16]; however, a larger unit of 1000 m<sup>2</sup> is deemed more appropriate for the high-volume vacuum metallisation considered in this case. Selecting 1000 m<sup>2</sup> as a functional unit would be advantageous, as this quantity can be converted further into a certain number of end products, such as pouches.

The system boundary, used within this analysis, as per Figure 5, employs a “cradle-to-gate” methodology to include the raw material and manufacturing stage, as these stages most often contribute to the largest proportion of the life cycle impacts [14,15]. The relevant transportation phase has also been included within this study to understand the impacts associated with the shipments of the raw materials and process aid consumables. Assessment beyond this boundary is both difficult and limiting to the application of findings, as there is significant variability in how the product is further converted and used in product packaging, which is outside of the control of the authors and would reduce the data quality. The cradletogate values allow the findings to be further input into many alternative process LCAs. This system boundary is illustrated in Figures 5 and 6.



**Figure 5.** System boundaries for metallisation process.



**Figure 6.** Cradle-to-gate methodology used within this project.

Within this stage of the study, an area region must be selected on which to base the LCA study. An exploration of choosing different area regions can have an impact on inputs such as electricity generation and transportation, as these are location-dependent and vary from country to country. This LCA study is based on production at Bobst Manchester Ltd., located in the North-West of England, United Kingdom (UK). Hence, the electricity consumption is based on the UK electricity grid, and the transportation has been calculated based on shipping the raw materials to this location.

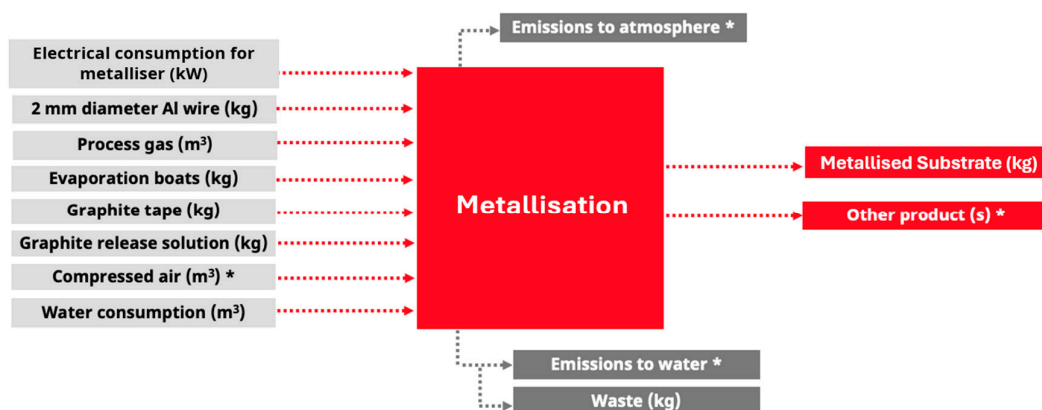
#### 2.4. Life Cycle Inventory Analysis

The inventory analysis step collects the appropriate inputs and outputs associated with the scope. The selection of inputs was informed by consultation and review with specialist teams for each stage of the process using BOBST's network of subsidiaries and commercial partners. All energy consumptions, raw material compositions, and manufacturing processes are defined by industry data provided courtesy of BOBST and suppliers in the ecosystem.

The power and consumable consumptions for the BOBST EXPERT K5 1350 coater presented in Figure 7 have been provided by Bobst Manchester Ltd. [6].

The data obtained within this study has been directly measured and obtained, based on industrial trials performed on the EXPERT K5 1350 metalliser.

The inventory data collected is then normalised in accordance with the functional unit [21] and used within the study to determine the resulting environmental impacts [9].



**Figure 7.** Metallisation process identified using typical categories of numerical data collected to describe processes. \* represents if the process is applicable to the study [9].

Data collection is the most time-consuming element of any LCA, with the data origins varying from study to study [9]. Within this study the data collection is primary data originating from the Bobst Manchester Ltd. site based in Heywood, Manchester. Suppliers of the raw materials for the process provided energy consumption to manufacture the raw material along with the manufacturing processes, which provided confidence in data accuracy and compensated for a lack of resources in the software database. In this study a raw material is defined as a material that is added into the layer composition of the final product, whereas materials used in the process but not featuring in the final product have been named as process aid consumables.

Figure 7 presents the inputs associated with metallisation. The electrical consumption for the metalliser refers to the energy consumption of the EXPERT K5 1350 when the machine is in operation, provided by Bobst Manchester Ltd. and measured in kWh.

The electrical consumption of standard boat-type metallisation takes place in a vacuum as a batch process involving a typical cycle consisting of:

- Pump-down—to reach the required vacuum pressure level of approximately  $5 \times 10^{-4}$  mbar in the evaporation zone and  $5 \times 10^{-2}$  mbar in the winding zone can be achieved.;
- Processing;
- Venting—to return to atmospheric pressure and opening;
- Changeover—including cleaning and removal of process roll and loading new unprocessed material.

The electricity data is then selected within the ecoinvent database for the average power grid based in the UK. The 2 mm-diameter aluminium (Al) wire refers to the aluminium wire that is fed onto the evaporation boats to be vaporised to produce the barrier layer. Additionally, process gas is introduced, which can be identified as 100% oxygen. Process aid consumables include ceramic evaporation boats, graphite tape for connection of boats, and a graphite release solution for removal of excess coating from the metalliser walls.

Ancillary processes include a closed-loop cooling system required for the operation of the metalliser. This LCA considers the changing and maintenance of the closed water system, with the amount of water proportioned in accordance with the total yearly output and then normalised to provide an input for the functional unit of 1000 m<sup>2</sup> coated film. Compressed air necessary for various systems in the vacuum coater is also accounted for. A further study into the regular servicing of the metalliser and the inputs associated with this has been undertaken; however, with a <0.05% total impact on the LCA results attributed to the service having an almost negligible impact, it is not included in this report.

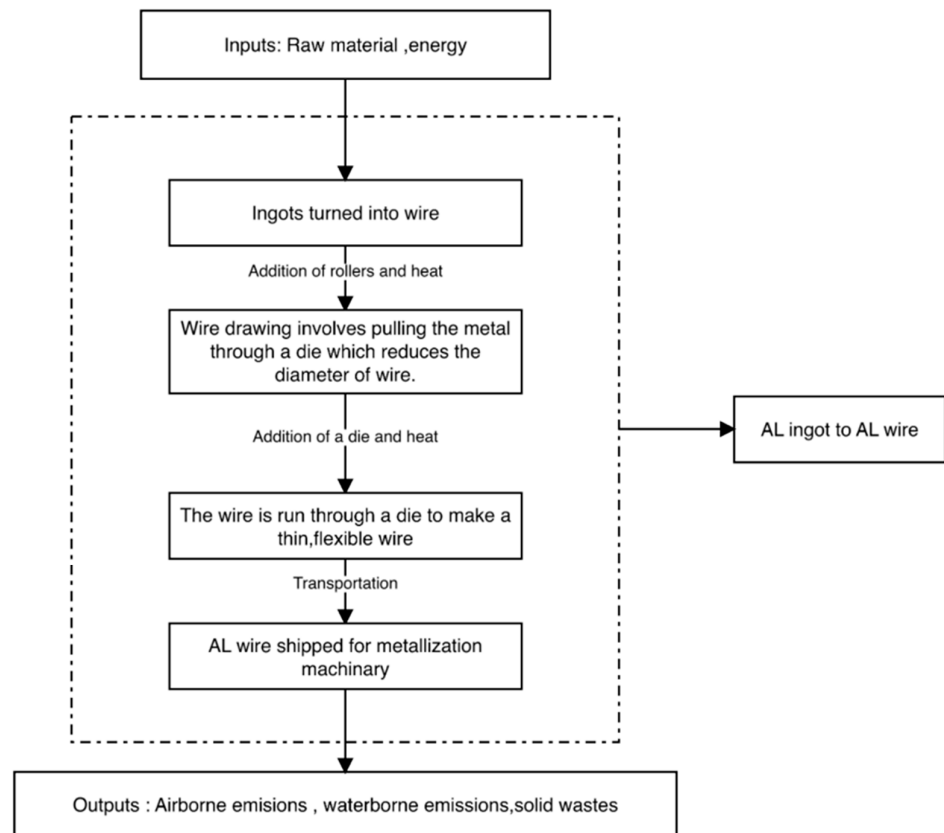
In addition to identified inputs, the process throughputs must be considered. This highlights any emissions to the atmosphere during production. Due to the efficient design of the EXPERT K5 1350 metalliser, no process materials are emitted to the atmosphere or to the water supply from the process. Although these throughputs have no impact, it has been included within Figure 7 to indicate that this factor was identified and explored within this study.

Waste products within the process can comprise substrate film that is lost between the start-up phase and slowdown phase of the machine and excess aluminium coating within the vacuum chamber walls. Since the evaporation boats have a typical operational life of up to 20 h, they must be changed after this period; however, they are subsequently collected and recycled by the manufacturers to be fabricated into other products and not classified here as waste.

Figure 7 also identifies the process outputs, which are the main desired output of the metallised substrate and any byproducts. Although no further byproducts are produced by this process (a key benefit of PVD processing over chemical treatments), this section is included within the figure to indicate that this has been investigated within the inventory accumulation for the LCA.

### 2.5. The 2 mm-Diameter Aluminium Wire

A manufacturing process for the production of the 2 mm-diameter aluminium wire is illustrated in Figure 8. For the EXPERT K5 1350, the aluminium wire is fed constantly onto the evaporation boats, measured by the wire feed rate (WFR) with cm/min as the unit of measure. The WFR is directly proportional to the quantity of aluminium wire used. For this LCA study, the quantity of aluminium wire used was normalised for the functional unit of 1000 m<sup>2</sup>. Due to the commercial sensitivity of the electrical consumption to produce the aluminium wire, the overall consumption cannot be stated, but a range of 1–2 kWh can be disclosed.



**Figure 8.** Manufacturing process to produce a 2 mm-diameter aluminium wire.

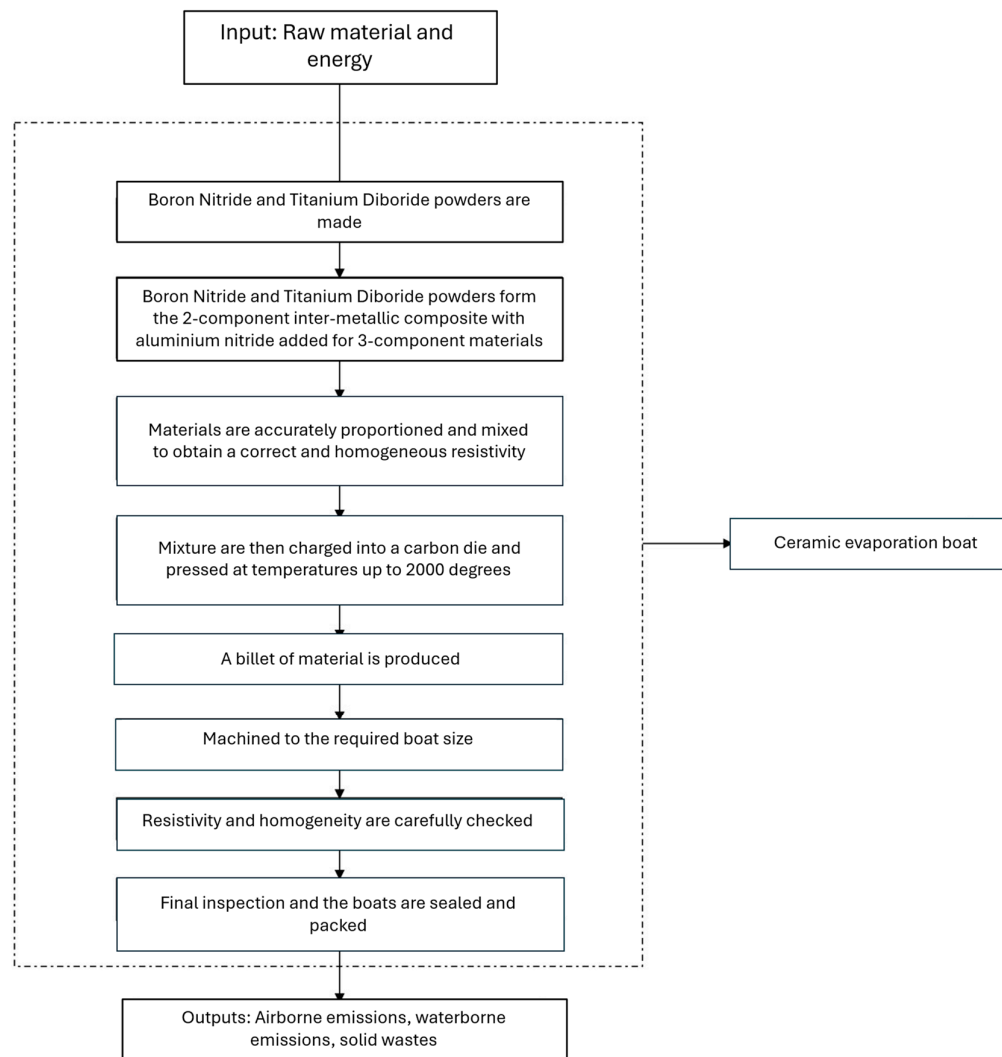
### 2.6. Ceramic Evaporation Boats

The main process aid consumables used are the evaporation boats composed of inter-metallic composites (IMC), uniquely developed materials that combine electrically insulating and electrically conductive materials to form a ceramic [22]. This ceramic can then be heated to extremely high temperatures via electrical resistance heating or with an electrical current. This type of composite can withstand the required evaporation temperatures ranging from 1500 to 1650 °C. Evaporation boats can be supplied in a variety of shapes to provide a range of resistivity levels to match the power consumption of the machine. For this study we have selected the standard rectangular evaporation boats with a weight of 132 g and a size of approximately 12 cm in length and 4 cm in width. This boat is an inter-metallic, two-component ceramic boat consisting of Boron Nitride (BN) and Titanium Diboride (TiB<sub>2</sub>).

For the EXPERT K5 1350, the total number of boats used was twenty to generate a high rate and uniform deposition across the full polymer web width. Evaporation boats

have a recommended lifespan of up to 20 hours (depending on the operating conditions) before they should be discarded. For this study, a boat life of 12 h will be used.

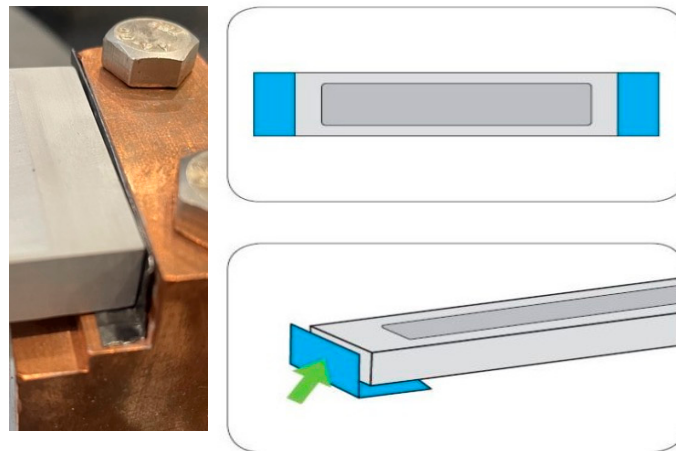
The total energy consumption for fabricating a single boat has been determined for this study. Due to the commercial sensitivity of this data, a simplified methodology is presented in Figure 9.



**Figure 9.** Manufacturing process map to produce rectangular evaporation boats from ceramic powders.

## 2.7. Graphite Tape/Foil

Graphite tape is a process aid consumable used to improve electrical contact between the evaporation boat and the EXPERT K5 1350 machine contacts (Figure 10). The tape must cover the entire side surface of the evaporation boat and is removed and changed with every boat change after 11/12 h (lifespan of a boat for our studies specific operation conditions). For this study, a single piece of tape on both contacts will be used, as this is the amount used for the EXPERT K5 1350 within this study.



**Figure 10.** Representation of the graphite tape used for the evaporation boats.

### 2.8. Graphite Solution

After the evaporation of the aluminium during the metallisation process, excess aluminium is deposited within the walls of the vacuum chamber itself, which needs to be removed to maintain machine efficiency, correct vacuum levels and coating properties. To facilitate and ease the removal of the unwanted coating inside the vacuum chamber, a layer of water-based graphite solution is painted on the walls prior to deposition. Once the process has been conducted, this coating is then removed by the operator and collected in an Al waste bin. The disposal of this waste is dependent on the converter; in this study's case, the waste is collected by an external third party to be effectively recycled.

### 2.9. Inventory Data

Table 1 provides the inventory associated with the evaporation boats, including the mass per boat, the total number of boats used within the machine, the boat lifetime, and the material composition of the boats. Transportation routes have been included to represent the route between the manufacturing and distribution site of the evaporation boats. The transportation mode has been selected from the ecoinvent database to represent the vehicle specifications. Table 2 provides the mass of one graphite tape piece, the total number of tapes used for each boat, the lifespan, and finally the material composition. The transportation routes have also been included with the same representation as previously mentioned. Table 3 contains the inventory associated with the graphite release solution. Table 4 represents the main raw material, the 2 mm-diameter aluminium wire, incorporating the energy consumption for its manufacture.

**Table 1.** Inventory of one rectangular evaporation boat.

|                                              |                   |                                                                                                                 |
|----------------------------------------------|-------------------|-----------------------------------------------------------------------------------------------------------------|
| Mass of one rectangular boat (kg)            | 0.132             |                                                                                                                 |
| Number of boats used in metalliser           | 20                |                                                                                                                 |
| Boat life (hrs)                              | 12                |                                                                                                                 |
|                                              | Titanium Diboride | Boron Nitride                                                                                                   |
| Composition                                  | 50%               | 50%                                                                                                             |
| Mass (kg)                                    | 0.066             | 0.066                                                                                                           |
| Energy consumption to produce one boat (kWh) | XXX               | Redacted commercially sensitive data                                                                            |
| Transportation (km)                          | 293               | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW}<br>transport, lorry 16–32 metric ton, EURO5  Cut-off, U |

**Table 2.** Inventory for one strip of graphite tape.

|                                                     |          |                                                                                                             |
|-----------------------------------------------------|----------|-------------------------------------------------------------------------------------------------------------|
| Mass of one strip of graphite tape (g)              | 0.1512   |                                                                                                             |
| Number of tape strips used                          | 2        |                                                                                                             |
| Lifespan (Hours)                                    | 12       |                                                                                                             |
|                                                     | Graphite |                                                                                                             |
| Composition                                         | 99%      |                                                                                                             |
| Mass (g)                                            | 0.1512   |                                                                                                             |
| Energy consumption for every 1 kg of Graphite (kWh) | 0.55     | [23]                                                                                                        |
| Transportation (km)                                 | 293      | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |

**Table 3.** Inventory for one coating of graphite solution.

|                                                                            |                           |                                                                                                             |
|----------------------------------------------------------------------------|---------------------------|-------------------------------------------------------------------------------------------------------------|
| Mass of one coating of graphite solution used per metallising process (kg) | 0.05                      |                                                                                                             |
| Lifespan (Hours)                                                           | Dependent on the run time |                                                                                                             |
|                                                                            | Graphite paste            | Deionised water                                                                                             |
| Composition                                                                | 25%                       | 75%                                                                                                         |
| Mass (kg)                                                                  | 0.0125                    | 0.0375                                                                                                      |
| Energy consumption for every 1 kg of Graphite paste (kWh)                  | 12.74                     | [24]                                                                                                        |
| Transportation (km)                                                        | 293                       | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |

**Table 4.** Inventory for 2 mm-diameter aluminium wire.

|                                                                           |           |                                                                                                             |
|---------------------------------------------------------------------------|-----------|-------------------------------------------------------------------------------------------------------------|
| Mass of consumed 2 mm aluminium wire for 1000 m <sup>2</sup> (kg)         | 0.14      | This weight accounts for the collection efficiency                                                          |
|                                                                           | Aluminium |                                                                                                             |
| Composition                                                               | 99.8%     |                                                                                                             |
| Mass (g)                                                                  | 0.2715    |                                                                                                             |
| Energy consumption for 1 kg of wire from raw material extraction (kWh/kg) | 213–215   |                                                                                                             |
| Transportation (km)                                                       | 357       | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |
|                                                                           | 35        | Transport, barge ship, bulk, 12,000 t, 100%LF, default {GLO} Economic, U                                    |
|                                                                           | 398       | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |

To normalise the inventory data in accordance with the functional unit, the data must be scaled appropriately. The data is based on trials conducted at the Bobst Manchester Ltd. site based in Manchester to deposit a 50–60 nm metallised layer, running at 800 m/min production speed, based on a 25 km Machine-Direction-Oriented Polyethylene (MDOPE) roll length and a substrate width of 1350 mm. Since this study focuses solely on the environmental impacts associated with the metallisation process, the specific substrate inputs can be omitted from this LCA. This allows the LCA outputs to be applied within multiple

LCAs for a wide variety of products that make use of various substrate materials. Table 5 provides the typical process energy consumption of the EXPERT K5 1350. This value includes the measurements for:

- Pump-down—to reach the required vacuum pressure level of  $5 \times 10^{-4}$  mbar and  $5 \times 10^{-4}$  mbar in winding zone;
- Processing;
- Venting—to atmospheric pressure and opening;
- Changeover—including cleaning and removal of the process roll and loading new unprocessed material.

Data entered for raw materials were derived and selected from the ecoinvent database [25].

To provide a fully detailed LCA, additional inputs such as a cleaning solvent and water have been included, although the impact of these is expected to be negligible.

**Table 5.** LCA inventory data normalised to 1000 m<sup>2</sup>.

| Input Material for 1000 m <sup>2</sup> | Quantity | Uncertainty Distribution | Pedigree Matrix | DQR |
|----------------------------------------|----------|--------------------------|-----------------|-----|
| 2 mm-diameter Al wire consumed (kg)    | 0.14     | Lognormal                | [1, 1, 1, 1, 1] | 1   |
| Machine energy consumption (kWh)       | 5.4–6    | Lognormal                | [1, 1, 1, 1, 1] | 1   |
| Evaporation boat (g)                   | 0.05     | Lognormal                | [1, 2, 1, 1, 1] | 1.2 |
| Graphite tape (g)                      | 0.03     | Lognormal                | [2, 1, 1, 1, 1] | 1.2 |
| Graphite solution (kg)                 | <0.001   | Lognormal                | [2, 1, 1, 1, 1] | 1.2 |

#### 2.10. Data Quality Assessment

Data acquisition is a key element to any LCA study; the greater the validity of the data, the greater the accuracy, reliability, and confidence of the LCA results. The collected inventory data for this study was assessed using an industry-recognised pedigree matrix [26] based on a set of criteria:

- Time-related coverage, referring to the recency and relevance of the data used.
- Geographical coverage, assessing the degree to which the geographical location is reflected.
- Technology coverage, evaluating how well the data represents technologies used within the PLC.
- Completeness, involving checking the completeness of all data used and eliminating any gaps.
- Reliability for understanding validity and accuracy of the data used. This stage heavily depends on the data source.

The pedigree matrix was introduced to uncertainty analyses in 1990 as a tool for quantification of qualitative assessment descriptions [27]. Within this guidance the full details of the pedigree matrix can be found. The primary goal of this matrix is to identify and analyse the uncertainty associated with inventory data.

The pedigree matrix rates inventory data against the stated criteria with scores from 1 to 5 with respect to the criteria. The average can then be calculated, and a score for the data quality rating (DQR) can be obtained. Table 6 displays the data quality ratings to assess the data quality level.

**Table 6.** Overall data quality level according to the achieved data quality rating. Source: PEF method.

| Overall Data Quality Rating | Overall Data Quality Level |
|-----------------------------|----------------------------|
| $DQR \leq 1.5$              | Excellent quality          |
| $1.5 < DQR \leq 2.0$        | Very good quality          |
| $2.0 < DQR \leq 3.0$        | Good quality               |
| $3.0 < DQR \leq 4.0$        | Fair quality               |
| $DQR > 4$                   | Poor quality               |

Following the sum of the data quality ratings highlighted in Table 5, column 4, and divided by the total 16 inventory points, an overall DQR score of 1.1 can be calculated, representing “excellent quality” data. Over 80% of the total inputs for this LCA are from primary data from the manufacturer or courtesy of our partners, with limited literature data used to address any lack of primary data available, such as energy consumption data for the graphite tape, graphite release solution, and process gas. When undertaking an LCA study, the strength of collaborations throughout the value chain is critical to obtain reliable primary data and is perhaps uniquely strong in this case. For existing published LCA studies, the contribution of primary data used is difficult to determine due to the lack of transparency in the inventory data used, and in most cases, no specific claims on data provenance are made.

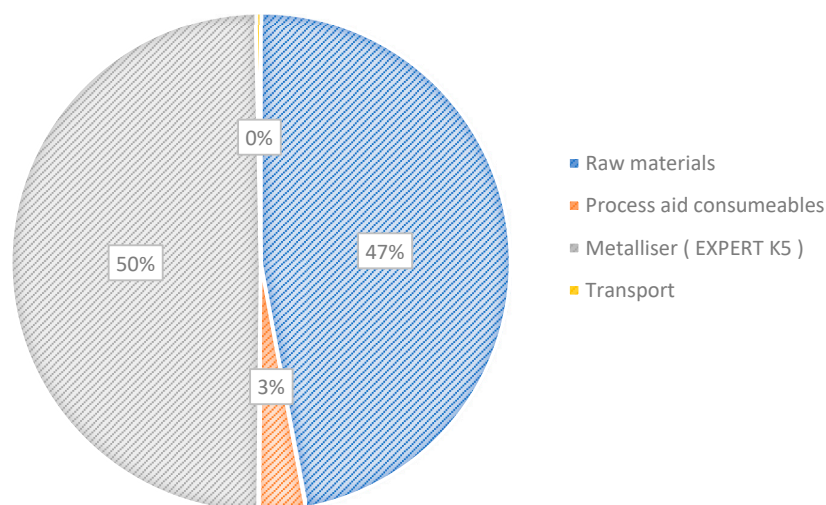
### 3. Results and Discussion

#### 3.1. Life Cycle Impact Assessment

Environmental impacts associated with climate change, freshwater consumption, and energy consumption have been assessed for this study, as these impacts hold the largest demand from an industrial market aspect, whereas other impacts (such as human toxicity, ecotoxicity, resource depletion, acidification, and eutrophication) hold little relevance to the processes involved, which produce no byproduct or appreciable chemical emissions and use abundant materials. Climate change, also referred to as global warming potential (GWP), is expressed as kg CO<sub>2</sub>-eq. This impact considers the greenhouse gases released during the material extraction, manufacturing process, and use. Freshwater consumption is expressed as m<sup>3</sup> and considers the water consumption during the metallisation process, raw material extraction, manufacturing process, and use. Within freshwater consumption there is a distinction between direct and indirect water consumption used within a life cycle [28]. Direct water consumption refers to water that is used and consumed within the life cycle being assessed, whereas indirect consumption is consumed during the production of the inputs [28]. Energy consumption refers to the total energy associated with the metallisation process, raw material extraction, manufacturing, and use. This category is expressed in MJ.

Figure 11 shows the total climate change impact associated with the metallisation process, calculated as 5.94 kg CO<sub>2</sub>-eq, with 50% of this impact (2.96 kg CO<sub>2</sub>-eq) attributed to the machine operation. This figure represents the emissions associated with the generation of the electricity needed to power the EXPERT K5 1350. As mentioned in the inventory collection, the metalliser does not release any emissions during the process. A total of 47% of the total climate change impact can be attributed to raw materials (2.82 kg CO<sub>2</sub>-eq). Process aid consumables contribute a total of 0.18 kg CO<sub>2</sub>-eq, or a 3% impact. The overall transportation of the raw materials and process aid consumables has the smallest contribution to climate change impact of <1%, equating to 0.019 kg CO<sub>2</sub>-eq.

### Climate change (kg CO<sub>2</sub>-eq) Total: 5.94 kg CO<sub>2</sub>-eq



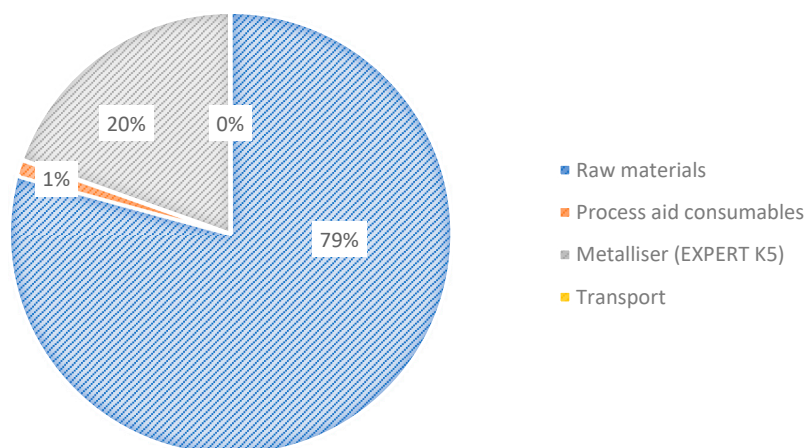
**Figure 11.** Climate change results from LCA study from primary data.

Figure 12 shows the distribution of the freshwater consumption impact, with a total consumption of 0.084 m<sup>3</sup>. Less than 1% of this impact is contributed by transportation. A total consumption of 0.067 m<sup>3</sup> can be attributed to raw materials, representing 79% of the overall contribution, and 0.0015 m<sup>3</sup> to the process aid consumables.

A closed-loop cooling system is required for the operation of the metalliser, and the changing and maintenance of the closed water system is considered here. The amount of water has then been normalised to provide an input for 1000 m<sup>2</sup>.

### Fresh water consumption (m<sup>3</sup>)

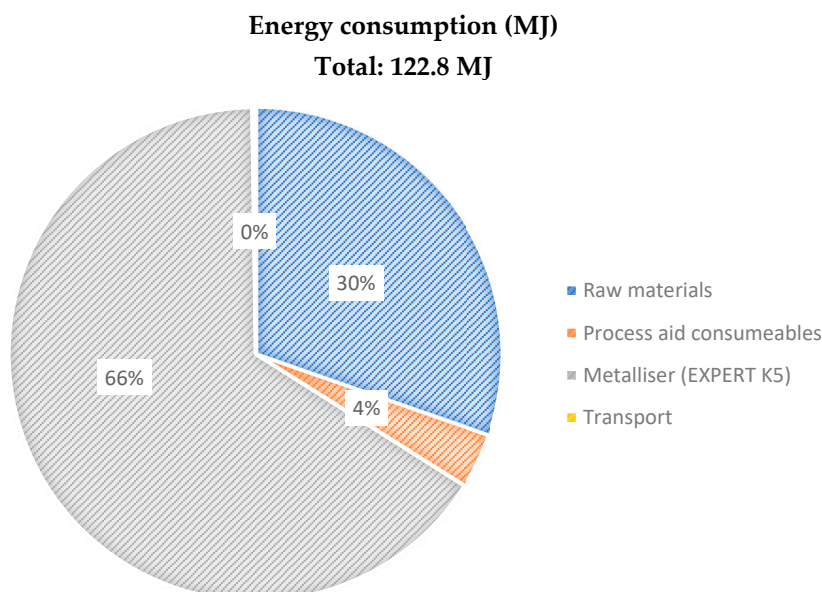
Total: 0.084 m<sup>3</sup>



**Figure 12.** Freshwater consumption results from LCA study from primary data.

A total energy consumption of 122.8 MJ is required to produce the functional unit. The distribution of energy consumption impacts for the metallisation process is shown in

Figure 13. Transportation has the smallest contribution to this impact, with a <1% contribution. The proportion attributed to the process aid consumables is much higher than for the other impact categories, at 4%, which includes the raw material extraction and the consumable manufacturing processes. The raw materials contribute a 30% share, or 37.01 MJ of energy consumption in the LCA, with a 66% contribution from the operation of the vacuum metalliser.



**Figure 13.** Energy consumption results from LCA study using primary data.

### 3.2. Comparative LCA Study Based Only on Secondary Data

To contrast the LCA study using a high percentage of high-quality primary data, an additional LCA study is presented, using only secondary reference data extracted from the literature and commercial datasets, along with relevant assumptions for electrical consumption. For consistency, transportation will remain the same as for the previous study, as the supplier locations are unchanged.

Table 7 displays the two main inventories comparing the energy consumption to produce one evaporation boat and the energy consumption of the 1 kg of 99.8% aluminium wire manufacturing process, along with assumptions made.

**Table 7.** Condensed table displaying inventory data taken from primary data vs. secondary data.

| Raw Material                                                              | Primary Data Value | Secondary Data Value | The Assumption Basis and Origin                                                                                                                                   | Unit   |
|---------------------------------------------------------------------------|--------------------|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| Energy consumption to produce one evaporation boat                        | <10                | 23.6                 | Using the confidentially shared manufacturing process to produce one boat, an energy consumption value for each manufacturing stage was taken from the literature | kWh/kg |
| Energy consumption for 1 kg of 99.8% aluminium wire manufacturing process | <0.15              | 0.18                 | The energy consumption to produce the desired wire from a billet                                                                                                  | kWh/kg |

For the LCI data for the evaporation boat within Table 1, the mass and material composition are publicly available data; however, the energy consumption to manufacture the evaporation boat is not. Based on the commercially sensitive manufacturing process for an evaporation boat shared by the partner company, a derived energy consumption of these manufacturing steps from multiple literature sources results in an energy consumption of 23.6 kWh/kg, in stark contrast to the accurate primary data for the energy consumption provided by the evaporation boat supplier shown within Table 8, which shows a 60–80% reduction in the amount.

**Table 8.** Inventory data for one evaporation boat using literature data in comparison to primary data.

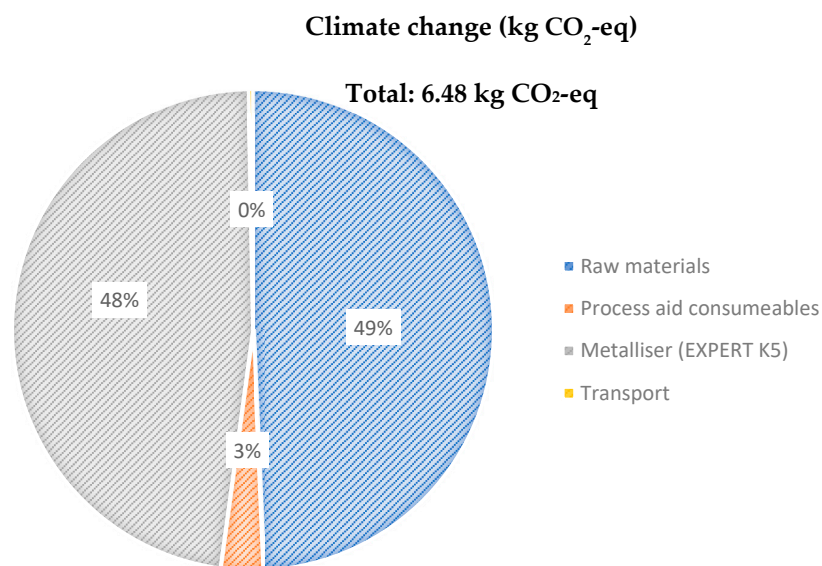
|                                      |                   |                                                                                                             |
|--------------------------------------|-------------------|-------------------------------------------------------------------------------------------------------------|
| Mass of rectangular boat (kg)        | 0.132             |                                                                                                             |
| Number of boats used in metalliser   | 20                |                                                                                                             |
| Boat life (hrs)                      | 12                |                                                                                                             |
|                                      | Titanium Diboride | Boron Nitride                                                                                               |
| Composition                          | 50%               | 50%                                                                                                         |
| Mass (kg)                            | 0.066             | 0.066                                                                                                       |
| Energy consumption per boat (kWh/kg) | 23.6              | Based on literature                                                                                         |
| Transportation (km)                  | 293               | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |

There is a lack of available data specifically for the fabrication of the 2 mm aluminium wire within the available database. Therefore, the energy consumption for the fabrication of a steel wire has been used as the best estimation for this inventory. Comparing this data to the primary data presented in Table 4 shows a 50–60% increase in consumption for the fabrication of the aluminium wire (provided under confidentiality agreements) to the calculated value of 0.18 kWh/kg, derived from publicly available data and displayed within Table 9.

**Table 9.** Inventory data for the 2 mm aluminium wire using literature data in comparison to primary data.

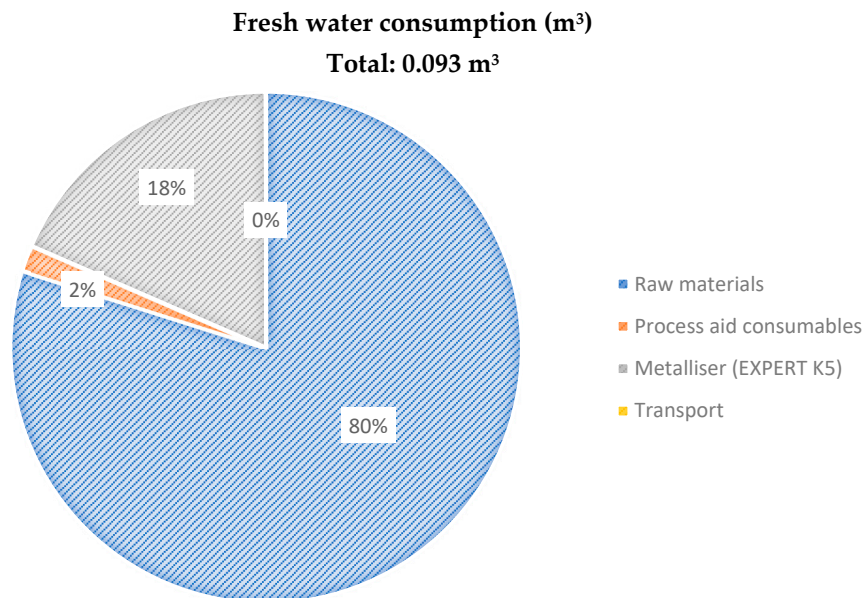
|                                                                                    |           |                                                                                                             |
|------------------------------------------------------------------------------------|-----------|-------------------------------------------------------------------------------------------------------------|
| Mass of consumed 2 mm aluminium wire for 1000 m <sup>2</sup> (kg)                  | 0.2715    | This weight takes into account the collection efficiency of the process                                     |
| Lifespan (minutes)                                                                 | 21        | Metallising time                                                                                            |
|                                                                                    | Aluminium |                                                                                                             |
| Composition                                                                        | 99.8%     |                                                                                                             |
| Mass (g)                                                                           | 0.2715    |                                                                                                             |
| Energy consumption for 1 kg of 99.8% aluminium wire manufacturing process (kWh/kg) | 0.18      | Based on literature                                                                                         |
| Energy consumption for 1 kg of wire from raw material extraction (kWh/kg)          | 213–215   | (ecoinvent database)                                                                                        |
| Transportation (km)                                                                | 357       | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |
|                                                                                    | 35        | Transport, barge ship, bulk, 12,000 t, 100%LF, default {GLO} Economic, U                                    |
|                                                                                    | 398       | Transport, freight, lorry 16–32 metric ton, EURO5 {RoW} transport, lorry 16–32 metric ton, EURO5 Cut-off, U |

Secondary data LCA results for the total climate change impact are given in Figure 14. There is an apparent increase of approximately 9% in emissions from 5.94 kg CO<sub>2</sub>-eq to 6.48 kg CO<sub>2</sub>-eq, as compared to the primary data findings. The contribution of transportation within this study has remained the same as for the primary data study. The largest contribution to the increase in impact is in process aid consumables; a total impact of 0.18 kg CO<sub>2</sub>-eq was calculated based on using primary data; however, by using secondary data, the energy consumption for the manufacturing and fabrication of the evaporation boats increases. At over 150% higher, this highlights significant inaccuracy through working with reference data as opposed to accurate figures. The impact associated with the raw materials is also increased by 14%, from 2.72 to 3.13 kg CO<sub>2</sub>-eq when relying on secondary data. A similar 5% apparent increase is calculated for the running of the metalliser based on secondary data.



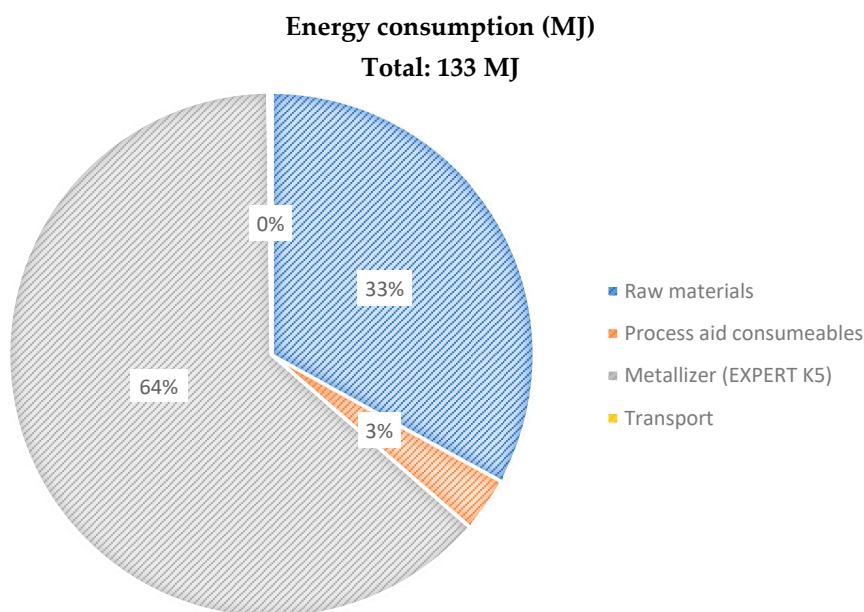
**Figure 14.** Climate change results from LCA study only using secondary data.

Figure 15 highlights the distribution of freshwater consumption, totalling 0.093 m<sup>3</sup> per 1000 m<sup>2</sup> of coated film as calculated using inventory data from secondary sources—a 10% increase compared to primary-data LCA. No change is seen in the calculated impact of transportation. A slight increase of 1.5% in the impact associated with raw materials from 0.066 m<sup>3</sup> to 0.075 m<sup>3</sup> is calculated using secondary data; however, a 1% increase in water usage for process aid consumables is indicated, which can be attributed to the consumption for the manufacturing and fabrication of the evaporation boats. A marginal increase of 1% water usage is calculated for operation of the metalliser from secondary data.



**Figure 15.** Freshwater consumption results from LCA study only using secondary data.

Figure 16 shows that the LCA calculation of impact for energy consumption increased by 8% to 122.8 MJ from 133 MJ using secondary data, as opposed to primary data. The impact associated with transport remained the same as the primary-data LCA. For raw materials there is a large increase in impact from 37.01 MJ to 43.81 MJ; similarly, for process aid consumables, a slight increase can be noticed, and for the metalliser operation, an increase from 80.3 MJ to 84.1 MJ is observed when primary data is not used.



**Figure 16.** Energy consumption results for LCA study only using secondary data.

Comparing LCA results derived from primary and secondary data sources highlights significant inaccuracy in the global warming potential of the process when not accessing up-to-date primary data from industry. A 9% overestimation of kg CO<sub>2</sub>—eq emissions is concerning for both the business image and informed decision-making to select the best opportunities for business improvement. Less significant is the discrepancy in overall water usage, being a 2% overestimate when relying on secondary data. However, at a higher level of granularity, a specific process aid consumable has been greatly misrepresented, with a 30% overestimate in water usage, which again inhibits informed decision-making and may have wrongly targeted measures for change.

During the LCI phase, a detailed inclusion of all the inputs was used; however, several inputs had a marginal input quantity along with a marginal environmental impact after performing the LCA study such as the solvent used for cleaning. These results mentioned in the reflection did not contribute more than 1% of the impact and, as such, were not included in this study.

#### 4. Conclusions

An LCA study highlighting the environmental impacts associated with vacuum metallisation was conducted to evaluate the impacts associated with the deposition of a thin aluminium barrier layer using roll-to-roll PVD vacuum evaporation onto a large-area polymeric web using a functional unit of 1000 m<sup>2</sup> substrate.

The impacts were generated using the SimaPro software and calculated using the ReCiPe midpoint (H) assessment methodology. Focusing on the impact categories with the largest industrial demand and relevance to the process, the LCA results for climate change, freshwater consumption, and energy consumption were identified.

Drawing on an extensive use of over 80% primary data for the Life Cycle Inventory (LCI), the data quality rating for this study has been conducted to an “excellent quality” by the industry-recognised pedigree matrix [26], solidifying the quality and reliability of the LCA results. Additional quality assurance and scientific rigor are derived from validation assessments of the manufacturing process analysis and data collection strategy by industrial experts. Based on Figure 7, an inventory flowchart for the metallisation process was created and shared with practising industry experts to eliminate any missing inventory aspects.

Within the industry, BOBST has currently over 400 metallisers in operation, indicating the validity and global commercial relevance of this particular study. Findings show that although the operation of the metalliser accounts for two thirds of the energy input, the contribution to climate change is roughly one half and freshwater usage one fifth of the process impact. A comparative LCA study has been conducted in which no primary data has been used, relying on secondary data found from publicly available literature and datasets. A 9% overestimation in climate change impact (CO<sub>2</sub>—equivalent emissions) was observed by using secondary data. More detailed examination has also shown individual elements of the inventory to be overestimated in negative impact by up to 30% in the case of water usage. The findings from this comparative study highlight the importance of using robust, contemporary, and accurate primary data to eliminate inaccuracy in LCA results.

#### 5. Limitations to the Study

The focus of this study is solely on the metallisation process; base substrate production and downstream usage are not included in this specific analysis, as this can vary widely between products. A cradle-to-gate methodology, including the coating raw material extraction, manufacturing process, and transportation, has been selected as the base

of this study. This neglects further conversion steps, packaging use, and end-of-life considerations; however, the outputs from this work will inform a wide range of beneficiaries downstream of the metallisation process, involving diverse conversion, filling, and disposal scenarios. The restriction to three impact categories addresses the major interest within the specific flexible packaging industry and reflects the limited external impacts resulting from evaporative PVD metallisation, which produces no process emissions or byproducts. Sensitivity analysis cannot be reproduced here due to commercial restrictions on input data.

## 6. Future Work

The metallisation technique has the potential to produce recyclable packaging due to the very small amount of barrier material used on the base film, where mono-material developments allow, with recyclability being dependent on the proportion of additional materials contained in the structure. Further studies will compare established recyclable solutions to standard metallised films to give a true picture of environmental impact over the life cycle and evaluate suitability toward circular economy in flexible packaging. End-of-life solutions, including recycling, composting, incineration, and landfill, will need to be balanced by the full life cycle impact (including their impact on food waste by variation in performance) to enable informed decision-making by industry and consumers; LCA for roll-to-roll vacuum metallisation will form a key component of this analysis.

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## Abbreviations

|                  |                        |
|------------------|------------------------|
| AC               | Alternating Current    |
| Al               | Aluminium              |
| AlO <sub>x</sub> | Aluminium Oxide        |
| DQR              | Data Quality Rating    |
| EOL              | End-Of-Life            |
| EVOH             | Ethylene Vinyl Alcohol |
| FU               | Functional Unit        |

|       |                                            |
|-------|--------------------------------------------|
| ISO   | International Organization Standardisation |
| LCA   | Life Cycle Assessment                      |
| LCIA  | Life Cycle Impact Assessment               |
| MDOPE | Machine-Direction-Oriented Polyethylene    |
| PE    | Polyethylene                               |
| PLC   | Product Life Cycle                         |
| PVD   | Physical Vapour Deposition                 |
| TED   | Thermal Evaporation Deposition             |
| UK    | United Kingdom                             |

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