# Supplementary Material

## Part A: Scenario-level indicator values, excluded indicators, and scope-based omissions for the PVC extrusion case study

Part A presents the scenario-level values for all circularity, environmental sustainability, and social sustainability indicators operationalized in this study for the PVC extrusion modelling scenario under investigation. The definitions and theoretical justification of the indicators used in this study are described in detail in (Aretoulaki et al., 2026). Tables SA1-SA3 report the scenario-level values for the indicators operationalized in the case study, while Table SA4 lists indicators excluded from it and the reasons for exclusion. Indicators were excluded for four main reasons: (i) they require full life-cycle or end-of-life information beyond the gate-to-gate boundary adopted in this study, (ii) they are not applicable to the examined product type, namely a homogeneous semi-finished extrusion component without modularity, repairability, or reuse loops, (iii) the company-level economic or social data required for their calculation were not available, or (iv) they overlap with another metric within the defined scope.

### 1. Circularity

Circularity indicators (**Table SA1**) were operationalised to reflect manufacturing-stage performance within the gate-to-gate boundary, focusing on material efficiency, internal scrap handling, recyclability by design and process-level resource retention. Indicators requiring life-cycle, end-of-life, or downstream market information were not operationalised and are listed in Table SA4. A key modelling choice concerns internal scrap recycling. When process scrap is milled and reintroduced into the same production system, it is treated as internal process recovery rather than external recycled content. Accordingly, the Circular Input Rate (CIR), Circular Material Use Rate (CMU) and percentage of recycled content remain 0% across all scenarios. Based on facility data, process scrap generation was assumed to be 5% of throughput. In scenarios where scrap exits the system as waste, this leads to non-zero material loss and exported waste, whereas in internal-recycling scenarios, these losses remain within the system boundary, resulting in higher conversion efficiency and zero exported waste. Product-related indicators such as the Material Durability Indicator (MDI) and Recycling Desirability Index (RDI) were scored qualitatively using structured Likert-type values informed by process characteristics and operator knowledge. Twin-screw configurations with inverter control were assigned higher scores due to improved process stability and product consistency. Renewable raw material content remained 0% throughout, while the percentage of recyclable materials was set to 100% for all alternatives.

### 2. Environmental Sustainability

Environmental sustainability indicators (**Table SA2**) were quantified for the manufacturing stage using plant-level data, engineering calculations, and background environmental characterisation data. Differences among scenarios arise primarily from variations in electricity demand and electricity source, particularly the contrast between grid electricity and photovoltaic electricity. For this reason, impact categories such as climate change, acidification, ozone depletion, photochemical ozone formation, fossil resource use, toxicity, eutrophication, and water footprint vary systematically with the energy configuration of each alternative. Photovoltaic-based alternatives perform substantially better than grid-electricity alternatives in most environmental indicators, but they do not exhibit zero impacts because the corresponding inventories include upstream burdens from system manufacturing, transport, maintenance and end-of-life treatment. Some indicators were constant across all scenarios by construction. Packaging-related indicators remained unchanged because packaging mass was fixed at the functional-unit level, while marine litter was set to zero under the assumption of controlled factory handling. Likewise, biodegradability and material degradation time were constant because the material composition of the final product did not vary. Water-management indicators such as BOD, COD, suspended solids, wastewater treated and recycled water were set to zero due to the absence of wastewater streams with organic loading in the extrusion process itself, whereas water footprint remained non-zero because it captures upstream water use associated with electricity generation and photovoltaic system production.

## 3. Social Sustainability

The social sustainability assessment focused on workplace organisational and operational conditions that could plausibly vary across the defined production alternatives. All indicators were scored qualitatively using Likert-type values based on the technological characteristics of the alternatives and their implications for work organisation and operating conditions (**Table SA3**). Twin-screw extrusion systems with inverter-driven motors were assigned higher scores in indicators related to worker qualification, training, educational background and career development, reflecting their greater degree of automation and higher skill requirements compared with single-screw fixed-speed configurations. Insulation was also operationalised as an important differentiator, with insulated scenarios receiving improved scores in ergonomics, thermal comfort and psycho-physical interaction. Personal protective equipment was held constant across all scenarios, while workplace safety control, the health and safety injury and accident indicators, and the reporting indicator vary with extrusion route, elucidating the more automated and closely monitored twin-screw configurations. Broader social indicators related to wages, equality, labour rights across the supply chain and community-level effects were not operationalised due to data and scope limitations and are reported in Table SA4.

## 4. Excluded indicators and reasons

**Table SA4** reports the indicators from the broader framework that were not operationalised in the PVC extrusion case study due to either boundary limitations, product-type incompatibility, data unavailability or overlap with other indicators already included within the case-specific assessment.

**Table SA1.** Circularity Indicators for Alt 1 to Alt 18

| Indicator Category | Indicator | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 | Alt 7 | Alt 8 | Alt 9 | Alt 10 | Alt 11 | Alt 12 | Alt 13 | Alt 14 | Alt 15 | Alt 16 | Alt 17 | Alt 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System-Level Circularity | CIR | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | CMU | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Product Design & Adaptability | MDI | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Recycling Desirability Index (RDI) | 4.5 | 4.5 | 4.5 | 4.5 | 4 | 4 | 4 | 4 | 4 | 4.5 | 4.5 | 4.5 | 4.5 | 4 | 4 | 4 | 4 | 4 |
| Material & Composition | Fraction of renewable raw materials | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | Presence of toxic substances | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | % of RC | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | % of recyclable materials | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table SA1.** Circularity Indicators for Alt 1 to Alt 18 (continued)

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Efficiency & Value Performance** | Conversion efficiency % | 95% | 95% | 95% | 95% | 100% | 100% | 100% | 100% | 95% | 95% | 95% | 95.00% | 95% | 100% | 100% | 100% | 100% | 95% |
| | Material loss (kg) | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0 | 0 | 0 | 0 | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0 | 0 | 0.00 | 0.00 | 0.0158 |
| **Waste Generation & Management** | W (kg) | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0 | 0 | 0 | 0 | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0 | 0 | 0 | 0 | 0.0158 |
| | WF (kg) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | WO (kg) | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0 | 0 | 0 | 0 | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0.0158 | 0 | 0 | 0 | 0 | 0.0158 |
| | WC (kg) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table SA2.** Environmental Sustainability Indicators for Alt 1 to Alt 18

| **Indicator Category** | **Indicator** | **Alt 1** | **Alt 2** | **Alt 3** | **Alt 4** | **Alt 5** | **Alt 6** | **Alt 7** | **Alt 8** | **Alt 9** | **Alt 10** | **Alt 11** | **Alt 12** | **Alt 13** | **Alt 14** | **Alt 15** | **Alt 16** | **Alt 17** | **Alt 18** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Air Pollutant Emissions** | NOx (kg Nox/FU) | 1.10E-04 | 9.89E-05 | 1.10E-04 | 9.89E-05 | 1.16E-04 | 1.04E-04 | 1.16E-04 | 1.04E-04 | 1.16E-04 | 1.74E-08 | 1.56E-08 | 1.74E-08 | 1.56E-08 | 1.83E-08 | 1.65E-08 | 1.83E-08 | 1.65E-08 | 1.83E-08 |
| | PM (kg PM/FU) | 2.73E-09 | 2.46E-09 | 2.73E-09 | 2.46E-09 | 2.88E-09 | 2.60E-09 | 2.88E-09 | 2.60E-09 | 2.88E-09 | 8.33E-10 | 7.49E-10 | 8.33E-10 | 7.49E-10 | 8.79E-10 | 7.91E-10 | 8.79E-10 | 7.91E-10 | 8.79E-10 |
| | SOx (kg Sox/FU) | 4.65E-04 | 4.19E-04 | 4.65E-04 | 4.19E-04 | 4.91E-04 | 4.42E-04 | 4.91E-04 | 4.42E-04 | 4.91E-04 | 7.41E-08 | 6.66E-08 | 7.41E-08 | 6.66E-08 | 7.82E-08 | 7.03E-08 | 7.82E-08 | 7.03E-08 | 7.82E-08 |
| **Climate Change** | Climate change – $GWP_{100}$ (fossil) (kg $CO_2$-eq/FU) | 1.40E-01 | 1.26E-01 | 1.40E-01 | 1.26E-01 | 1.48E-01 | 1.33E-01 | 1.48E-01 | 1.33E-01 | 1.48E-01 | 1.14E-02 | 1.03E-02 | 1.14E-02 | 1.03E-02 | 1.21E-02 | 1.09E-02 | 1.21E-02 | 1.09E-02 | 1.21E-02 |

**Table SA2.** Environmental Sustainability Indicators for Alt 1 to Alt 18 (continued)

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Atmospheric Impact** | ODP (kg CFC-11-eq/FU) | 1.28E-08 | 1.15E-08 | 1.28E-08 | 1.15E-08 | 1.35E-08 | 1.22E-08 | 1.35E-08 | 1.22E-08 | 1.35E-08 | 1.34E-09 | 1.20E-09 | 1.34E-09 | 1.20E-09 | 1.41E-09 | 1.27E-09 | 1.41E-09 | 1.27E-09 | 1.41E-09 |
| | POCP (kg NMVOC-eq/FU) | 2.42E-04 | 2.18E-04 | 2.42E-04 | 2.18E-04 | 2.56E-04 | 2.30E-04 | 2.56E-04 | 2.30E-04 | 2.56E-04 | 4.96E-05 | 4.46E-05 | 4.96E-05 | 4.46E-05 | 5.23E-05 | 4.71E-05 | 5.23E-05 | 4.71E-05 | 5.23E-05 |
| | AP (mol H+-eq/FU) | 8.85E-04 | 7.96E-04 | 8.85E-04 | 7.96E-04 | 9.34E-04 | 8.41E-04 | 9.34E-04 | 8.41E-04 | 9.34E-04 | 9.56E-05 | 8.60E-05 | 9.56E-05 | 8.60E-05 | 1.01E-04 | 9.08E-05 | 1.01E-04 | 9.08E-05 | 1.01E-04 |
| **Packaging** | Package-to-Product indicator (%) | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 | 6.67E-02 |
| | MLI | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | Material-specific packaging efficiency (%) | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 | 9.38E-01 |
| **Material Sustainability** | Biodegra-dability (Likert) | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |
| | Material degrada-tion time (Likert) | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 | 5.00E+00 |

**Table SA2.** Environmental Sustainability Indicators for Alt 1 to Alt 18 (continued)

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Resource Use, Scarcity & Depletion** | ADP (kg Sb-eq/FU) | 1.72E-07 | 1.55E-07 | 1.72E-07 | 1.55E-07 | 1.82E-07 | 1.64E-07 | 1.82E-07 | 1.64E-07 | 1.82E-07 | 1.23E-06 | 1.11E-06 | 1.23E-06 | 1.11E-06 | 1.30E-06 | 1.17E-06 | 1.30E-06 | 1.17E-06 | 1.30E-06 |
| | Fossil resource use (non-renewable energy, MJ/FU) | 2.03E+00 | 1.83E+00 | 2.03E+00 | 1.83E+00 | 2.15E+00 | 1.93E+00 | 2.15E+00 | 1.93E+00 | 2.15E+00 | 1.47E-01 | 1.32E-01 | 1.47E-01 | 1.32E-01 | 1.55E-01 | 1.39E-01 | 1.55E-01 | 1.39E-01 | 1.55E-01 |
| | MIU | 1.12E+00 | 1.12E+00 | 1.12E+00 | 1.12E+00 | 1.07E+00 | 1.07E+00 | 1.07E+00 | 1.07E+00 | 1.12E+00 | 1.12E+00 | 1.12E+00 | 1.12E+00 | 1.12E+00 | 1.07E+00 | 1.07E+00 | 1.07E+00 | 1.07E+00 | 1.12E+00 |
| | % of ren. energy in total use | 1.91E-01 | 1.91E-01 | 1.91E-01 | 1.91E-01 | 2.02E-01 | 2.02E-01 | 2.02E-01 | 2.02E-01 | 2.02E-01 | 6.37E-01 | 6.37E-01 | 6.37E-01 | 6.37E-01 | 6.73E-01 | 6.73E-01 | 6.73E-01 | 6.73E-01 | 6.73E-01 |
| | Total energy consumption (ren. + non-ren.) (MJ/FU) | 2.23E+00 | 2.02E+00 | 2.23E+00 | 2.02E+00 | 2.35E+00 | 2.13E+00 | 2.35E+00 | 2.13E+00 | 2.35E+00 | 7.84E-01 | 7.69E-01 | 7.84E-01 | 7.69E-01 | 8.27E-01 | 8.12E-01 | 8.27E-01 | 8.12E-01 | 8.27E-01 |
| | Land requirement | 7.96E-02 | 7.17E-02 | 7.96E-02 | 7.17E-02 | 8.41E-02 | 7.57E-02 | 8.41E-02 | 7.57E-02 | 8.41E-02 | 5.12E-02 | 4.61E-02 | 5.12E-02 | 4.61E-02 | 5.41E-02 | 4.86E-02 | 5.41E-02 | 4.86E-02 | 5.41E-02 |

**Table SA2.** Environmental Sustainability Indicators for Alt 1 to Alt 18 (continued)

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Toxicity & Eutrophication** | Hazardous waste load / total waste (kg/FU) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | FAETP (CTUe/FU) | 5.88E-01 | 5.29E-01 | 5.88E-01 | 5.29E-01 | 6.20E-01 | 5.58E-01 | 6.20E-01 | 5.58E-01 | 6.20E-01 | 1.11E-01 | 1.00E-01 | 1.11E-01 | 1.00E-01 | 1.18E-01 | 1.06E-01 | 1.18E-01 | 1.06E-01 | 1.18E-01 |
| | Human toxicity potential, cancer (CTUh/FU) | 4.86E-11 | 4.37E-11 | 4.86E-11 | 4.37E-11 | 5.13E-11 | 4.62E-11 | 5.13E-11 | 4.62E-11 | 5.13E-11 | 1.62E-11 | 1.45E-11 | 1.62E-11 | 1.45E-11 | 1.71E-11 | 1.53E-11 | 1.71E-11 | 1.53E-11 | 1.71E-11 |
| | Human toxicity potential, non-cancer (CTUh/FU) | 1.87E-09 | 1.68E-09 | 1.87E-09 | 1.68E-09 | 1.97E-09 | 1.77E-09 | 1.97E-09 | 1.77E-09 | 1.97E-09 | 7.33E-10 | 6.59E-10 | 7.33E-10 | 6.59E-10 | 7.73E-10 | 6.96E-10 | 7.73E-10 | 6.96E-10 | 7.73E-10 |
| | EP freshwater (kg P-eq/FU) | 3.10E-04 | 2.79E-04 | 3.10E-04 | 2.79E-04 | 3.27E-04 | 2.94E-04 | 3.27E-04 | 2.94E-04 | 3.27E-04 | 7.58E-06 | 6.82E-06 | 7.58E-06 | 6.82E-06 | 8.00E-06 | 7.20E-06 | 8.00E-06 | 7.20E-06 | 8.00E-06 |
| | EP marine (kg N-eq/FU) | 1.29E-04 | 1.16E-04 | 1.29E-04 | 1.16E-04 | 1.36E-04 | 1.23E-04 | 1.36E-04 | 1.23E-04 | 1.36E-04 | 1.32E-05 | 1.18E-05 | 1.32E-05 | 1.18E-05 | 1.39E-05 | 1.25E-05 | 1.39E-05 | 1.25E-05 | 1.39E-05 |
| | EP terrestrial (mol N-eq/FU) | 7.33E-04 | 6.59E-04 | 7.33E-04 | 6.59E-04 | 7.73E-04 | 6.96E-04 | 7.73E-04 | 6.96E-04 | 7.73E-04 | 1.43E-04 | 1.29E-04 | 1.43E-04 | 1.29E-04 | 1.51E-04 | 1.36E-04 | 1.51E-04 | 1.36E-04 | 1.51E-04 |

**Table SA2.** Environmental Sustainability Indicators for Alt 1 to Alt 18 (continued)

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water Management | BOD (kg/FU) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | COD (kg/FU) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | SS (kg/FU) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | Volume of wastewater treated ($m^3$/FU) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | Volume of water recycled & reused ($m^3$/FU) | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| | WF ($m^3$/FU) | 4.36E-02 | 3.93E-02 | 4.36E-02 | 3.93E-02 | 4.60E-02 | 4.14E-02 | 4.60E-02 | 4.14E-02 | 4.60E-02 | 1.23E-02 | 1.11E-02 | 1.23E-02 | 1.11E-02 | 1.30E-02 | 1.17E-02 | 1.30E-02 | 1.17E-02 | 1.30E-02 |

**Table SA3.** Social Sustainability Indicators for Alt 1 to Alt 18

| Indicator Category | Indicator | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 | Alt 7 | Alt 8 | Alt 9 | Alt 10 | Alt 11 | Alt 12 | Alt 13 | Alt 14 | Alt 15 | Alt 16 | Alt 17 | Alt 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Employment Practices | Job Creation & Qualification | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Educational Background of Employees | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Career Plan Programs | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Qualification / Requalification of Workers | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Training | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |

**Table SA3.** Social Sustainability Indicators for Alt 1 to Alt 18 (continued)

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Labor Standards & Workplace Conditions** | Working Hour Control | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Cognitive Parameters (Mental Workload) | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Ergonomics / Physical Parameters | 4 | 5 | 4 | 5 | 3 | 4 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 3 | 4 | 3 | 4 | 3 |
| | Psycho-physical Interaction (Noise, Heat, etc.) | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 3 |
| | Worker Satisfaction | 3 | 4 | 3 | 4 | 2 | 3 | 2 | 3 | 2 | 3 | 4 | 3 | 4 | 2 | 3 | 2 | 3 | 2 |
| **Ethical Practices** | Ethical Sourcing & Supplier Responsibility | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 3 |
| **Health & Safety** | Work-related Injuries (overall) | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Work Accidents (catastrophic events) | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Personal Protective Equipment (PPE) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | Lost Workdays | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| | Workplace Safety Control | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| **Governance & Reporting** | Reporting Indicator | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |

**Table SA4.** Indicators excluded from the PVC extrusion case study and reasons for exclusion*

| Pillar | Indicator Category | Indicator | Reason for Exclusion |
|---|---|---|---|
| Circularity | System-Level Circularity | CIRC, CEI, MCI, CEPI, EOLI, MRS, % Collected EoL Products vs. Sales | R1 |
| | Product Design & Adaptability | RRR | R4 |
| | | RI | R2 |
| | Disassembly & Repair | Cost of non-destructive disassembly, DEI, EDT, Degree of repairability, Energy consumption for disassembly | R2 |
| | Reuse, Remanufacturing & Refurbishment | RPI, ReR, % of reused components, Market share of reuse & repair services, % Products remanufactured, # of refurbished products | R2 |
| | Efficiency & Value Performance | REA | R1 |
| | | EVR, VRE | R3 |
| | Waste Generation & Management | EF, By-product recovery %, Energy Recovery | R1 |
| | Resource Retention & Product Lifespan | Acircularity, FRS, UOR, Resource Duration Indicator (RDI) | R1 |
| | Recycling Performance | PRI, R, EOL RC, EOL RIR, EOL ER, EOL PR | R1 |
| | | OPR | R4 |
| Environmental Sustainability | Climate Change | $CO_2$-efficiency indicator, GHG from fossil fuels/transport/electricity/waste | R4 |
| | Environmental-Economic Trade-Off | Cost-Benefit Ratio | R3 |
| | | Net Environmental Benefit | R1 |
| Social Sustainability | Employment Practices | Formalized Work, Inclusive Employment Practices, Social Security, Equal Pay, Equal Leadership Opportunities, Subsidized Employment of Vulnerable Groups, Encouragement of Local Labor | R3 |
| | Labor Standards & Workplace Conditions | Policies against Harassment / Abuse | R3 |
| | Fair Compensation & Benefits | Pay Levels, Living Wage Compliance, Workers' Benefits (transport, food, health), Additional Benefits (bonuses, profit sharing) | R3 |
| | Ethical Practices | Child Labor, Forced / Compulsory Labor, Freedom of Association | R3 |
| | Governance & Reporting | Location Indicator | R3 |
| | Impacts on Society | No. of Workplaces & Personnel in CE Industries, Consumer Health & Safety, Relationship with Local Communities, Opportunities to situate facilities improving residents' lives, Potential to attract government attention to community needs, Fair Trading Relationships, Philanthropy | R3 |

**Note: R1 - System boundary limitation, R2 – Not applicable to product type, R3 – Data unavailable, R4 - Indicator overlaps with another metric within the defined scope*

# Part B: Data Sources & Modelling Approach

Part B provides detailed documentation of the data sources, engineering calculations, and modelling procedures used to quantify electricity consumption, cooling demand, and material flows in the PVC extrusion case study.

## 1. Data Sources

The plastics case study is based primarily on foreground data collected from the studied PVC extrusion facility. These data include measured electrical currents of key equipment, nameplate specifications, observed operating conditions and production throughput values for both single-screw and twin-screw extrusion lines. Plant-specific information was complemented by engineering calculations and standard electrical power functions to derive energy consumption per unit of output. The main data sources can be summarised as follows:

- **Plant measurements and specifications**: Electrical currents, voltage levels and chiller specifications were obtained directly from the facility. These data form the basis for estimating electricity consumption of extrusion lines, mixers and auxiliary equipment.
- **Operational production data**: Throughput rates (kg/h) for the mixer as well as the single-screw and twin-screw extrusion lines were provided by the facility. These values were used to convert hourly energy consumption into energy intensity per kilogram of product and per functional unit.
- **Engineering calculations**: Electrical power and energy consumption were derived using standard three-phase power equations, consistent with the plant's operating conditions (380 V, three-phase).
- **Secondary sources**: Where needed for contextual interpretation (e.g. packaging material characteristics, internal recycling practices) were also directly obtained through interviews with the facility manager.

Electricity supplied to the production system is modelled using background electricity datasets from ecoinvent (Wernet et al., 2016), consistent with the EF 3.1 midpoint impact assessment method. Grid electricity is represented by the corresponding ecoinvent "market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – GR)" dataset, which reflects the national electricity mix applicable to the studied facility. On the other hand, Photovoltaic (PV) electricity is modelled using the "electricity production, photovoltaic, 3kWp, slanted roof installation, multi-Si, panel, mounted | electricity, low voltage | Cutoff, U - GR" ecoinvent dataset, which represents on-site photovoltaic electricity generation (Wernet et al., 2016).

## 2. Electricity Consumption Modelling

Electricity consumption constitutes the dominant environmental and operational input within the system boundary. For each major piece of equipment, electrical power was calculated based on measured current and voltage, assuming three-phase operation. Given the gate-to-gate boundary and the closed-loop cooling system, electricity consumption constitutes the dominant environmental and operational input across all alternatives. For three-phase systems, electrical power was calculated using:

$P = \sqrt{3} \cdot V \cdot I \cdot PF$ where P is electrical power (W), $V$ is line voltage (380 V), $I$ is measured current (A) and $PF$ is the power factor.

A power factor of 0.88 was assumed for all major equipment, based on the chiller specification and consistent with typical industrial motor performance under load.

Energy consumption per kilogram of product was derived by dividing calculated power by line throughput (kg/h) and subsequently converted to energy per functional unit (kWh/FU). This gives a conversion factor:

$P(W) = 1.732 \cdot 380 \cdot 0.88 \cdot I = 579.18 \cdot I$ or $P(kW) = 0.57918 * I$

Energy per kilogram is then calculated as: $E_{kg} = \frac{P(kW)}{\text{throughput (kg/h)}}$

and energy per functional unit as: $E_{FU} = E_{kg} * 0.3$

## 3. Mixing and Extrusion Stages

Electricity demand was modelled separately for the main processing stages.

The Twin-screw extrusion line (powder-fed, inverter-driven, profile extrusion) where we have the following specs:

- Measured current: $I = 50$ A
- Power: $P = 0.57918 \cdot 50 = 28.96$ kW
- Throughput: 80 kg/h
- Specific energy: $E_{kg} = \frac{28.96}{80} = 0.362$ kWh/kg
- Per functional unit we have: $E_{FU} = 0.362 \cdot 0.300 = 0.109$ kWh/FU

The Single-Screw extrusion line (pellet-fed, fixed-speed motor, profile extrusion) where we have the following specs:

- Measured current: $I = 25$ A
- Power: $P = 0.57918 \cdot 25 = 14.48$ kW
- Throughput: 60 kg/h
- Specific energy: $E_{kg} = \frac{14.48}{60} = 0.241$ kWh/kg
- Per functional unit: $E_{FU} = 0.241 \cdot 0.300 = 0.072$ kWh/FU

The Pelletiser line (pellet extrusion) that creates the pellets used by the single-screw extrusion line, where we have the following specs:

- Measured current: $I = 35$ A
- Power: $P = 0.57918 \cdot 35 = 20.27$ kW
- Throughput: 200 kg/h
- Specific energy: $E_{kg} = \frac{20.27}{200} = 0.101$ kWh/kg
- Per functional unit: $E_{FU} = 0.101 \cdot 0.300 = 0.030$ kWh/FU

The Mixer, which is included in all scenarios, we have the following specs:

- Measured current: $I = 80$ A

- Power: $P = 0.57918 \cdot 80 = 46.33$ kW
- Throughput: 300 kg/h
- Specific energy: $E_{kg} = \frac{46.33}{300} = 0.154$ kWh/kg
- Per functional unit: $E_{FU} = 0.154 \cdot 0.300 = 0.046$ kWh/FU

## 4. Cooling Modelling: Chiller for Profile Extrusion & Air Cooling for Pelletisation

Cooling demand in the studied facility is provided through two distinct mechanisms, depending on the process step. Profile extrusion and calibration/cooling (single-screw and twin-screw profile lines) are served by a central water chiller system. The central chiller has:

- Rated power: 35.3 kW
- Measured current: 60.7 A
- Voltage: 380 V
- Power factor: 0.88

Hourly electricity demand per line (chiller can support 5 lines in summer and 7 in winter):

- Summer: $\frac{35.3}{5} =$ 7.06 kWh/h
- Winter: $\frac{35.3}{7} =$ 5.04 kWh/h

Seasonal chiller electricity demand was approximated using a weighted average of summer and winter operating conditions. The annual average is calculated as follows, with the weighting reflecting the relative duration of summer and winter operating regimes:

$$E_{chiller,h} = \frac{7.06 * 5 + 5.04 * 7}{12} = 5.8817 \text{ kWh/h}$$

- Per functional unit for the twin-screw line: $E_{FU} = \frac{5.88*0.3}{80} = 0.0221$ kWh/FU
- Per functional unit for the single-screw line: $E_{FU} = \frac{5.88*0.3}{60} = 0.0294$ kWh/FU

The upstream pelletisation extrusion step does not use the chiller. Cooling at this stage is provided through forced air transfer, represented by a dedicated motor. It is characterised by the following parameters:

- Motor power: $P_{air} = 5.5$ kW
- Operating energy per hour: $E_{air,h} = 5.5$ kWh/h
- Pelletisation throughput: $Q = 200$ kg/h
- The specific electricity demand for air cooling is: $E_{air,kg} = \frac{5.5}{200} = 0.0275$ kWh/kg
- Normalised to the functional unit: $E_{air,FU} = 0.0275 \cdot 0.300 = 0.00825$ kWh/FU

## 5. Line electricity totals

Electricity totals per functional unit are computed by summing the contributions of each included process step, based on **Table SB1**.

**Table SB1.** Mapping of unit process electricity contributions to the twin-screw and single-screw PVC profile production routes.

| **Process Step** | **Twin-screw route** | **Single-screw route** |
|---|---|---|
| Mixer | ✓ | ✓ |
| Pelletisation Extrusion | ✕ | ✓ |
| Pelletisation Air Cooling | ✕ | ✓ |
| Profile Extrusion | ✓ (twin) | ✓ (single) |
| Water Chiller (profile cooling) | ✓ | ✓ |

So, for the twin-screw route (powder-fed profile extrusion), we have:

$E_{TS,FU} = E_{extr,TS} + E_{mixer} + E_{ch,FU}^{TS}$ where:

- Twin-screw extrusion: 0.109 kWh/FU
- Mixer / feed preparation: 0.046 kWh/FU
- Chiller (twin): 0.022 kWh/FU

$$E_{TS,FU} = 0.109 + 0.046 + 0.022 \approx 0.177 \text{ kWh/FU}$$

And for the single-screw route with pelletisation upstream, we have:

$E_{SS,FU} = E_{extr,SS} + E_{pellet} + E_{mixer} + E_{ch,FU}^{SS} + E_{air,FU}$, where:

- Single-screw profile extrusion: 0.072 kWh/FU
- Pelletisation (extrusion): 0.030 kWh/FU
- Mixer: 0.046 kWh/FU
- Chiller (single): 0.0294 kWh/FU
- Pelletisation (air cooling): 0.00825 kWh/FU

$$E_{SS,FU} = 0.072 + 0.030 + 0.046 + 0.0294 + 0.00825 \approx 0.187 \text{ kWh/FU}$$

## 6. Internal Scrap Handling

Process scrap corresponds to approximately 5% of material input, equivalent to a process yield of 95%. In the facility's current operating practice, this scrap is milled and reintroduced into the process as internal regrind, resulting in typical feed mixes of approximately 5-10% regrind and 90-95% virgin material. In this case study, internal recycling is treated as a scenario axis. Scenarios labelled RS represent operation with internal scrap recycling, while VI scenarios represent operation without internal recycling (scrap removed from the system boundary). So, for scenarios with internal recycling (RS) we have:

- Internal scrap reintroduced: $m_{regrind} = 0.05 \cdot 0.300 = 0.015$ kg
- Virgin input: $m_{virgin} = 0.300$ kg

No scrap leaves the system boundary. For scenarios without internal recycling (VI), the virgin input required is calculated as follows:

- $m_{virgin} = \frac{0.300}{1-0.05} = 0.3158$ kg

Scrap leaving system: $m_{waste} = 0.3158 - 0.300 = 0.0158$ kg

## 7. Packaging data calculation

For 30 m of PVC profile product, the packaging used is 6 m nylon film, corresponding to 600 g nylon (i.e., 0.6 kg).

Functional unit (FU): 1 m of product, with product mass 0.3 kg (300 g).

$$m_{pack,FU} = \frac{600 \text{ g}}{30 \text{ m}} = 20 \text{ g per m}$$

So, for 1 FU (1 m): Packaging mass = 20 g nylon = 0.02 kg/FU

## References

Aretoulaki, E., Rentizelas, A., Florios, K., Simos, E., 2026. A Comprehensive Framework for Circular Economy, Environmental, and Social Sustainability Indicators in Manufacturing. Circular Economy and Sustainability 6, 1–36. https://doi.org/10.1007/s43615-026-00843-0

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8