

Supporting Information

Development of Eco-efficient Smart Electronics for Anticounterfeiting and Shock Detection Based on Printable Inks

Edis Glogic^{a*}, Romain Futsch^{b,d}, Victor Thenot^c, Antoine Iglesias^c, Blandine Joyard-Pitiot^c

Gael Depres^c, Aline Rougier^b, Guido Sonnemann^a

^aUniversity of Bordeaux, ISM – CyVi, UMR 5255, 351 Cours de la Libération, 33405 Talence Cedex, France

^bCNRS, Univ. Bx, Bx INP, ICMCB, UMR 5026, F-33600 Pessac, France

^cArjowiggins France, 10 rue Jean Arnaud, 38500 Voiron, France

^dLuquet-Duranton, 07100 Annonay, France

*Corresponding author: edis.glogic@u-bordeaux.fr

Glossary:

- ACL – anti-counterfeit label
- ECD – electrochromic display
- PS – piezoelectric sensor
- SDT – shock-detection tag

Number of pages: 6

Number of tables: 11

Number of figures: 0

Table S-1. Inventory for manufacturing of paper (Powercoat XD125)

| Production of Powercoat XD125 | | Reference flow: 1kg | |
|------------------------------------|---|---------------------|----------------|
| Input/Output | Ecoinvent dataset | Value | Unit |
| Inputs | | | |
| Paper pulp | sulfate pulp production, from eucalyptus, bleached, U - RLA | 0.815 | kg |
| Mineral filler (calcium carbonate) | calcium carbonate, precipitated_RER_2019 | 0.291 | kg |
| Additive (1% bronolop) | - | 0.031 | kg |
| Additive (starch ester 26%) | polyester-complexed starch biopolymer production | 0.146 | kg |
| Mineral filler (acrylic ester 25%) | acrylic filler production - RER | 0.058 | kg |
| Electricity | electricity production, medium voltage_ES | 1.407 | kWh |
| Natural gas | natural gas, high pressure, U - ES | 0.330 | m ³ |
| Water | tap water - Europe w/o Switzerland | 39.146 | kg |
| Outputs | | | |
| Wastewater | treatment of wastewater, average - Europe w/o Switzerland | 0.039 | m ³ |

Table S-2. Inventory for printing antenna and ECD

| Production of electrochromic display (ECD) | | Reference flow: 1 ECD | |
|--|---|-----------------------|------|
| Input/Output | Ecoinvent dataset | Value | Unit |
| Inputs | | | |
| Microsilver ink | - | 0.1313 | g |
| Carbon ink | graphite, battery grade, U - GLO | 0.0065 | g |
| PEDOT:PSS ink | - | 0.0150 | g |
| UV photopolymer ink | epoxy resin, U - RER | 0.0950 | g |
| LiTFSI:EmimTFSI | - | 0.0300 | g |
| Ethyl acetate (for cleaning) | ethyl acetate, U - GLO | 0.0156 | g |
| Ethyl acetate (for ink formulation) | ethyl acetate, U - GLO | 0.0544 | g |
| Electricity | electricity, medium voltage, U - FR | 0.0276 | kWh |
| Water | water, ultrapure, U - RER | 0.0667 | g |
| Outputs | | | |
| Waste | average incineration residue, U – RoW | 1.8500 | g |
| Wastewater | treatment of wastewater, average - Europe w/o Switzerland | 1.1250 | g |

Table S-3. Inventory for printing and poling PS

| Production of piezo sensor | | Reference flow: 1 sensor | |
|----------------------------|-------------------------------------|--------------------------|------|
| Input/Output | Ecoinvent dataset | Value | Unit |
| Inputs | | | |
| Microsilver ink | - | 0.160 | g |
| UV photopolymer ink | epoxy resin, liquid, U - RER | 0.030 | g |
| PVDF-TrFe | Polyvinylfluoride, U-GLO | 0.040 | g |
| PEDOT:PSS ink | - | 0.060 | g |
| Ethyl acetate | ethyl acetate , U - GLO | 0.105 | g |
| Water | water, ultrapure, U - RER | 0.022 | g |
| Electricity | electricity, medium voltage, U - FR | 0.041 | kWh |
| Outputs | | | |

| | | | |
|------------|---|-------|---|
| Waste | average incineration residue, U – RoW | 3.083 | g |
| Wastewater | treatment of wastewater, average - Europe w/o Switzerland | 1.875 | g |

Table S-4. Consumption of electricity for fabrication of one antenna with ECD shown per component and activity

| Reference flow: 1ECD | | |
|-----------------------------------|-------|------|
| Per component | Value | Unit |
| Antenna | 3.31 | Wh |
| Insulator | 4.29 | Wh |
| Antenna tracks + Bottom electrode | 3.31 | Wh |
| Bottom electrode - Second step | 2.43 | Wh |
| Electrochromic layer | 2.53 | Wh |
| Electrolyte | 6.33 | Wh |
| Top electrode | 2.83 | Wh |
| Encapsulation | 2.52 | Wh |
| For activity | | |
| Screen manufacture | 3.94 | Wh |
| Air Exhaust | 3.50 | Wh |
| Oven | 5.51 | Wh |
| Screen printing | 2.83 | Wh |
| UV lamp | 7.52 | Wh |
| Compressor | 4.24 | Wh |

Table S-5. Consumption of electricity for fabrication of one antenna and piezo sensor shown per component and activity

| Reference flow: 1PS | | |
|---------------------|-------|------|
| Per component | Value | Unit |
| Antenna | 6.84 | Wh |
| Insulator | 9.02 | Wh |
| Antenna tracks | 6.84 | Wh |
| Bottom electrode | 4.48 | Wh |
| Piezoelectric layer | 5.28 | Wh |
| Top electrode | 4.48 | Wh |
| For activity | | |
| Screen manufacture | 5.91 | Wh |
| Air exhaust | 5.71 | Wh |
| Oven | 9.85 | Wh |
| Screen printing | 4.96 | Wh |
| UV lamp | 4.39 | Wh |
| Compressor | 6.12 | Wh |

Table S-6. Inventory for chip manufacturing and bonding

| Fabrication and bonding of chip | | Reference flow: 1 chip | |
|---------------------------------|-------------------|------------------------|------|
| Inputs | Ecoinvent dataset | Value | Unit |

| | | | |
|--------------------|--|-------|-----------------|
| Chip | wafer, fabricated, for integrated circuit, U - GLO | 5.544 | mm ² |
| Adhesive | market for acrylic binder, without water, in 34% solution state, U - RER | 3.5 | mg |
| Electricity | electricity, medium voltage, U - FR | 1.008 | Wh |

Table S-7. Inventory for battery manufacturing and bonding

| Fabrication and bonding of battery | | Reference flow: 1 battery | |
|---|---|----------------------------------|-------------|
| Inputs | Ecoinvent dataset | Value | Unit |
| Battery | battery cell, Li-ion, U - GLO | 0.86 | g |
| Adhesive | acrylic binder, without water, in 34% solution state, U - RER | 0.073 | g |
| Electricity | electricity, medium voltage, U - FR | 1.008 | Wh |

Table S-8. The removal rate of printed inks used in fabrication of ECD and piezo sensor by paper recycling process

| Components | Removal rate (screening) | Removal rate (floatation) | Removal rate (total) |
|------------------------------|--------------------------|---------------------------|----------------------|
| | % | % | % |
| Microparticles silver | 4.96 | 36.26 | 40 |
| UV photopolymer | 100 | - | 100 |
| NFC chip | 100 | - | 100 |
| PVDF-TrFE | 100 | - | 100 |
| PEDOT:PSS | 43.62 | 19.95 | 54.9 |
| Electrolyte | 17.18 | 39.1 | 49.5 |

Note: The table does not include the removal rates of carbon electrode as this information was not available at the time of this study.

Table S-9. Inventory for recycling of ACL and SDT

| Recycling of EOL ACL/SDT | | Reference flow: 1kg of EOL ACL/SDT | | ACL | SDT |
|------------------------------------|--|---|--------------|-------------|------------|
| Input/Output | Ecoinvent dataset | Value | Value | Unit | |
| Inputs | | | | | |
| Surfactant | non-ionic surfactant, U - GLO | 0.58 | 0.68 | mg | |
| Water | tap water - Europe w/o Switzerland | 2.84 | 3.30 | g | |
| Electricity | electricity, medium voltage, U - FR | 0.45 | 0.53 | Wh | |
| Natural gas | heat, district or industrial, natural gas - Europe w/o Switzerland | 0.62 | 0.72 | Wh | |
| Outputs | | | | | |
| Sludge use in brickmaking | - | 0.09 | 0.11 | g | |
| Solid waste | process-specific burdens, sanitary landfill | 0.03 | 0.03 | g | |
| Sludge use in agriculture | treatment, sludge from pulp and paper production, landfarming - Europe w/o Switzerland | 0.21 | 0.25 | g | |
| Secondary pulp (avoided product) | deinked pulp, wet lap, U - GLO | 0.39 | 0.45 | g | |
| Silver (to soil) from paper sludge | emissions to agricultural soil | 42.56 | 29.13 | mg | |

Insert table S-10. Impact assessment values of different components of antenna and ECD

| Impact categories | Units | Silver ink | LiTFSI:emim | PEDOT:PSS ink | Carbon ink | UV Photopolymer | Ethyl acetate | Electricity | Water | Solid waste | Wastewater | Total |
|---|--------------------------|------------|-------------|---------------|------------|-----------------|---------------|-------------|---------|-------------|------------|---------|
| Land use | m ² a crop eq | 5.2E-03 | 1.1E-05 | 6.8E-07 | 3.7E-06 | 6.7E-06 | 8.1E-07 | 1.0E-04 | 4.9E-09 | 8.1E-06 | 3.1E-08 | 5.4E-03 |
| Marine eutrophication | kg N eq | 3.9E-06 | 2.2E-08 | 2.7E-09 | 7.1E-09 | 1.2E-08 | 8.7E-10 | 3.3E-07 | 4.2E-10 | 4.6E-09 | 6.7E-09 | 4.2E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 2.0E-01 | 2.7E-05 | 3.1E-06 | 1.5E-05 | 3.4E-05 | 3.2E-06 | 2.7E-04 | 5.2E-09 | 8.2E-04 | 7.9E-08 | 2.0E-01 |
| Freshwater eutrophication | kg P eq | 1.9E-04 | 2.3E-07 | 3.1E-08 | 1.2E-07 | 1.7E-07 | 1.7E-08 | 7.2E-07 | 3.0E-09 | 3.4E-06 | 1.3E-09 | 2.0E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 8.2E-08 | 1.9E-09 | 5.6E-11 | 9.4E-11 | 1.8E-10 | 1.9E-11 | 3.3E-09 | 1.6E-13 | 6.1E-11 | 1.6E-12 | 8.8E-08 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.2E-01 | 2.0E-05 | 2.3E-06 | 1.2E-05 | 2.7E-05 | 2.5E-06 | 2.1E-04 | 4.0E-09 | 5.9E-04 | 6.1E-08 | 1.3E-01 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 1.9E+00 | 3.4E-04 | 4.2E-05 | 1.8E-04 | 3.5E-04 | 3.3E-05 | 1.7E-03 | 3.9E-08 | 1.4E-02 | 3.2E-06 | 1.9E+00 |
| Global warming | kg CO ² eq | 6.7E-02 | 1.0E-03 | 1.7E-04 | 2.2E-04 | 4.8E-04 | 4.5E-05 | 2.4E-03 | 4.9E-08 | 5.4E-04 | 5.6E-07 | 7.2E-02 |
| Ionizing radiation | kBq Co-60 eq | 7.5E-03 | 9.6E-05 | 7.1E-06 | 1.1E-05 | 3.2E-05 | 1.7E-06 | 1.6E-02 | 5.7E-09 | 2.1E-05 | 6.4E-08 | 2.3E-02 |
| Fossil resource scarcity | kg oil eq | 1.8E-02 | 3.2E-04 | 1.0E-04 | 1.2E-04 | 2.0E-04 | 2.4E-05 | 6.7E-04 | 8.0E-09 | 5.4E-05 | 1.2E-07 | 1.9E-02 |
| Fine particulate matter formation | kg PM2.5 eq | 2.1E-04 | 1.9E-06 | 1.9E-07 | 4.5E-07 | 7.2E-07 | 7.0E-08 | 2.8E-06 | 6.8E-11 | 3.0E-07 | 1.5E-09 | 2.1E-04 |
| Ozone formation, Human health | kg NO _x eq | 5.5E-04 | 2.8E-06 | 2.4E-07 | 6.3E-07 | 1.1E-06 | 1.2E-07 | 4.4E-06 | 1.0E-10 | 9.8E-07 | 2.1E-09 | 5.6E-04 |
| Mineral resource scarcity | kg Cu eq | 1.9E-02 | 6.4E-06 | 2.3E-07 | 7.0E-07 | 1.6E-06 | 1.7E-07 | 2.0E-05 | 8.0E-10 | 1.4E-06 | 1.2E-08 | 1.9E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 6.5E-03 | 2.8E-05 | 5.6E-06 | 9.7E-06 | 1.6E-05 | 1.5E-06 | 1.1E-04 | 1.3E-08 | 7.7E-03 | 1.2E-07 | 1.4E-02 |
| Terrestrial acidification | kg SO ₂ eq | 4.6E-04 | 5.6E-06 | 3.9E-07 | 8.7E-07 | 1.5E-06 | 1.8E-07 | 6.6E-06 | 1.3E-10 | 8.1E-07 | 4.2E-09 | 4.7E-04 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 4.6E-01 | 1.6E-03 | 1.0E-04 | 5.9E-04 | 1.5E-03 | 1.4E-04 | 9.9E-03 | 2.0E-07 | 4.5E-04 | 2.8E-06 | 4.8E-01 |
| Ozone formation, Terrestrial ecosystems | kg NO _x eq | 5.6E-04 | 2.8E-06 | 2.5E-07 | 7.0E-07 | 1.1E-06 | 1.3E-07 | 4.4E-06 | 1.1E-10 | 9.8E-07 | 2.1E-09 | 5.7E-04 |
| Water consumption | m ³ | 5.9E-04 | 7.7E-06 | 1.6E-05 | 2.9E-06 | 6.3E-06 | 6.8E-07 | 9.2E-05 | 8.3E-08 | 2.5E-06 | -1.0E-06 | 7.2E-04 |

Insert table S-11. Impact assessment values of different components of antenna and PS

| Impact categories | Units | Silver ink | Piezo ink | PEDOT:PSS ink | UV Photopolymer | Ethyl acetate | Electricity | Water | Solid waste | Wastewater | Total |
|---|--------------------------|------------|-----------|---------------|-----------------|---------------|-------------|---------|-------------|------------|---------|
| Land use | m ² a crop eq | 4.8E-03 | 5.9E-06 | 2.7E-06 | 2.1E-06 | 5.5E-06 | 1.5E-04 | 1.6E-09 | 1.4E-05 | 5.2E-08 | 5.0E-03 |
| Marine eutrophication | kg N eq | 3.5E-06 | 1.2E-08 | 1.1E-08 | 3.9E-09 | 5.9E-09 | 4.8E-07 | 1.4E-10 | 7.7E-09 | 1.1E-08 | 4.1E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 1.8E-01 | 3.0E-05 | 1.2E-05 | 1.1E-05 | 2.2E-05 | 3.9E-04 | 1.7E-09 | 1.4E-03 | 1.3E-07 | 1.8E-01 |
| Freshwater eutrophication | kg P eq | 1.8E-04 | 1.9E-07 | 1.2E-07 | 5.2E-08 | 1.2E-07 | 1.1E-06 | 1.0E-09 | 5.7E-06 | 2.1E-09 | 1.9E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 7.5E-08 | 1.7E-10 | 2.2E-10 | 5.8E-11 | 1.3E-10 | 4.9E-09 | 5.5E-14 | 1.0E-10 | 2.7E-12 | 8.1E-08 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.1E-01 | 2.3E-05 | 9.2E-06 | 8.5E-06 | 1.7E-05 | 3.1E-04 | 1.3E-09 | 9.8E-04 | 1.0E-07 | 1.1E-01 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 1.7E+00 | 3.3E-04 | 1.7E-04 | 1.1E-04 | 2.3E-04 | 2.5E-03 | 1.3E-08 | 2.4E-02 | 5.4E-06 | 1.7E+00 |
| Global warming | kg CO ² eq | 6.2E-02 | 6.4E-04 | 6.7E-04 | 1.5E-04 | 3.1E-04 | 3.6E-03 | 1.6E-08 | 8.9E-04 | 9.3E-07 | 6.8E-02 |
| Ionizing radiation | kBq Co-60 eq | 6.9E-03 | 5.2E-05 | 2.8E-05 | 1.0E-05 | 1.1E-05 | 2.3E-02 | 1.9E-09 | 3.5E-05 | 1.1E-07 | 3.0E-02 |
| Fossil resource scarcity | kg oil eq | 1.6E-02 | 1.3E-04 | 4.1E-04 | 6.2E-05 | 1.6E-04 | 9.9E-04 | 2.7E-09 | 9.0E-05 | 2.0E-07 | 1.8E-02 |
| Fine particulate matter formation | kg PM2.5 eq | 1.9E-04 | 8.7E-07 | 7.4E-07 | 2.3E-07 | 4.8E-07 | 4.1E-06 | 2.3E-11 | 4.9E-07 | 2.6E-09 | 2.0E-04 |
| Ozone formation, Human health | kg NO _x eq | 5.0E-04 | 8.7E-07 | 9.6E-07 | 3.3E-07 | 7.9E-07 | 6.5E-06 | 3.5E-11 | 1.6E-06 | 3.5E-09 | 5.2E-04 |
| Mineral resource scarcity | kg Cu eq | 1.7E-02 | 2.4E-06 | 9.3E-07 | 5.1E-07 | 1.2E-06 | 3.0E-05 | 2.7E-10 | 2.3E-06 | 2.0E-08 | 1.7E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 6.0E-03 | 1.5E-05 | 2.2E-05 | 5.2E-06 | 1.0E-05 | 1.6E-04 | 4.4E-09 | 1.3E-02 | 2.0E-07 | 1.9E-02 |
| Terrestrial acidification | kg SO ₂ eq | 4.2E-04 | 1.8E-06 | 1.5E-06 | 4.6E-07 | 1.2E-06 | 9.8E-06 | 4.3E-11 | 1.4E-06 | 7.0E-09 | 4.4E-04 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 4.2E-01 | 1.1E-03 | 4.1E-04 | 4.7E-04 | 9.5E-04 | 1.5E-02 | 6.6E-08 | 7.4E-04 | 4.6E-06 | 4.4E-01 |
| Ozone formation, Terrestrial ecosystems | kg NO _x eq | 5.1E-04 | 8.9E-07 | 1.0E-06 | 3.6E-07 | 8.5E-07 | 6.5E-06 | 3.6E-11 | 1.6E-06 | 3.6E-09 | 5.2E-04 |
| Water consumption | m ³ | 5.4E-04 | 6.4E-06 | 6.3E-05 | 2.0E-06 | 4.6E-06 | 1.4E-04 | 2.8E-08 | 4.2E-06 | -1.7E-06 | 7.5E-04 |