Supplementary Information:

Assessing the Environmental Footprint of Electrochromic Windows: A Comparative LCA with AI-Based Forecasting

Mohsen Rabbani[1], Olivia Tahti[2], Sabinus Essel Arthur[1], Macy A. Hopping[3], Christopher J. Barile[3], Mohd Hassan Karim[4], Ario Fahimi [5], Ehsan Vahidi[1,*]

[1]Department of Mining and Metallurgical Engineering, Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, NV, USA, 89557

[2]Department of Civil and Environmental Engineering, University of Nevada, Reno, NV, USA, 89557

[3]Department of Chemistry, University of Nevada, Reno, NV, USA, 89557

[4]Department of Computer Engineering, Medipol University, Istanbul, Türkiye, 34810

Aleon Metals, 302 Midway Rd Freeport TX, 77542

[*] Corresponding Author: Ehsan Vahidi (evahidi@unr.edu)

LCA results

Table S1. Life cycle inventory of electrochromic preparation stage for 1 m^2 EC window.

Input	Consumption	Unit	Ecoinvent Unit Process
Input from Nature			
Water	70.2	kg	Water, decarbonised {GLO}| market for water, decarbonised | CUT-OFF, U
Input from Technosphere			
Flat Glass	9.75	Kg	Float Glass {GLO}| production | CUT-OFF, U
Electricity	27.47	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U

Table S2. Life cycle inventory of hot coater stage for 1 m2 EC window.

Input	Consumption	Unit	Ecoinvent Unit Process
Input from Technosphere			
WO_3	1.25E-03	kg	1 kg Tungsten carbide powder {GLO}| market for tungsten carbide powder | Cut-off, U Tungsten carbide powder {CN}| tungsten carbide powder production | APOS, U
V_2O_5	2.00E-04	kg	Titania slag, 94% titanium dioxide {CN}| vanadium-titanomagnetite mine operation and beneficiation | CUT-OFF, U
$LiClO_4$	5.50E-04	kg	Lithium chloride {GLO}| production | CUT-OFF, U
fluorine-doped tin oxide (FTO)	3.44E-03	kg	Sputtering target, sintered, indium tin oxide {GLO}| market for | CUT-OFF, U
Electricity	43.00	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Hot sputter deposition, 400 - 500°C	21.5	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Cold sputter deposition, 150 °C	21.5	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U

Table S3. Life cycle inventory of first preparation loop for 1 m^2 EC window.

Input	Consumption	Unit	Ecoinvent Unit Process
Input from Technosphere			
electricity	15.16	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Data matric code with laser	0.255	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Oven	14.9	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U

Table S4. Life cycle inventory of the second and third preparation loops for a 1 m² EC window.

Input	Consumption	Unit	Ecoinvent Unit Process
Input from Technosphere			
Electricity	36.95	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Glass cutting	11.00	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Grinding and edging	15.00	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Cleaning and surface preparation	1.10	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Coating application	2.50	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Curing and drying	2.00	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Electrode integration	1.75	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Sealing and encapsulation	1.40	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Assembly and integration	1.90	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Packaging and shipping	0.30	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Natural gas	46.76	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Coating application	13.19	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Curing and drying	26.60	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Electrode integration	3.17	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Assembly and integration	3.80	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U

Table S5. Life Cycle Inventory of the Frame Design Stage for a 1 m² EC Window.

Input	Consumption	Unit	Ecoinvent Unit Process
Input from Technosphere			
Polypropylene	0.18	kg	Polystyrene, extruded {GLO}| market for | Cut-off, U
Copper	0.50	kg	Wire drawing, copper {GLO}| processing | CUT-OFF, U
Stainless steel	1.75	kg	Selective coat, stainless steel sheet, black chrome {GLO}| market for | CUT-OFF, U
Silicon dioxide gel	3.31	kg	Silicon dioxide gel {GLO}| market for | CUT-OFF, U

Table S6. Life cycle inventory of 1 m² DP window.

Input	Consumption	Unit	Ecoinvent Unit Process
Input from Technosphere			
Silica sand SiO_2	7.10	kg	Silica sand {GLO}| market for silica sand | Cut-off, U
Soda (Na_2O)	1.40	kg	Soda {GLO}, Market
Lime (CaO)	0.90	kg	Lime {GLO}| market for lime | Cut-off, U
Magnesia (MgO)	0.40	kg	Magnesium oxide {GLO}| market for magnesium oxide | Cut-off, U
Respiratory effects	0.15	kg	Aluminum oxide, non-metallurgical {GLO}| market for aluminum oxide, non-metallurgical | Cut-off, U
Electricity	24.91	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Batch preparation	0.88	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Ecotoxicity	3.81	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Fossil fuel depletion	4.40	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Annealing	1.17	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Tempering	11.72	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Laminating	2.93	kWh	Electricity, medium voltage {GLO}| market group for | CUT-OFF, U
Natural gas	22850.54	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Autoclave	434.33	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Ecotoxicity	16077.88	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U

Annealing	30.91	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Tempering	6307.42	MJ	Heat, district or industrial, natural gas {GLO}| market group for | CUT-OFF, U
Aluminum	5.40	kg	Aluminum oxide, non-metallurgical, {GLO}| market group for | CUT-OFF, UGLO
Stainless steel	1.75	kg	Selective coat, stainless steel sheet, black chrome {GLO}| market for | CUT-OFF, U
Polypropylene	0.18	kg	Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U
vinyl	3.00	kg	Vinyl chloride {GLO}| market for vinyl chloride | Cut-off, U
Adhesive	0.68	oz	Adhesive, for metal {GLO}| market for adhesive, for metal | Cut-off, U
Sealant	1.01	oz	Silicone product {GLO}| market for silicone product | Cut-off, U
Desiccant	3.31	kg	Silicon dioxide gel {GLO}| market for silicone product | Cut-off, U
Argon	0.11	kg	Inert gas for discharge lamps {GLO}| argon to generic market for inert gas for discharge lamps | Cut-off, U
Output			
DP window	1	m^2	Generated

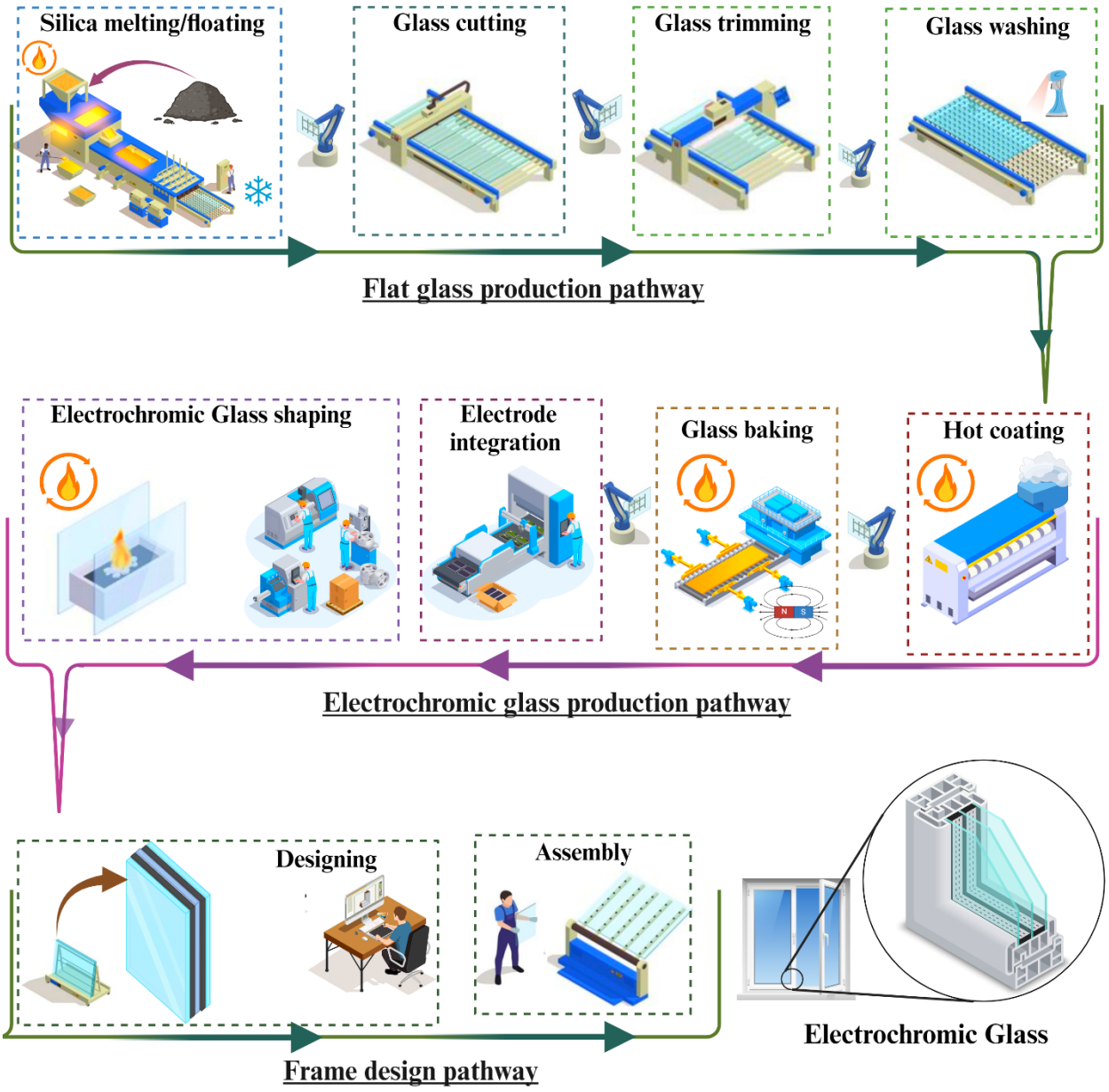

Fig. S1. EC window production pathway.

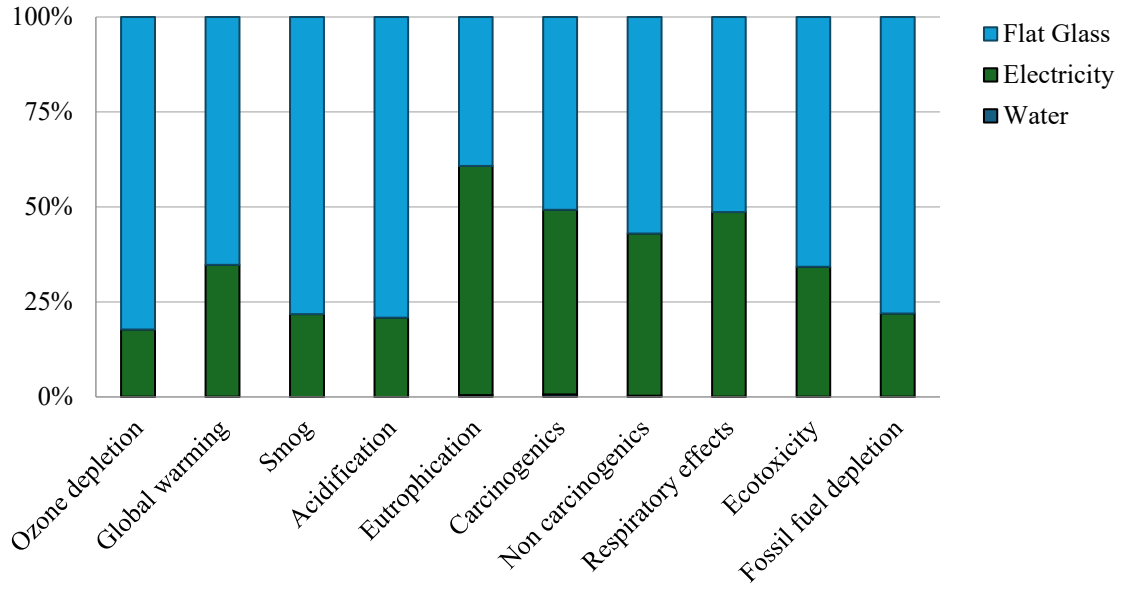

Fig. S2. Contribution of process energy and material flows in the electrochromic preparation step using TRACI.

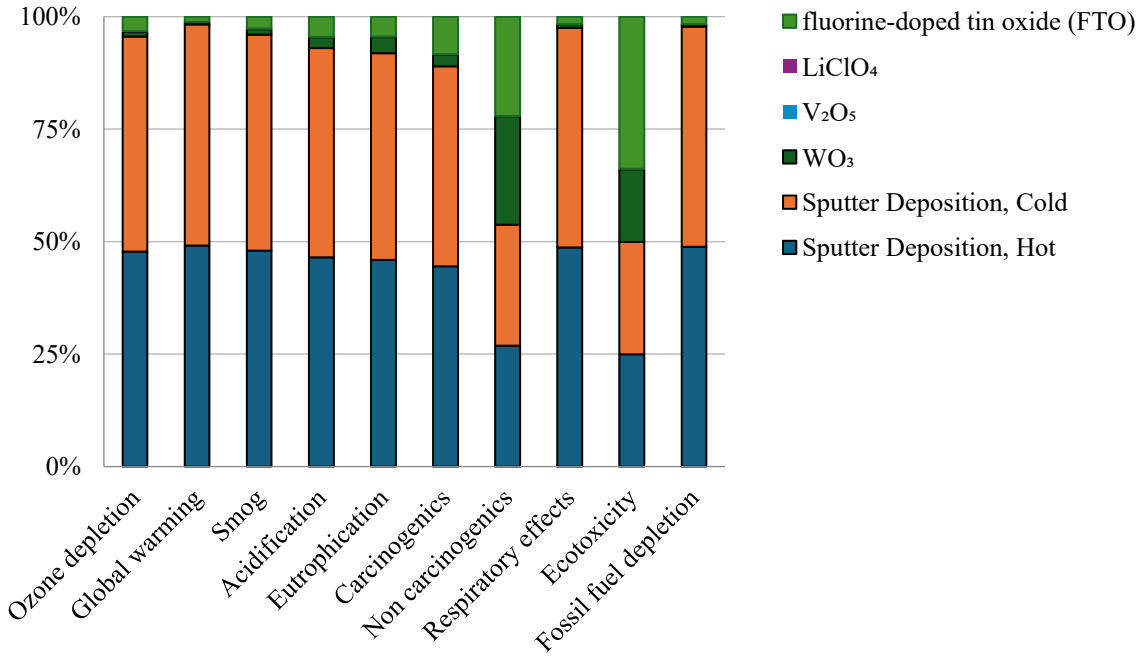

Fig. S3. Contribution of process energy and material flows in the hot coater stage using TRACI.

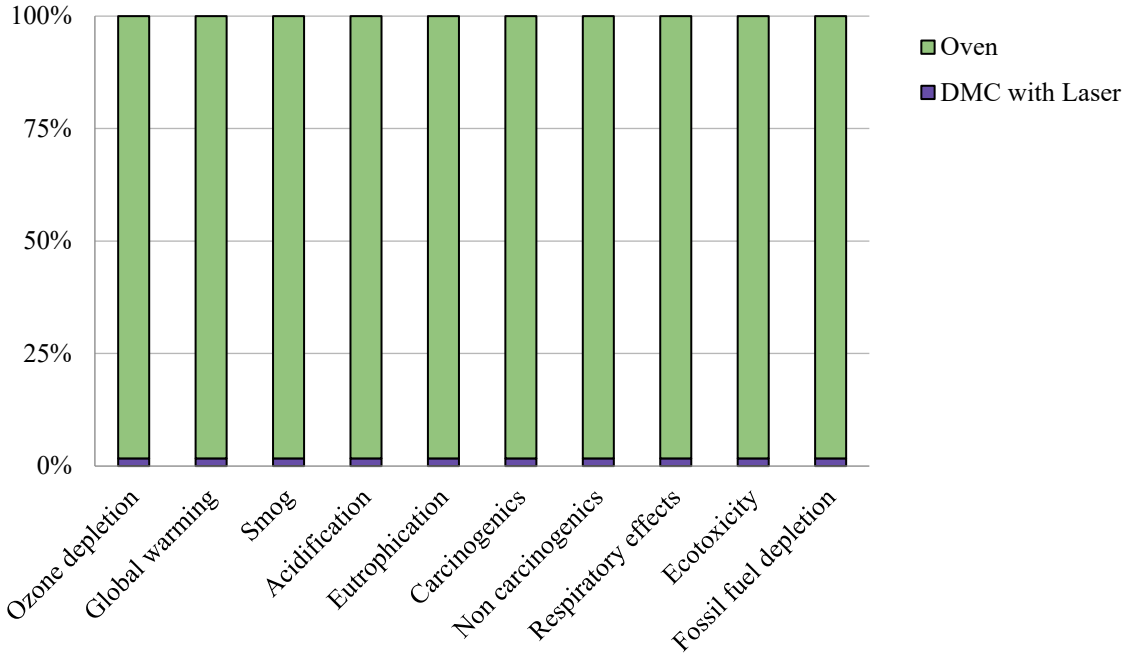

Fig. S4. Contribution of process energy and material flows in the first preparation loop stage using TRACI.

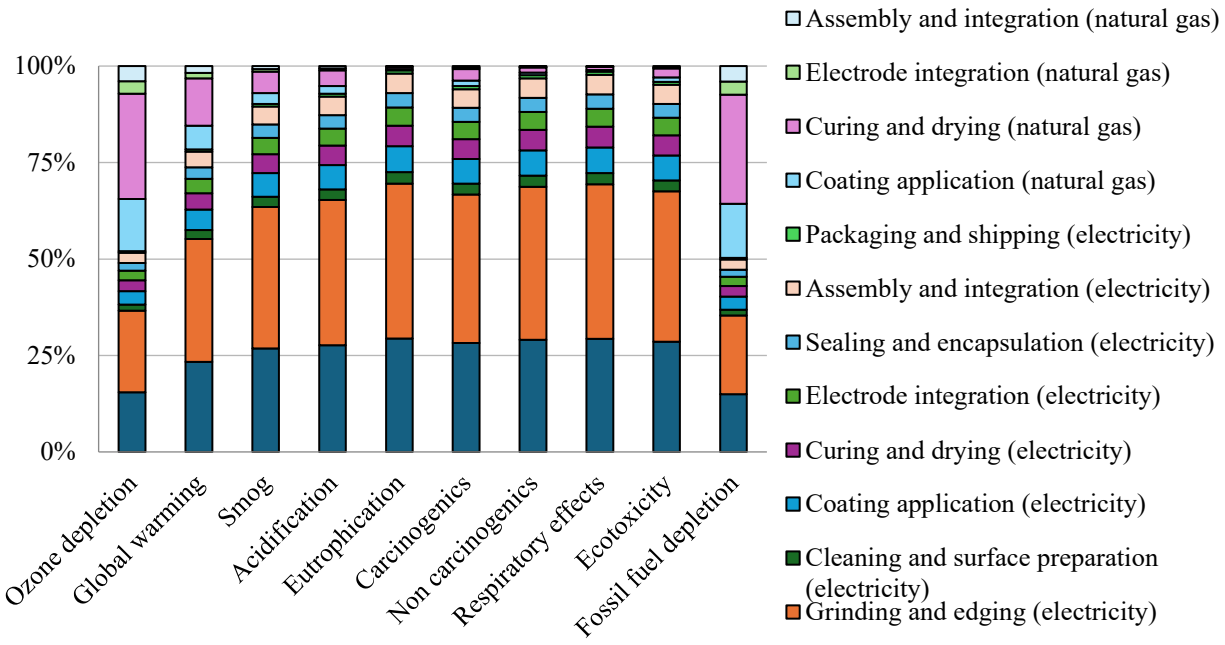

Fig. S5. Contribution of process energy and material flows in the second and third preparation stages using TRACI.

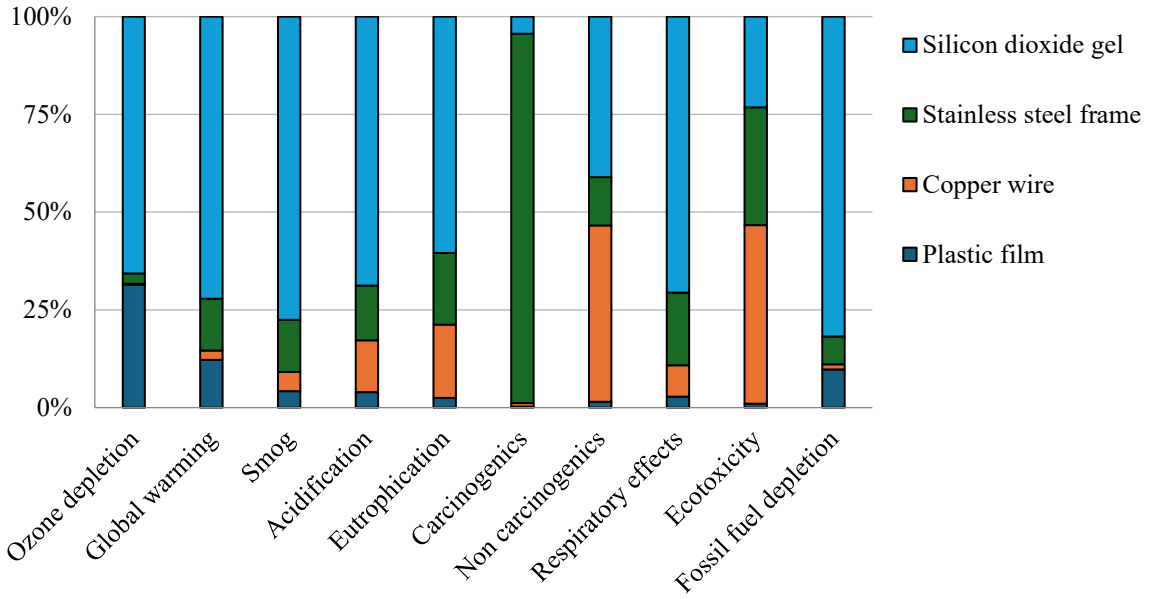

Fig. S6. Contribution of process energy and material flows in the frame design stage using TRACI.

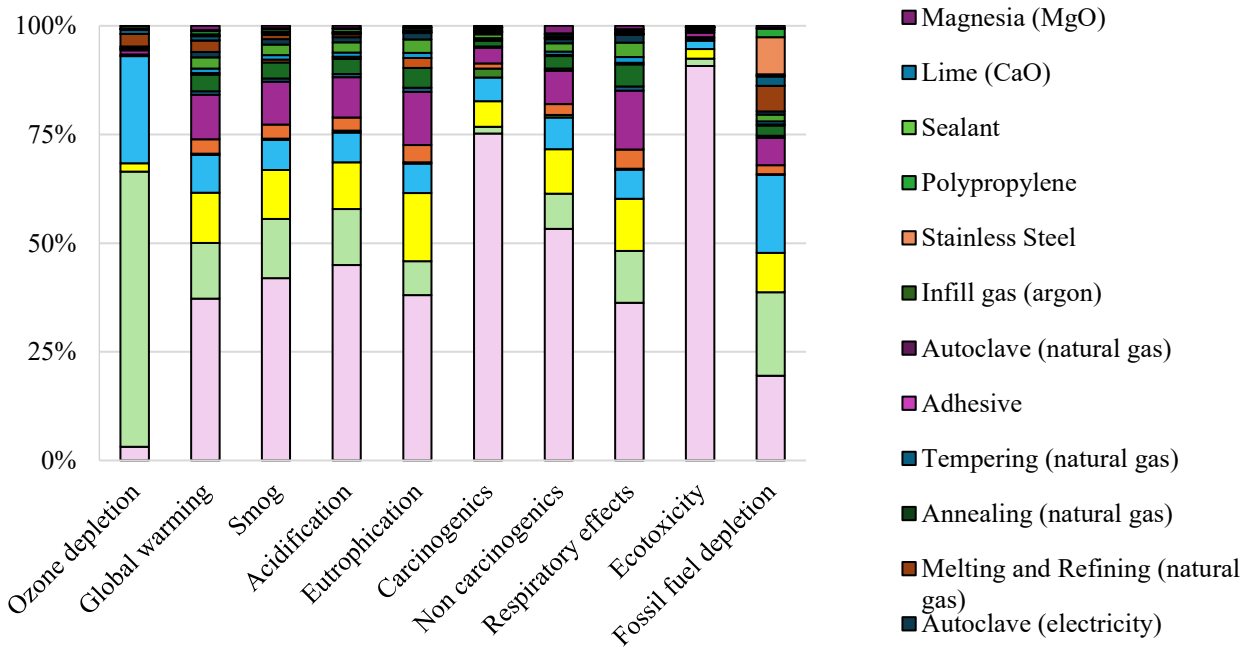

Fig. S7. Contribution of process energy and material flows in the production of a conventional DP window using TRACI.

ANN Model results

Table S7. Predictive results for electrochromic preparation stage from Pytorch's ANN model.

Output	Unit	Float Glass	Water	De-ionized Water	Electricity
Ozone depletion	kg CFC-11 eq	5.29E-07	4.89E-07	8.67E-09	2.03E-07
Global warming	kg CO2 eq	9.722972	5.775475	0.01737	0.842872
Smog	kg O3 eq	1.026678	0.659332	0.001054	0.102417
Acidification	kg SO2 eq	0.082287	0.055414	0.000127	0.009777
Eutrophication	kg N eq	0.012914	0.009754	6.53E-05	0.002479
Carcinogenics	CTUh	3.19E-07	2.76E-07	5.58E-09	1.07E-07
Non carcinogenics	CTUh	1.41E-06	1.17E-06	1.23E-08	3.75E-07
Respiratory effects	kg PM2.5 eq	0.008104	0.005473	2.22E-05	0.001102
Ecotoxicity	CTUe	13.89973	10.44206	0.825549	3.962105
Fossil fuel depletion	MJ surplus	13.9859	8.923151	0.019743	1.46887

Table S8. Error metrics results for comparison of true and predicted values of electrochromic preparation stage from Pytorch's ANN model.

ANN model sets	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Overall R	5.63E-01	7.12E-01	7.74E-01	7.61E-01	-4.66E-02	3.25E-01	4.32E-01	1.95E-01	7.28E-01	7.29E-01
Overall RMSE	3.34E-07	3.12E+00	3.30E-01	2.78E-02	1.20E-02	1.64E-07	6.44E-07	5.04E-03	3.14E+01	4.56E+00
Overall MAPE	9.87E+04	1.21E+05	2.89E+05	3.39E+05	7.21E+03	8.27E+03	1.80E+04	5.68E+04	1.04E+04	1.49E+05
Train R	9.82E-01	9.69E-01	1.00E+00	9.99E-01	1.97E-01	8.08E-01	9.04E-01	4.87E-01	9.81E-01	9.91E-01
Train RMSE	2.63E-07	1.37E+00	2.15E-03	2.58E-03	1.27E-02	1.03E-07	3.11E-07	4.88E-03	3.57E+01	1.07E+00
Train MAPE	1.78E+01	2.55E+01	1.11E+00	1.37E+01	3.06E+01	4.61E+01	2.26E+01	2.97E+01	2.83E+01	1.89E+01
Test R	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
Test RMSE	4.89E-07	5.77E+00	6.59E-01	5.54E-02	9.72E-03	2.75E-07	1.17E-06	5.47E-03	1.04E+01	8.92E+00
Test MAPE	3.95E+05	4.85E+05	1.16E+06	1.35E+06	2.88E+04	3.29E+04	7.17E+04	2.27E+05	4.17E+04	5.95E+05

Table S9. Predictive results for hot coater stage from Pytorch's ANN model.

Output	Unit	Sputter Deposition, Hot	Sputter Deposition, Cold	WO_3	V_2O_5	$LiClO_4$	fluorine-doped tin oxide (FTO)
Ozone depletion	kg CFC-11 eq	1.18E-07	1.18E-07	6.66E-10	6.66E-10	6.66E-10	6.67E-10
Global warming	kg CO2 eq	2.52E+00	2.52E+00	4.78E-03	4.78E-03	4.78E-03	4.79E-03
Smog	kg O3 eq	8.20E-02	8.20E-02	3.98E-04	3.98E-04	3.98E-04	3.98E-04
Acidification	kg SO2 eq	5.60E-03	5.60E-03	3.47E-05	3.47E-05	3.47E-05	3.47E-05
Eutrophication	kg N eq	1.90E-02	1.90E-02	4.85E-05	4.85E-05	4.85E-05	4.86E-05
Carcinogenics	CTUh	2.24E-07	2.24E-07	4.52E-10	4.52E-10	4.52E-10	4.53E-10
Non carcinogenics	CTUh	2.34E-07	2.34E-07	2.21E-09	2.21E-09	2.21E-09	2.21E-09
Respiratory effects	kg PM2.5 eq	7.46E-03	7.46E-03	5.89E-06	5.88E-06	5.88E-06	5.90E-06
Ecotoxicity	CTUe	3.03E+01	3.03E+01	1.18E-01	1.18E-01	1.18E-01	1.19E-01
Fossil fuel depletion	MJ surplus	2.60E+00	2.60E+00	5.20E-03	5.20E-03	5.20E-03	5.20E-03

Table S10. Error metrics results for comparison of true and predicted values of hot coater stage from Pytorch's ANN model.

ANN model sets	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Overall R	7.88E-01	7.74E-01	3.13E-01	2.08E-01	9.90E-01	9.48E-01	4.73E-01	9.80E-01	4.17E-01	9.15E-01
Overall RMSE	5.82E-08	8.83E-01	6.43E-02	5.08E-03	1.80E-03	4.28E-08	5.15E-07	7.98E-04	1.93E+01	5.52E-01
Overall MAPE	5.45E+01	4.75E+01	4.89E+01	4.91E+01	4.90E+01	4.93E+01	7.22E+01	4.87E+01	4.98E+01	4.64E+01
Train R	7.04E-01	6.88E-01	2.47E-01	1.62E-01	9.83E-01	9.17E-01	3.84E-01	9.68E-01	3.35E-01	8.69E-01
Train RMSE	6.13E-08	9.67E-01	7.04E-02	5.56E-03	1.97E-03	4.69E-08	5.21E-07	8.74E-04	2.12E+01	6.05E-01
Train MAPE	6.04E+01	5.70E+01	5.86E+01	5.89E+01	5.86E+01	5.92E+01	7.32E+01	5.84E+01	5.97E+01	5.56E+01
Test R	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Test RMSE	3.96E-08	1.29E-03	5.41E-04	6.24E-06	1.88E-04	3.59E-10	4.82E-07	1.76E-05	4.88E-02	1.12E-03
Test MAPE	2.50E+01	5.12E-02	6.64E-01	1.12E-01	9.81E-01	1.60E-01	6.73E+01	2.35E-01	1.61E-01	4.32E-02

Table S11. Predictive results for first preparation loop stage from Pytorch's ANN model.

Output	Unit	Data Matric Code with Laser	Oven
Ozone depletion	kg CFC-11 eq	4.18E-05	0.007773
Global warming	kg CO2 eq	0.029801	0.162418
Smog	kg O3 eq	0.000966	0.023617
Acidification	kg SO2 eq	6.92E-05	0.005859
Eutrophication	kg N eq	0.000227	0.011393
Carcinogenics	CTUh	5.45E-05	0.005824
Non carcinogenics	CTUh	0.000159	0.0133
Respiratory effects	kg PM2.5 eq	0.000153	0.01727
Ecotoxicity	CTUe	0.360009	0.405142
Fossil fuel depletion	MJ surplus	0.030895	1.798448

Table S12. Error metrics results for comparison of true and predicted values of first preparation loop stage from Pytorch's ANN model.

ANN model sets	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Overall R	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
Overall RMSE	5.50E-03	1.12E+00	2.33E-02	1.41E-03	1.35E-03	4.12E-03	9.40E-03	8.54E-03	1.46E+01	1.14E+00
Overall MAPE	4.64E+06	4.53E+01	2.91E+01	2.79E+01	7.17E+00	2.91E+06	2.28E+06	1.53E+02	4.90E+01	4.49E+01
Train R	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00
Train RMSE	4.18E-05	8.77E-07	4.43E-08	2.89E-06	1.09E-08	5.45E-05	1.59E-04	6.42E-05	8.57E-06	1.27E-07
Train MAPE	2.22E+06	2.94E-03	4.59E-03	4.35E+00	4.81E-03	2.05E+06	1.88E+06	7.23E+01	2.38E-03	4.11E-04
Test R	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
Test RMSE	7.77E-03	1.58E+00	3.29E-02	1.99E-03	1.91E-03	5.82E-03	1.33E-02	1.21E-02	2.06E+01	1.62E+00
Test MAPE	7.07E+06	9.07E+01	5.82E+01	5.14E+01	1.43E+01	3.76E+06	2.68E+06	2.33E+02	9.81E+01	8.98E+01

Table S13. Predictive results for second and third preparation loop stage from Pytorch's ANN model.

Output	Unit	Glass Cutting	Grinding and Edging	Cleaning and Surface Preparation	Coating Application	Curing and Drying	Electrode Integration	Sealing and Encapsulation
Ozone depletion	kg CFC-11 eq	8.10E-08	2.01E-07	4.69E-09	7.36E-09	6.27E-09	5.78E-09	5.17E-09
Global warming	kg CO2 eq	1.037275	1.761702	0.126989	0.190603	0.16487	0.153338	0.138535
Smog	kg O3 eq	0.026324	0.056517	0.001546	0.002606	0.002163	0.001971	0.001729
Acidification	kg SO2 eq	0.001636	0.003885	0.0001	0.000152	0.000131	0.000122	0.00011
Eutrophication	kg N eq	0.000259	0.000766	9.22E-06	1.52E-05	1.27E-05	1.16E-05	1.03E-05
Carcinogenics	CTUh	3.63E-08	1.57E-07	5.11E-10	9.99E-10	7.86E-10	6.98E-10	5.90E-10
Non carcinogenics	CTUh	3.43E-08	1.09E-07	9.38E-10	1.66E-09	1.36E-09	1.22E-09	1.06E-09
Respiratory effects	kg PM2.5 eq	0.000237	0.000964	3.36E-06	6.65E-06	5.21E-06	4.61E-06	3.89E-06
Ecotoxicity	CTUe	0.104025	0.100868	0.363019	0.257312	0.290966	0.309409	0.33721
Fossil fuel depletion	MJ surplus	1.323253	2.021138	0.151712	0.243511	0.205649	0.188986	0.167901

Table S13. Predictive results for second and third preparation loop stage from Pytorch's ANN model (continued).

Output	Unit	Assembly and Integration	Packaging and Shipping	Coating Application	Curing and Drying	Electrode Integration	Assembly and Integration
Ozone depletion	kg CFC-11 eq	0.000522	0.000302	0.005868	2.22E-06	0.000498	0.000486
Global warming	kg CO2 eq	0.18718	0.121825	1.153127	1.12109	0.199559	0.1897
Smog	kg O3 eq	0.004279	0.00478	0.027951	0.006261	0.001884	0.001324
Acidification	kg SO2 eq	0.001147	0.000921	0.000923	7.32E-11	0.001131	0.001069
Eutrophication	kg N eq	0.001155	0.001206	0.010629	0.000369	0.000388	0.000215
Carcinogenics	CTUh	0.00107	0.000398	0.015327	1.14E-05	0.00124	0.001237
Non carcinogenics	CTUh	0.003649	0.001768	0.018564	0.000181	0.004776	0.005284
Respiratory effects	kg PM2.5 eq	0.000478	0.000378	0.006445	9.98E-06	0.000272	0.000194
Ecotoxicity	CTUe	2.578987	0.535717	4.20607	1.224942	0.901262	0.263728
Fossil fuel depletion	MJ surplus	0.214125	0.094402	1.512508	3.021685	0.359257	0.436708

Table S14. Error metrics results for comparison of true and predicted values of second and third preparation loop stage from Pytorch's ANN model.

ANN model sets	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Overall R	5.75E-01	8.74E-01	8.18E-01	7.93E-01	6.93E-01	7.42E-01	7.21E-01	7.20E-01	-3.23E-01	9.93E-01
Overall RMSE	5.19E-08	2.83E-01	1.05E-02	7.57E-04	4.53E-03	3.36E-08	1.49E-07	1.61E-03	7.41E+00	1.18E-01
Overall MAPE	5.84E+01	5.17E+01	5.94E+01	6.58E+01	1.08E+02	1.55E+02	1.20E+02	1.59E+02	6.60E+01	2.72E+01
Train R	5.49E-01	9.87E-01	9.68E-01	9.57E-01	8.96E-01	8.98E-01	9.26E-01	8.93E-01	-4.17E-01	9.97E-01
Train RMSE	5.19E-08	9.78E-02	5.89E-03	4.52E-04	4.92E-03	2.71E-08	1.61E-07	1.74E-03	8.06E+00	7.14E-02
Train MAPE	5.56E+01	3.80E+01	4.36E+01	4.51E+01	8.05E+01	6.67E+01	8.35E+01	7.90E+01	6.61E+01	2.87E+01
Test R	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
Test RMSE	5.19E-08	6.84E-01	2.28E-02	1.61E-03	3.08E-04	5.77E-08	4.39E-08	3.64E-04	3.79E-01	2.49E-01
Test MAPE	7.35E+01	1.27E+02	1.46E+02	1.79E+02	2.61E+02	6.38E+02	3.20E+02	5.98E+02	6.54E+01	1.88E+01

Table S15. Predictive results for frame design stage from Pytorch's ANN model.

Output	Unit	Plastic film (polypropylene)	Copper wire	Stainless steel frame	Silicon dioxide gel
Ozone depletion	kg CFC-11 eq	1.96E-08	5.32E-08	2.57E-07	1.18E-06
Global warming	kg CO2 eq	0.539599	0.565618	1.918287	10.3857
Smog	kg O3 eq	0.030451	0.034298	0.119674	0.633033
Acidification	kg SO2 eq	0.002173	0.003141	0.011458	0.049038
Eutrophication	kg N eq	0.000315	0.000576	0.00339	0.023607
Carcinogenics	CTUh	3.61E-09	1.01E-08	7.17E-08	5.61E-07
Non carcinogenics	CTUh	5.14E-08	1.32E-07	5.66E-07	2.22E-06
Respiratory effects	kg PM2.5 eq	0.000382	0.000733	0.002561	0.009764
Ecotoxicity	CTUe	4.969003	4.405288	18.18617	117.4548
Fossil fuel depletion	MJ surplus	2.025492	1.87444	1.66766	1.454901

Table S16. Error metrics results for comparison of true and predicted values of frame stage from Pytorch's ANN model.

ANN model sets	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Overall R	9.87E-01	1.00E+00	1.00E+00	9.88E-01	9.61E-01	-1.85E-01	5.00E-01	9.99E-01	-3.01E-02	-7.99E-01
Overall RMSE	2.64E-06	8.45E-02	1.17E-02	3.22E-03	3.79E-03	5.96E-06	1.09E-06	2.24E-04	1.27E+02	8.71E+00
Overall MAPE	2.76E+01	1.04E+01	8.89E+00	2.06E+01	3.62E+01	7.02E+01	3.86E+01	9.61E+00	4.71E+01	1.13E+02
Train R	9.87E-01	1.00E+00	1.00E+00	9.99E-01	9.86E-01	-3.64E-01	9.99E-01	1.00E+00	3.93E-01	-7.73E-01
Train RMSE	3.05E-06	2.85E-02	1.20E-02	8.86E-04	2.19E-03	6.89E-06	6.21E-08	1.48E-05	7.65E+01	1.00E+01
Train MAPE	2.73E+01	5.17E-01	4.04E+00	5.24E+00	1.76E+01	6.31E+01	2.00E+01	1.74E-01	3.01E+01	3.18E+01
Test R	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
Test RMSE	1.18E-08	1.62E-01	1.05E-02	6.26E-03	6.57E-03	1.07E-07	2.18E-06	4.47E-04	2.16E+02	1.46E+00
Test MAPE	2.84E+01	4.00E+01	2.34E+01	6.66E+01	9.19E+01	9.14E+01	9.43E+01	3.79E+01	9.80E+01	3.58E+02

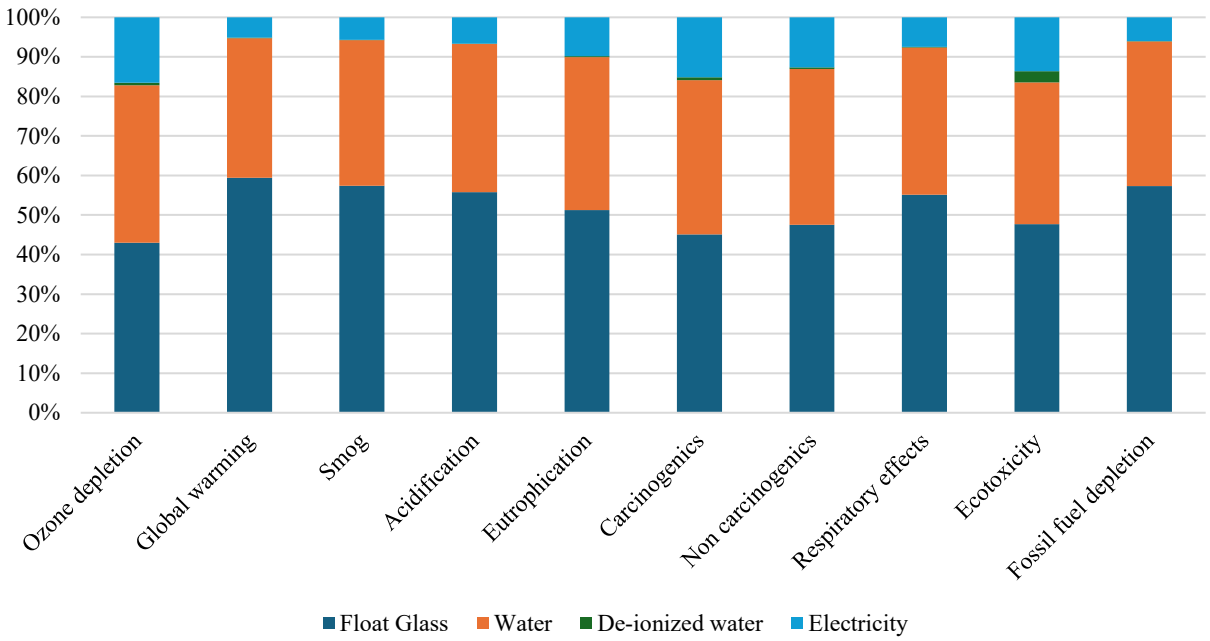

Fig. S8. Contribution of process energy and material flows in the electrochromic preparation stage using Pytorch's ANN model.

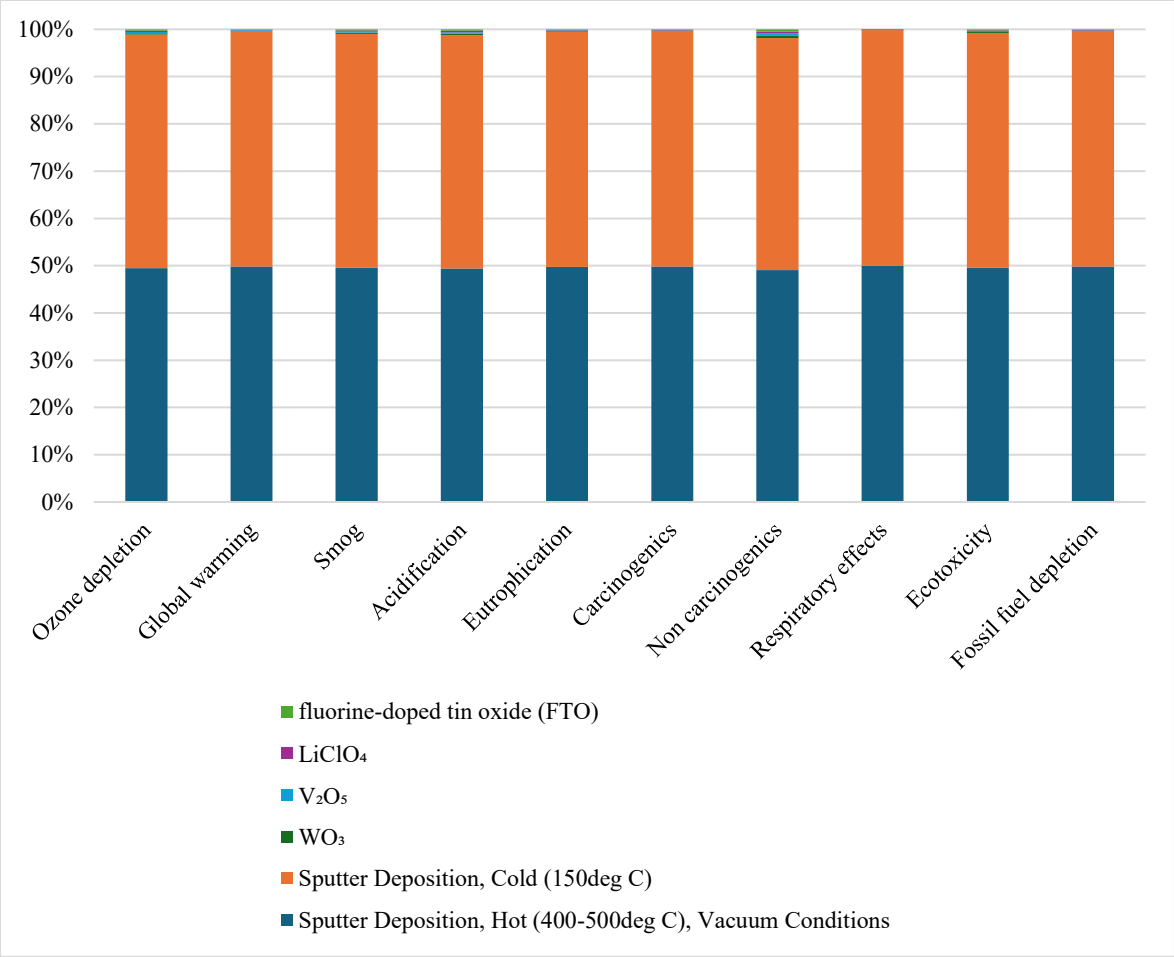

Fig. S9. Contribution of process energy and material flows in the hot coater stage using Pytorch's ANN model.

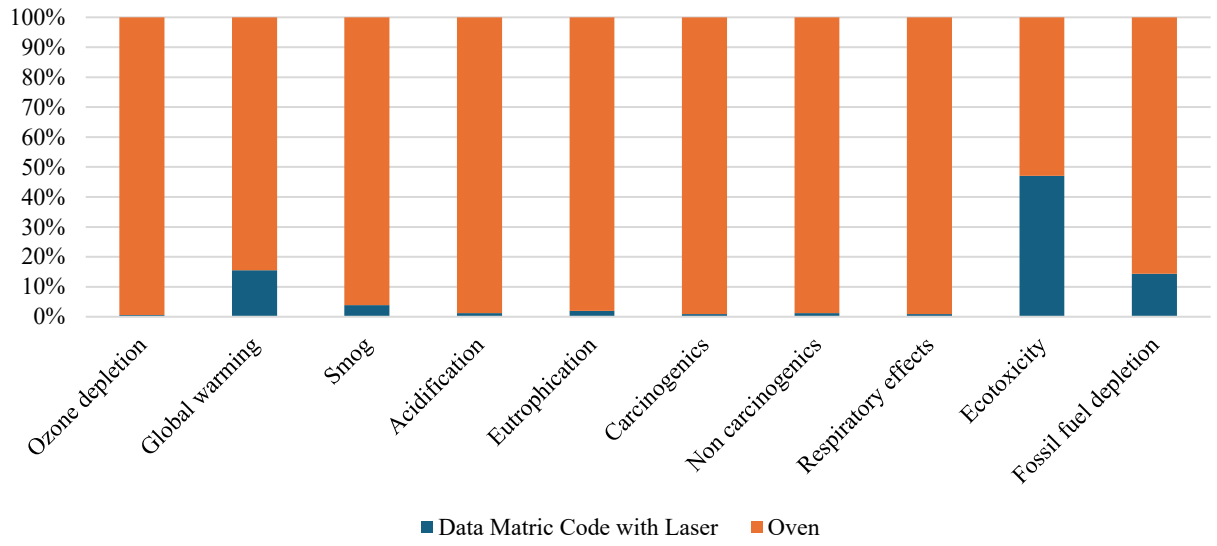

Fig. S10. Contribution of process energy and material flows in the first preparation loop stage using Pytorch's ANN model.

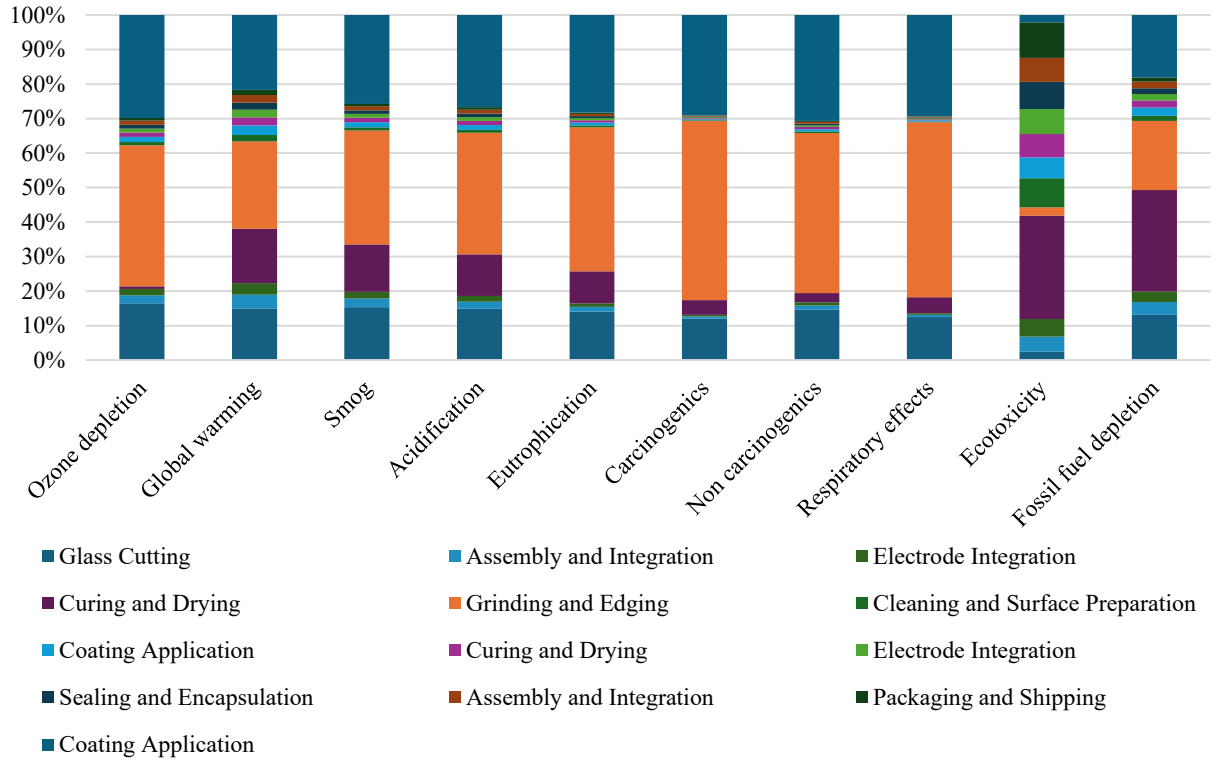

Fig. S11. Contribution of process energy and material flows in the second and third preparation loop stage using Pytorch's ANN model.

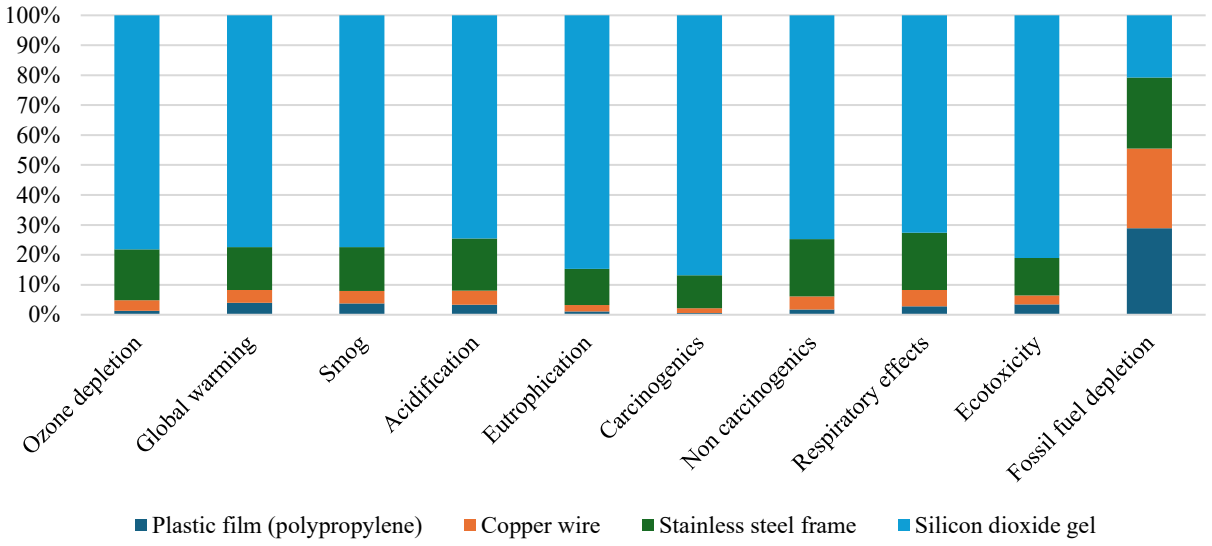

Fig. S12. Contribution of process energy and material flows in the frame design stage using Pytorch's ANN model.

ANFIS Model results

Table S17. Predictive results for electrochromic preparation stage from Pytorch's ANFIS model.

Output	Unit	Float Glass	Water	De-ionized Water	Electricity
Ozone depletion	kg CFC-11 eq	9.81E-07	1.25E-10	8.71E-09	2.56E-07
Global warming	kg CO2 eq	1.01E+01	7.42E-04	2.07E-02	3.18E+00
Smog	kg O3 eq	1.05E+00	3.02E-05	1.21E-03	1.04E-01
Acidification	kg SO2 eq	8.78E-02	1.87E-06	1.49E-04	7.13E-03
Eutrophication	kg N eq	1.30E-02	1.09E-05	7.70E-05	2.44E-02
Carcinogenics	CTUh	3.26E-07	3.02E-10	3.75E-09	2.86E-07
Non-carcinogenics	CTUh	1.43E-06	5.20E-10	1.59E-08	9.15E-07
Respiratory effects	kg PM2.5 eq	8.32E-03	7.72E-07	2.62E-05	9.55E-03
Ecotoxicity	CTUe	7.76E+01	2.12E-02	8.75E-01	4.03E+00
Fossil fuel depletion	MJ surplus	1.44E+01	1.27E-03	2.10E-02	3.29E+00

Table S18. Error metric results for the comparison of true and predicted values of the electrochromic preparation stage from PyTorch's three-level ANFIS model.

ANFIS model	MF Input	MF Output	MF count	Epoch	Learning method	Impact category	R	RMSE	MAPE (%)
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Ozone depletion	1.000E+00	2.000E-10	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Ozone depletion	1.000E+00	1.000E-10	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Ozone depletion	9.999E-01	2.110E-08	1.046E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Global warming	1.000E+00	1.854E-03	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Global warming	1.000E+00	2.170E-03	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Global warming	9.999E-01	1.486E-01	2.127E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Smog	1.000E+00	1.948E-04	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Smog	1.000E+00	5.972E-05	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Smog	9.954E-01	2.954E-02	1.575E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Acidification	1.000E+00	1.616E-05	2.073E-03
ANFIS 2	Gaussian	Non-linear	10	500	Hybrid (Adam)	Acidification	1.000E+00	3.825E-06	2.168E-03

		(tanh + abs)							
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Acidification	9.965E-01	2.047E-03	1.763E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Eutrophication	1.000E+00	2.392E-06	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Eutrophication	1.000E+00	6.680E-06	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Eutrophication	9.952E-01	1.103E-03	1.385E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Carcinogenics	1.000E+00	1.000E-10	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Carcinogenics	1.000E+00	1.000E-10	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Carcinogenics	9.969E-01	6.200E-09	1.694E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Non carcinogenics	1.000E+00	3.000E-10	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Non carcinogenics	1.000E+00	2.000E-10	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Non carcinogenics	9.971E-01	2.960E-08	1.987E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Respiratory effects	1.000E+00	1.525E-06	2.073E-03

ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Respiratory effects	1.000E+00	5.251E-07	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Respiratory effects	9.973E-01	2.129E-04	1.844E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Ecotoxicity	1.000E+00	1.422E-02	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Ecotoxicity	1.000E+00	2.264E-02	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Ecotoxicity	9.955E-01	2.138E+00	1.493E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	2.644E-03	2.073E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	1.815E-03	2.168E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	500	Hybrid (Adam)	Fossil fuel depletion	9.961E-01	3.320E-01	1.536E+01

Table S19. Predictive results for hot coater stage from Pytorch's three-level ANFIS model.

Output	Unit	Sputter Deposition, Hot	Sputter Deposition, Cold	WO_3	V_2O_5	$LiClO_4$	fluorine-doped tin oxide (FTO)
Ozone depletion	kg CFC-11 eq	3.05E+01	2.62E+00	3.56E-09	1.25E-07	6.29E-10	1.09E-08
Global warming	kg CO2 eq	2.62	1.59E-07	4.66E-02	2.05E+00	4.58E-03	9.52E-02
Smog	kg O3 eq	1.59E-07	2.54E+00	6.52E-03	1.49E-01	3.76E-04	1.21E-02
Acidification	kg SO2 eq	2.54E+00	8.21E-02	9.42E-04	1.17E-02	3.32E-05	1.66E-03
Eutrophication	kg N eq	8.21E-02	5.63E-03	1.16E-03	3.85E-03	4.70E-05	1.43E-03
Carcinogenics	CTUh	5.63E-03	1.93E-02	1.42E-08	8.95E-08	4.35E-10	4.35E-08
Non carcinogenics	CTUh	1.93E-02	2.25E-07	7.28E-07	3.40E-07	2.12E-09	6.56E-07
Respiratory effects	kg PM2.5 eq	2.25E-07	7.22E-07	1.08E-04	1.85E-03	5.66E-06	1.98E-04
Ecotoxicity	CTUe	7.22E-07	7.54E-03	1.96E+01	1.04E+01	1.13E-01	4.05E+01
Fossil fuel depletion	MJ surplus	7.54E-03	3.05E+01	3.07E-02	1.28E+00	4.99E-03	1.01E-01

Table S20. Error metrics results for comparison of true and predicted values of hot coater stage from Pytorch's three-level ANFIS model.

ANFIS model	MF Input	MF Output	MF count	Epoch	Learning method	Impact category	R	RMSE	MAPE (%)
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	6.860E-15	2.411E-05
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	5.523E-14	1.393E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	9.997E-01	7.260E-08	2.142E+03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	1.557E-08	6.852E-07
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	3.029E-03	2.258E+01
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	6.552E-03	2.120E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	1.076E-09	3.955E-06
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	4.263E-04	3.523E+01
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	3.849E-04	2.875E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Acidification	1.000E+00	2.253E-10	3.677E-06
ANFIS 2	Gaussian	Non-linear	10	1000	Hybrid (Adam)	Acidification	1.000E+00	1.154E-05	1.217E+01

		(tanh + abs)							
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Acidification	9.999E-01	3.215E-05	1.619E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	7.488E-10	7.052E-06
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	1.695E-07	1.314E-01
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	9.999E-01	7.804E-05	3.193E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	3.546E-15	2.631E-06
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	1.602E-09	1.082E+02
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	9.995E-01	9.226E-08	3.149E+03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	1.941E-14	2.415E-06
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	3.009E-12	4.916E-02
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	9.956E-01	2.714E-07	3.866E+03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	5.230E-10	8.729E-05

ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	7.002E-09	3.381E-02
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	9.999E-01	2.663E-05	5.159E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	1.000E+00	6.607E-07	2.318E-06
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	9.275E-01	4.742E+00	1.653E+03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	9.411E-01	3.334E+00	8.363E+02
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	7.787E-08	3.531E-06
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	1.745E-04	1.475E+00
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil fuel depletion	9.998E-01	1.644E-02	2.450E+01

Table S21. Predictive results for first preparation loop stage from Pytorch's three-level ANFIS model.

Output	Unit	Data Matric Code with Laser	Oven
Ozone depletion	kg CFC-11 eq	1.88E-09	1.10E-07
Global warming	kg CO2 eq	2.98E-02	1.74E+00
Smog	kg O3 eq	9.66E-04	5.65E-02
Acidification	kg SO2 eq	6.63E-05	3.87E-03
Eutrophication	kg N eq	2.27E-04	1.33E-02
Carcinogenics	CTUh	2.65E-09	1.55E-07
Non carcinogenics	CTUh	8.49E-09	4.96E-07
Respiratory effects	kg PM2.5 eq	8.87E-05	5.19E-03
Ecotoxicity	CTUe	3.60E-01	2.10E+01
Fossil fuel depletion	MJ surplus	3.09E-02	1.80E+00

Table S22. Error metrics results for comparison of true and predicted values of first preparation loop stage from Pytorch's three-level ANFIS model.

ANFIS model	MF Input	MF Output	MF count	Epoch	Learning method	Impact category	R	RMSE	MAPE (%)
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	2.840E-12	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	1.660E-09	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	5.000E-09	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	4.500E-04	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	2.630E-02	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	7.940E-02	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	1.460E-05	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	8.540E-04	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	2.570E-03	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Acidification	1.000E+00	1.000E-06	2.509E-03
ANFIS 2	Gaussian	Non-linear	10	1000	Hybrid (Adam)	Acidification	1.000E+00	5.850E-05	2.509E-03

		(tanh + abs)							
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Acidification	1.000E+00	1.760E-04	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	3.430E-06	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	2.010E-04	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	6.060E-04	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	4.000E-12	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	2.340E-09	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	7.050E-09	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	1.280E-11	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	7.490E-09	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	2.260E-08	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	1.340E-06	2.509E-03

ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	7.840E-05	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	2.360E-04	5.019E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	1.000E+00	5.440E-03	2.509E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	1.000E+00	3.170E-01	2.509E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	1.000E+00	9.57E-01	5.02E-03
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil Fuel Depletion	1.000E+00	4.67E-04	2.51E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil Fuel Depletion	1.000E+00	2.72E-02	2.51E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil Fuel Depletion	1.000E+00	8.21E-02	5.02E-03

Table S23. Predictive results for second and third preparation loop stage from Pytorch's three-level ANFIS model.

Output	Unit	Glass Cutting	Grinding and Edging	Cleaning and Surface Preparation	Coating Application	Curing and Drying	Electrode Integration	Sealing and Encapsulation
Ozone depletion	kg CFC-11 eq	8.31E-08	1.13E-07	7.82E-09	1.88E-08	1.50E-08	1.32E-08	1.05E-08
Global warming	kg CO2 eq	1.31E+00	1.79E+00	1.24E-01	2.98E-01	2.38E-01	2.09E-01	1.67E-01
Smog	kg O3 eq	4.24E-02	5.79E-02	4.02E-03	9.65E-03	7.72E-03	6.75E-03	5.41E-03
Acidification	kg SO2 eq	2.91E-03	3.97E-03	2.76E-04	6.62E-04	5.29E-04	4.63E-04	3.71E-04
Eutrophication	kg N eq	1.00E-02	1.36E-02	9.45E-04	2.27E-03	1.81E-03	1.59E-03	1.27E-03
Carcinogenics	CTUh	1.16E-07	1.59E-07	1.10E-08	2.65E-08	2.12E-08	1.86E-08	1.49E-08
Non carcinogenics	CTUh	3.74E-07	5.09E-07	3.53E-08	8.48E-08	6.78E-08	5.94E-08	4.75E-08
Respiratory effects	kg PM2.5 eq	3.91E-03	5.32E-03	3.69E-04	8.86E-04	7.09E-04	6.20E-04	4.96E-04
Ecotoxicity	CTUe	1.58E+01	2.16E+01	1.49E+00	3.59E+00	2.87E+00	2.51E+00	2.01E+00
Fossil fuel depletion	MJ surplus	1.36E+00	1.85E+00	1.28E-01	3.08E-01	2.46E-01	2.16E-01	1.72E-01

Table S23. Predictive results for second and third preparation loop stage from Pytorch's three-level ANFIS model (continued).

Output	Unit	Assembly and Integration	Packaging and Shipping	Coating Application	Curing and Drying	Electrode Integration	Assembly and Integration
Ozone	kg CFC-11 eq	1.43E-08	2.13E-09	7.56E-08	1.52E-07	1.81E-08	2.18E-08

depletion							
Global warming	kg CO2 eq	2.26E-01	3.38E-02	5.56E-01	1.12E+00	1.33E-01	1.60E-01
Smog	kg O3 eq	7.33E-03	1.09E-03	1.20E-02	2.42E-02	2.88E-03	3.46E-03
Acidification	kg SO2 eq	5.03E-04	7.50E-05	6.79E-04	1.37E-03	1.63E-04	1.96E-04
Eutrophication	kg N eq	1.72E-03	2.57E-04	8.37E-05	1.72E-04	2.06E-05	2.47E-05
Carcinogenics	CTUh	2.02E-08	3.00E-09	6.58E-09	1.32E-08	1.58E-09	1.90E-09
Non carcinogenics	CTUh	6.45E-08	9.62E-09	1.00E-08	2.02E-08	2.41E-09	2.89E-09
Respiratory effects	kg PM2.5 eq	6.73E-04	1.00E-04	4.43E-05	8.95E-05	1.07E-05	1.28E-05
Ecotoxicity	CTUe	2.73E+00	4.07E-01	6.37E-01	1.28E+00	1.53E-01	1.84E-01
Fossil fuel depletion	MJ surplus	2.34E-01	3.49E-02	1.51E+00	3.04E+00	3.62E-01	4.34E-01

Table S24. Error metrics results for comparison of true and predicted values of second and third preparation loop stage from Pytorch's three-level ANFIS model.

ANFIS model	MF Input	MF Output	MF count	Epoch	Learning method	Impact category	R	RMSE	MAPE (%)
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	1.000E+00	1.890 E-10	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	1.000E+00	4.310 E-10	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	1.000E+00	4.380 E-10	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	1.000E+00	3.120 E-09	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	9.999E-01	1.050 E-09	4.271E-01
NFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	9.998E-01	5.260 E-09	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ozone depletion	9.975E-01	7.150 E-09	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Global warming	1.000E+00	3.060 E-04	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Global warming	1.000E+00	1.260 E-04	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Global warming	1.000E+00	1.060 E-04	2.017E-03
ANFIS 4	Gaussian	Non-linear	10	200	Hybrid (Adam)	Global warming	1.000E+00	3.690 E-04	1.888E-03

		(tanh + abs)							
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Global warming	9.999E-01	1.687 E-02	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Global warming	9.998E-01	1.129 E-02	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Global warming	9.975E-01	2.216 E-02	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	1.000E+00	1.000 E-05	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	1.000E+00	4.000 E-06	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	1.000E+00	3.000 E-06	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	1.000E+00	1.100 E-05	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	9.999E-01	5.450 E-04	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	9.998E-01	3.590 E-04	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Smog	9.975E-01	7.110 E-04	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	1.000E+00	6.890 E-07	1.921E-03

ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	1.000E+00	2.800 E-07	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	1.000E+00	2.110 E-07	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	1.000E+00	7.950 E-07	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	9.999E-01	3.730 E-05	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	9.998E-01	2.470 E-05	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Acidification	9.975E-01	4.870 E-05	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	1.000E+00	2.370 E-06	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	1.000E+00	9.590 E-06	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	1.000E+00	7.240 E-07	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	1.000E+00	1.640 E-06	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	9.999E-01	1.280 E-04	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	9.998E-01	8.440 E-05	4.356E-01

ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Eutrophication	9.975E-01	1.670 E-04	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	1.000E+00	3.010 E-10	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	1.000E+00	1.220 E-10	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	1.000E+00	9.220 E-11	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	1.000E+00	3.470 E-10	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	9.999E-01	1.630 E-09	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	9.998E-01	1.080 E-09	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Carcinogenics	9.975E-01	2.130 E-09	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	1.000E+00	9.640 E-10	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	1.000E+00	3.910 E-10	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	1.000E+00	2.950 E-10	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	1.000E+00	1.110 E-09	1.888E-03

ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	9.999E-01	5.230 E-09	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	9.998E-01	3.470 E-09	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Non carcinogenics	9.975E-01	6.840 E-09	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	1.000E+00	1.010 E-06	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	1.000E+00	4.080 E-07	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	1.000E+00	3.080 E-07	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	1.000E+00	1.160 E-06	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	9.999E-01	5.460 E-05	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	9.998E-01	3.610 E-05	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Respiratory effects	9.975E-01	7.130 E-05	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	1.000E+00	3.677 E-03	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	1.000E+00	1.508 E-03	1.953E-03

ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	1.000E+00	1.279 E-03	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	1.000E+00	4.432 E-03	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	9.999E-01	2.025 E-01	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	9.998E-01	1.355 E-01	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Ecotoxicity	9.975E-01	2.659 E-01	1.246E+01
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	3.140 E-04	1.921E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	1.340 E-04	1.953E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	1.010 E-04	2.017E-03
ANFIS 4	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	4.070 E-04	1.888E-03
ANFIS 5	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	9.999E-01	1.743 E-02	4.271E-01
ANFIS 6	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	9.998E-01	1.166 E-02	4.356E-01
ANFIS 7	Gaussian	Non-linear (tanh + abs)	10	200	Hybrid (Adam)	Fossil fuel depletion	9.975E-01	2.296 E-02	1.246E+01

Table S25. Predictive results for frame design stage from Pytorch's three-level ANFIS model.

Output	Unit	Plastic film (polypropylene)	Copper wire	Stainless steel frame	Silicon dioxide gel
Ozone depletion	kg CFC-11 eq	1.96E-08	4.16E-08	2.46E-07	6.18E-06
Global warming	kg CO2 eq	0.546646	0.406402	1.842315	9.987099
Smog	kg O3 eq	0.031499	0.045069	0.107709	0.624791
Acidification	kg SO2 eq	0.00219	0.009453	0.009502	0.046929
Eutrophication	kg N eq	0.000317	0.007191	0.006868	0.022572
Carcinogenics	CTUh	3.49E-08	1.18E-07	1.15E-05	5.39E-07
Non carcinogenics	CTUh	9.43E-08	2.32E-06	6.37E-07	2.13E-06
Respiratory effects	kg PM2.5 eq	0.000384	0.001186	0.002446	0.009324
Ecotoxicity	CTUe	4.924047	221.2489	144.2082	111.3384
Fossil fuel depletion	MJ surplus	2.00924	0.411929	1.569978	18.00479

Table S26. Error metrics results for comparing true and predicted values of the frame design stage from PyTorch's three-level ANFIS model.

ANFIS model	MF Input	MF Output	MF count	Epoch	Learning method	Impact category	R	RMSE	MAPE (%)
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	1.320E-10	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	1.000E+00	1.940E-07	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ozone depletion	9.986E-01	7.420E-08	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	1.190E-04	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	1.000E+00	2.971E-02	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Global warming	9.986E-01	1.872E-01	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	7.000E-06	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	1.000E+00	1.857E-03	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Smog	9.986E-01	1.173E-02	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Acidification	1.000E+00	0.000E+00	1.895E-03
ANFIS 2	Gaussian	Non-linear	10	1000	Hybrid (Adam)	Acidification	1.000E+00	1.360E-04	2.153E-03

		(tanh + abs)							
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Acidification	9.986E-01	8.510E-04	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	0.000E+00	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	1.000E+00	5.700E-05	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Eutrophication	9.986E-01	3.620E-04	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	1.810E-10	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	1.000E+00	3.950E-07	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Carcinogenics	9.986E-01	1.530E-07	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	6.180E-10	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	1.000E+00	5.440E-08	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Non carcinogenics	9.986E-01	3.500E-08	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	0.000E+00	1.895E-03

ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	1.000E+00	2.500E-05	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Respiratory effects	9.986E-01	1.570E-04	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	1.000E+00	4.883E-02	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	1.000E+00	1.158E+00	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Ecotoxicity	9.986E-01	7.303E+00	4.863E+00
ANFIS 1	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	8.780E-04	1.895E-03
ANFIS 2	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil fuel depletion	1.000E+00	5.950E-02	2.153E-03
ANFIS 3	Gaussian	Non-linear (tanh + abs)	10	1000	Hybrid (Adam)	Fossil fuel depletion	9.986E-01	3.750E-01	4.863E+00

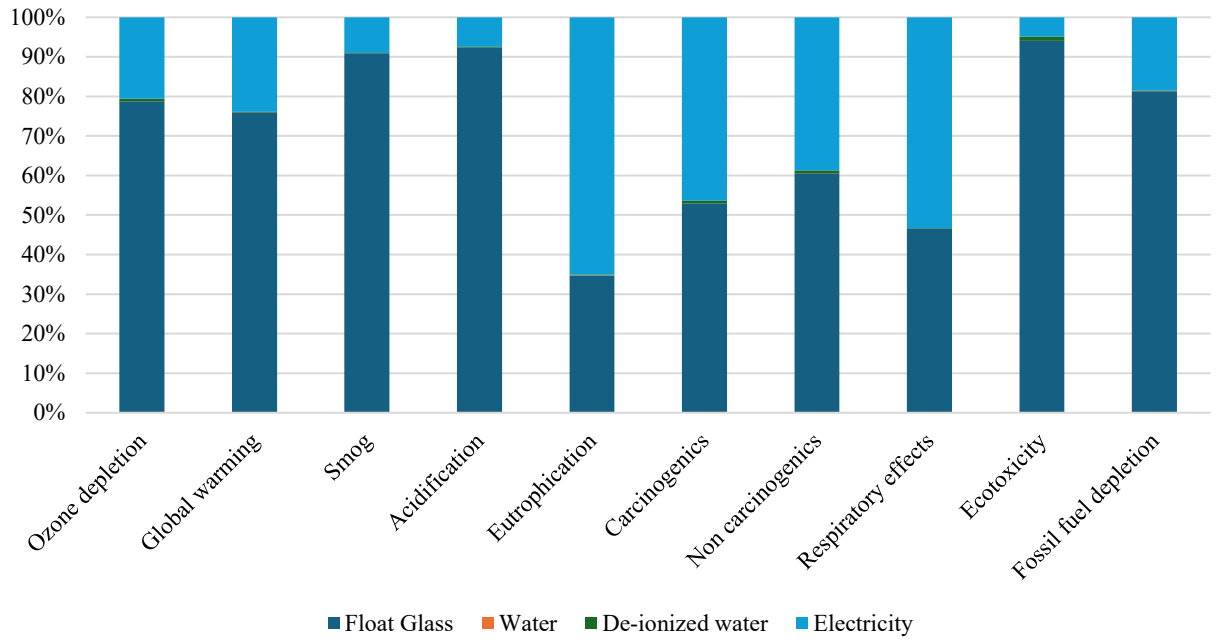

Fig. S13. Contribution of process energy and material flows in the electrochromic preparation stage using Pytorch's three-level ANFIS model.

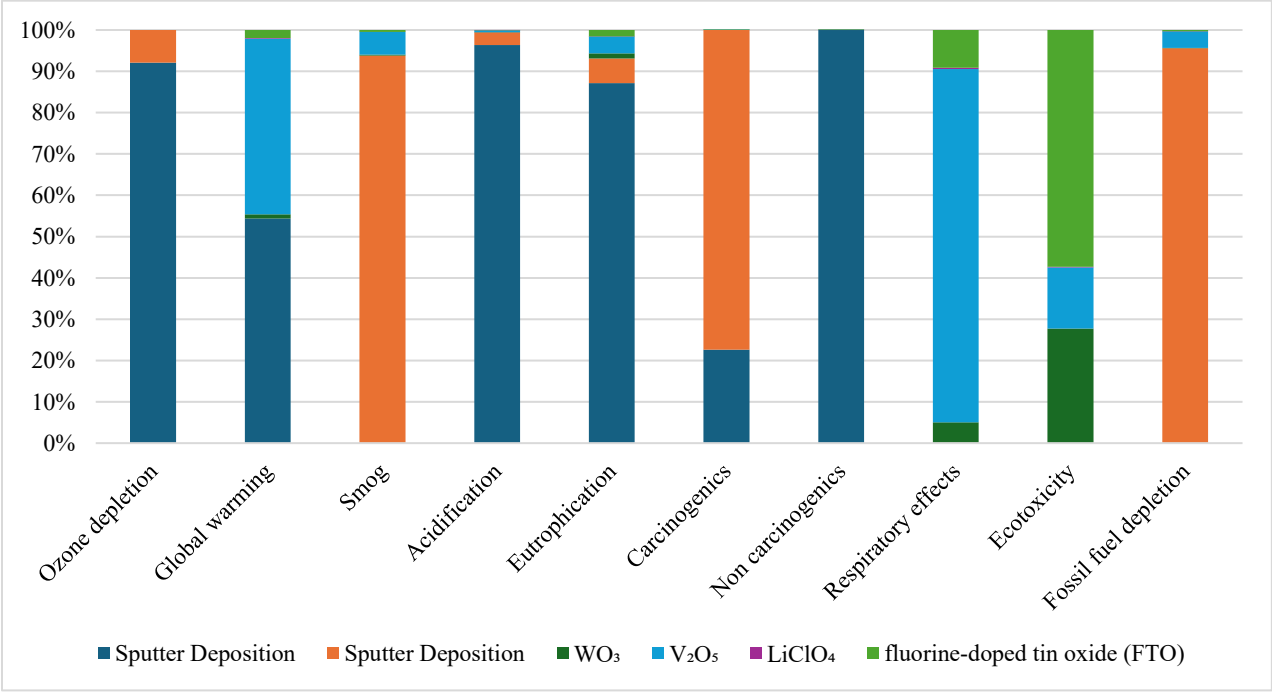

Fig. S14. Contribution of process energy and material flows in the hot coater stage using Pytorch's three-level ANFIS model.

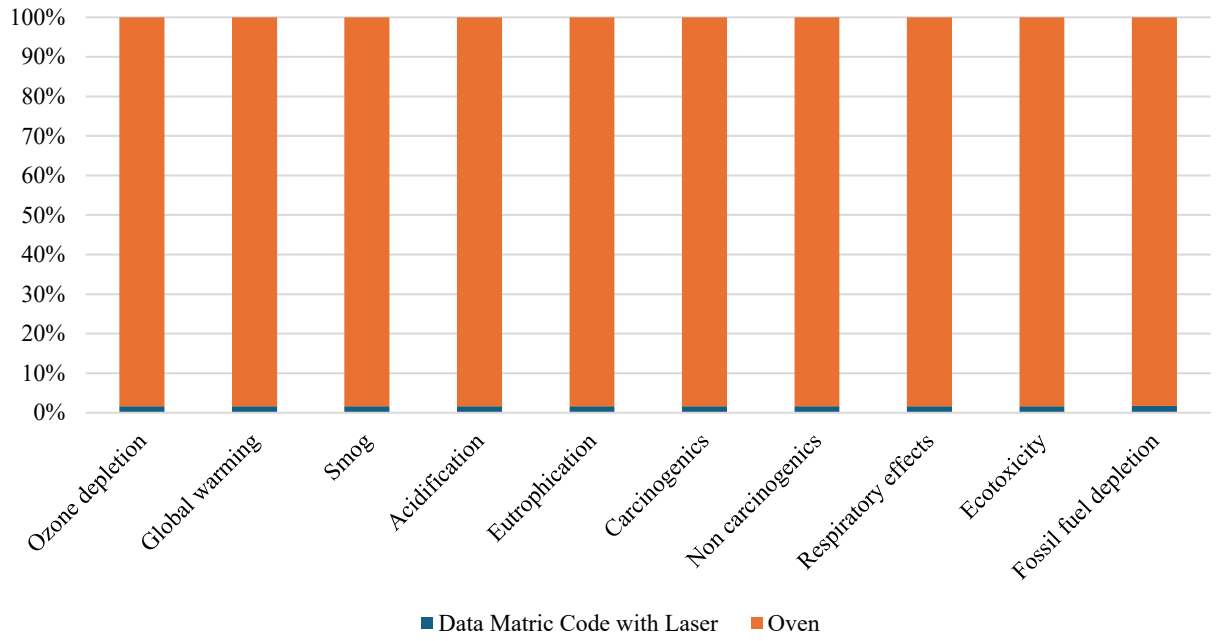

Fig. S15. Contribution of process energy and material flows in the first preparation loop stage using Pytorch's three-level ANFIS model.

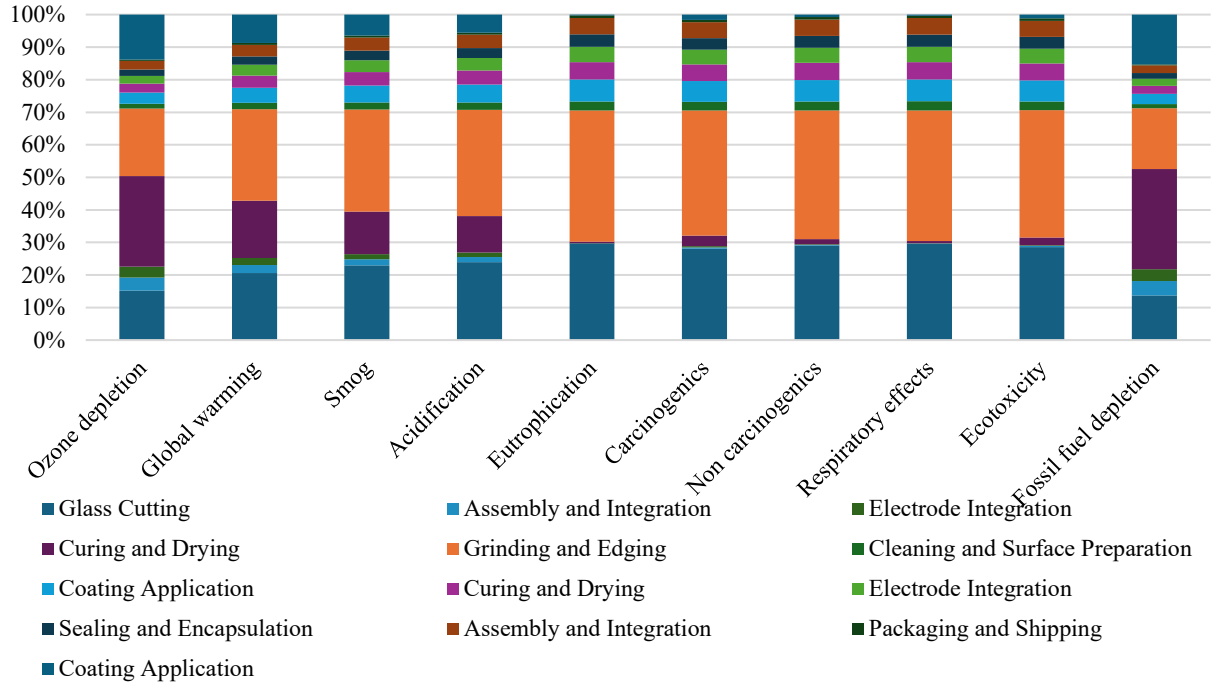

Fig. S16. Contribution of process energy and material flows in the second and third preparation loop stage using Pytorch's three-level ANFIS model.

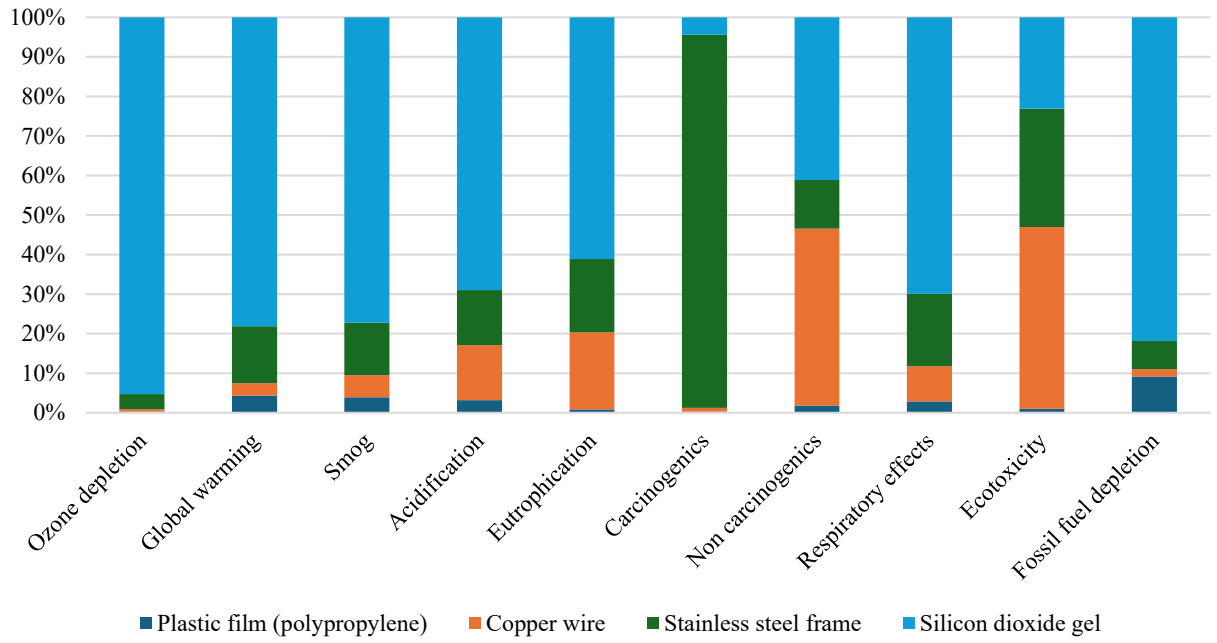

Fig. S17. Contribution of process energy and material flows in the frame design stage using Pytorch's three-level ANFIS model.

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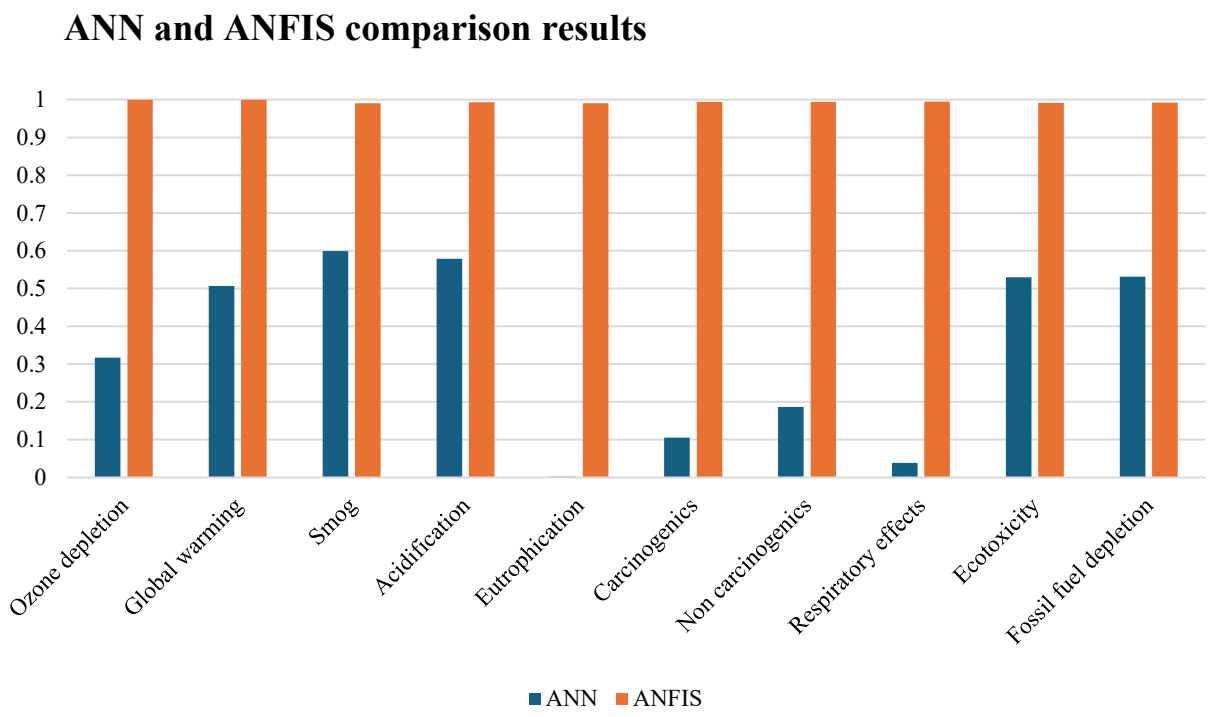

Fig. S18. Comparison of coefficient of determination in ANN and ANFIS modeling methods for energy output and environmental impacts of electrochromic preparation stage.

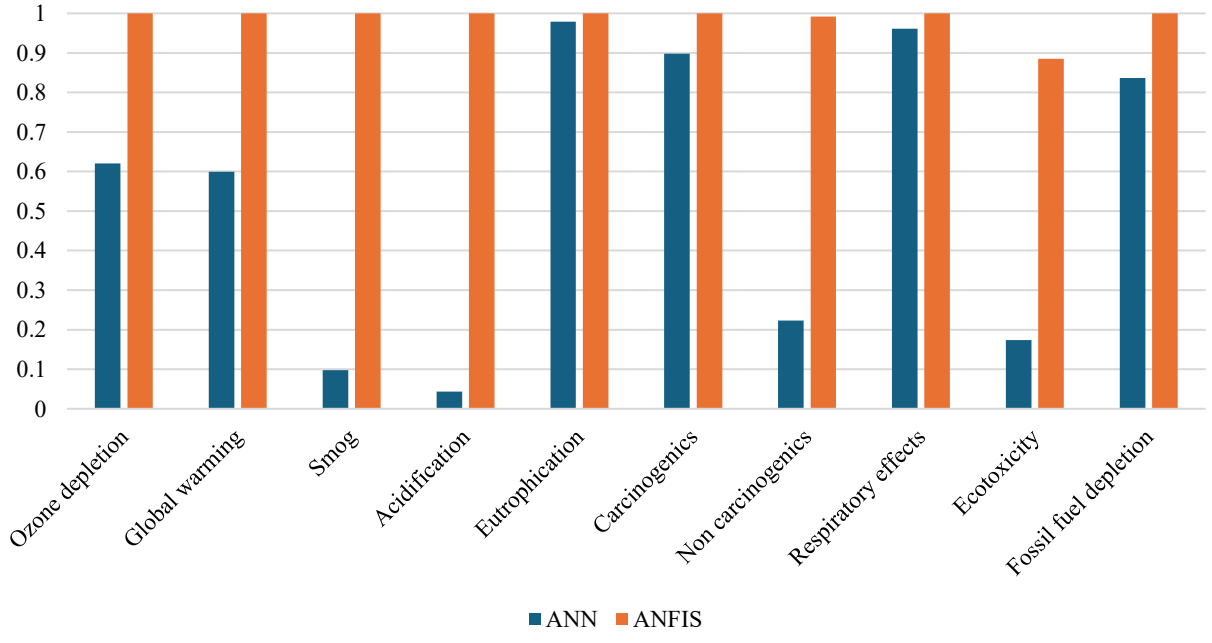

Fig. S19. Comparison of coefficient determination in ANN and ANFIS modeling methods for energy output and environmental impacts of hot coater stage.

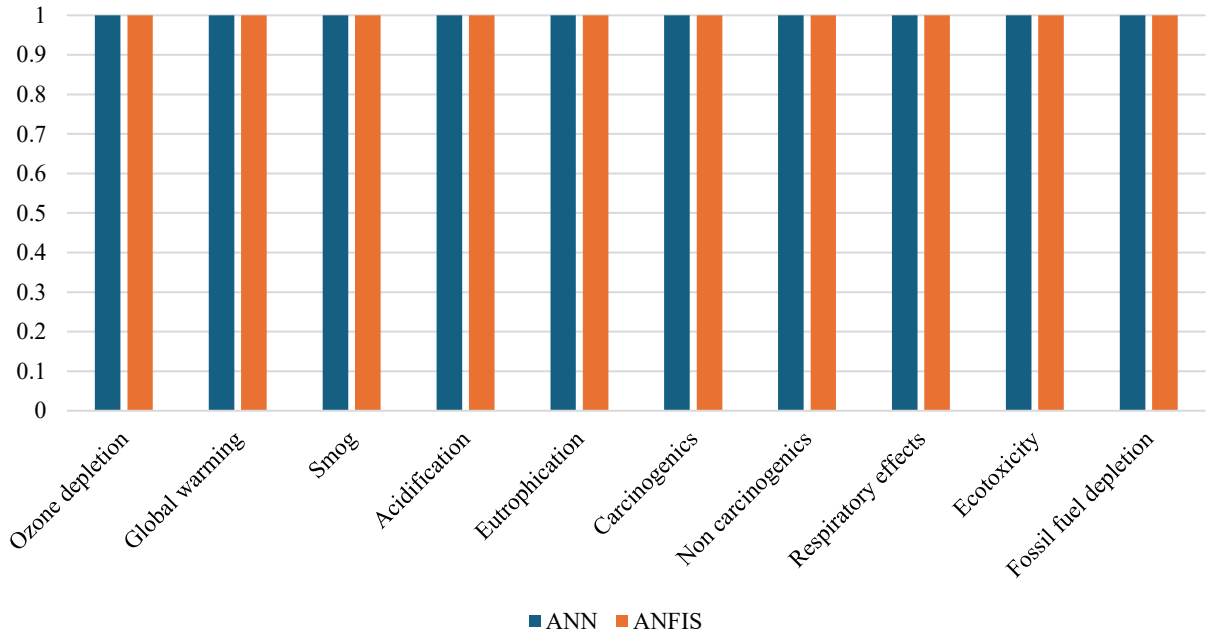

Fig. S20. Comparison of coefficient of determination in ANN and ANFIS modeling methods for energy output and environmental impacts of first preparation loop stage.

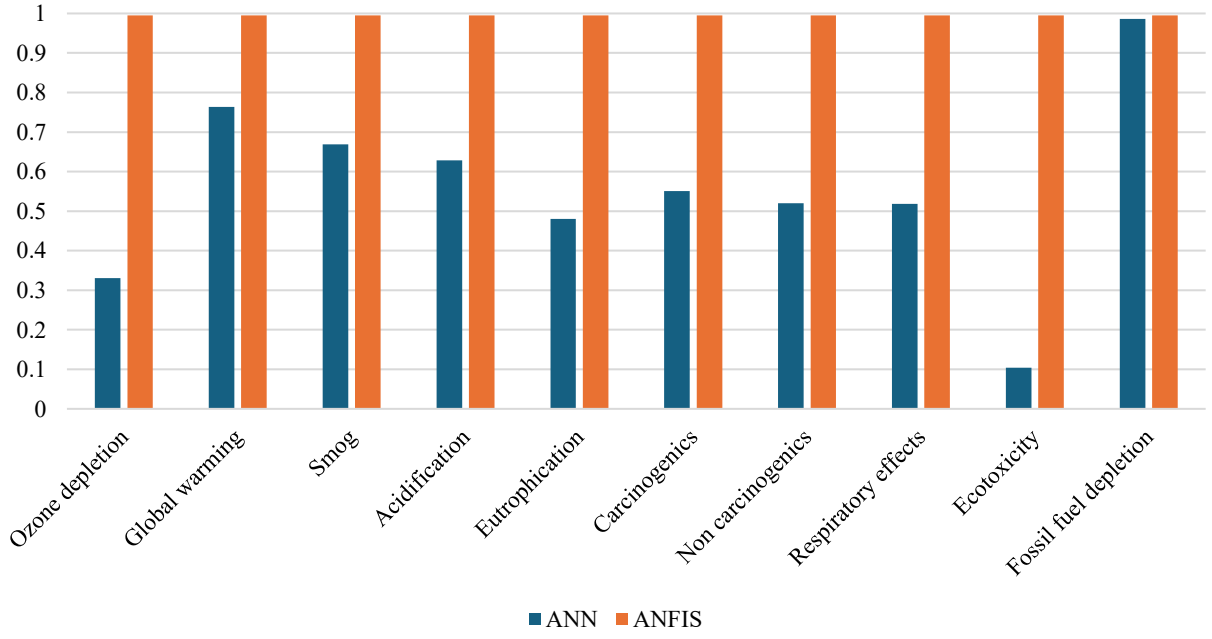

Fig. S21. Comparison of coefficient of determination in ANN and ANFIS modeling methods for energy output and environmental impacts of second and third preparation loop stage.

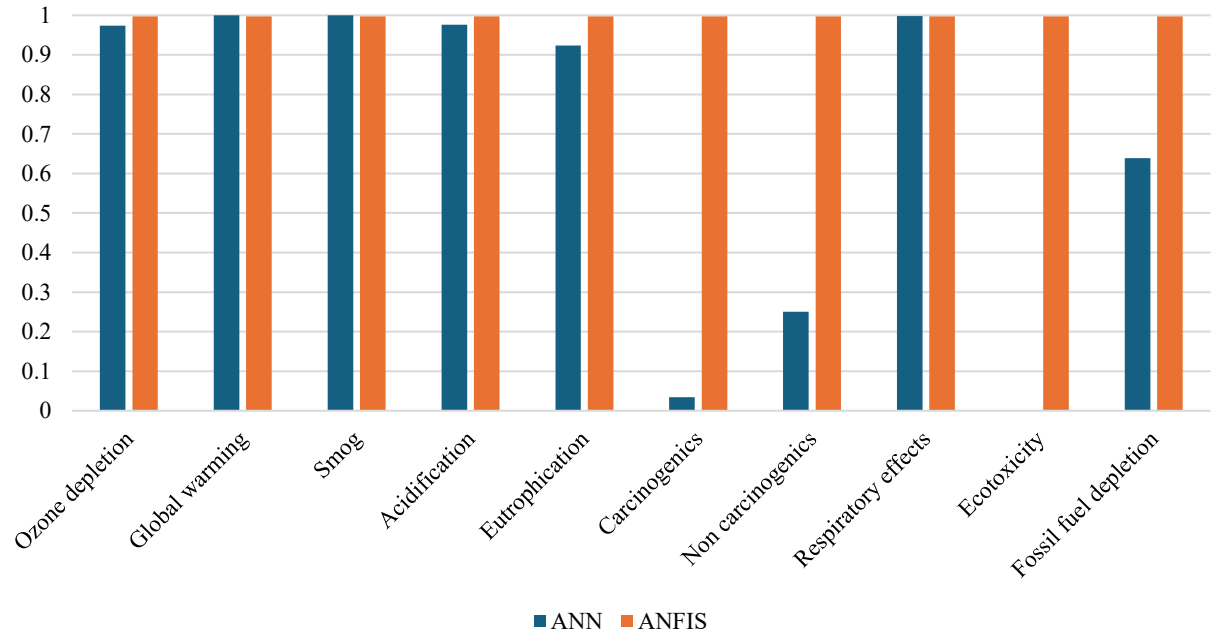

Fig. S22. Comparison of coefficient of determination in ANN and ANFIS modeling methods for energy output and environmental impacts of frame design stage.