Supplementary Materials: Environmental and Economic Performance of a Li-Ion Battery Pack. A Multiregional Input-Output Approach

Javier Sanfélix, Cristina de la Rúa, Jannick Hoejrup Schmidt, Maarten Messagie and Joeri Van Mierlo

Introduction to Input-Output Analysis

Input-output analysis estimates the direct and indirect effects on the economy associated to a change in the final demand of goods and services, and it permits to know the distribution by activity sector of an industry's output through the economy. The operations included in an input-output analysis contain, in an aggregated way, the total production account of the economy of a certain region, and normally, also the imported accounts.

Input-output tables are derived from the supply and use tables. These tables are matrices describing the values of transactions in products and services for the national or regional economy categorized by product type and industry. A supply table shows which industries supply the different goods and services distinguishing between domestic and imports supply. Table S1 shows a simplified version of a supply table.

Table S1. Schematic outline of a supply table.

Supplies		**Producing Industries**		**Rest of the World**	**Total**
		1	2		
Products	1	Output of product 1 by industry 1	Output of product 1 by industry 2	Import values of product 1	Total supply of product 1
Total		Total output of industry 1	Total output of industry 2	Total imports	Total supply

As it can be noticed in Table S1, the different industries are shown in columns, while the products are described in the rows. Thus, from the rows it is possible to see which industries produce product 1, and in the columns it is possible to see all the products produce by the different industries.

A use table is centered in the consumption matrix, which allows observing the amount consumed at a basic price by producing industry and product. It shows the use of goods and services categorized by product and by type of use. In other words, it indicates how much is allocated to intermediate consumption, final consumption, capital creation and exports. Table S2 shows a simplified use table.

Table S2. Schematic outline of a use table.

Uses		**Industries**	**Final Consumption**	**Gross Capital Formation**	**Rest of the World**	**Total**
		1				
Products	1	Intermediate consumption by product and industry			Exports	Total use by products
Total		Total intermediate consumption by industry	Final consumption	Gross capital formation	Total exports	Total use
Components of value added		Compensation of employees; Other taxes less subsidies; Net operating surplus; Consumption of fixed capital				

The supply and use tables are the base to create the symmetric input-output table that allows observing production relations of the economic sectors or activities. Supply and use tables are not symmetric, since there are industries that provide more than one good and/or service and there are goods and/or services that are produced by different industries.

The symmetric table is conformed as a matrix in which the producing industries are in the rows and columns, with the fluxes in basic prices. In order to create the symmetric table the following transformations have to be applied to the use table [1]:

1. convert the table in basic prices,
2. convert the producing industries in homogeneous industries,
3. aggregate the products in the rows to create the homogeneous industries identic to the ones listed in the columns.

In order to apply the mentioned steps, one of the following hypothesis has to be taken:

1. product technology: it is assumed that every product is produced with the same technology independently of the industry in which it is produced, thus, it requires the same consumables for its production.
2. industry technology: it is assumed that each industry of the table produces its different products with the same technology.

Table S3 shows a simplified input-output table. The matrix shows how supply matches uses via an industry-by-industry categorization of output and the detailed transactions of intermediate consumption and final uses.

Table S3. Schematic outline of a symmetric input-output table.

		Homogenized Industry	**Final Consumption**	**Gross Capital Formation**	**Rest of the World**	**Total**
		1				
Homogenized industry	1	Intermediate consumption	Final consumption of households, NPISHs [1] and government	Gross capital formation	Exports	Total use
Totals		Total supply			Total exports	Total use
Components of value added						
Rest of the world		Imports				
Total						

[1] NPISH—Non-Profit Institutions Serving Households.

An input-output table can have two alternative readings: columns show how products are used as intermediate consumption to make products, this is the production costs, and rows show how the outputs of industry are used in the intermediate consumption of other industries to create the industrial output, this is the distribution of the production among the sectors. Now that the origin of the input-output table has been expounded, hereunder the mathematical structure of an input-output model is described. Table S4 shows again the structure of an input-output table.

Table S4. Structure of an input-output table.

	Input to Sectors (*j*)				**Final Demand Y**	**Total Output X**
Output from sectors (*i*)	1	2	3	n		
1	x_{11}	x_{12}	x_{13}	x_{1n}	y_1	X_1
2	x_{21}	x_{22}	x_{23}	x_{2n}	y_2	X_2
3	x_{31}	x_{32}	x_{33}	x_{3n}	y_3	X_3
n	x_{n1}	x_{n2}	x_{n3}	x_{nn}	y_n	X_n
Intermediate input I	I_1	I_2	I_3	I_n		
Value added V	V_1	V_2	V_3	V_n	GDP	
Total input X	X_1	X_2	X_3	X_n		

where:

x_{ij} are the inputs to industrial sector j from sector *i*

y_i is the final demand of each sector *i*

X_i is the total output for each sector *i*

V_j is the difference between total output X_j and intermediate input I_j

Thus, the total production by sector 1 is given by Equation (S1).

$$X_1 = x_{11} + x_{12} + x_{13} + \cdots + x_{1n} + y_1 \quad \text{(S1)}$$

For calculation purposes another matrix has to be calculated. Known as the matrix of technical coefficients, it represents the inputs that one sector requires from other sectors to produce one monetary unit of output. The technical coefficients, a_{ij}, are calculated using Equation (S2).

$$\boldsymbol{a_{ij} = \frac{x_{ij}}{X_j}} \quad \text{(S2)}$$

Therefore, a_{ij} is the need that sector *j* has of the products from sector *i* to produce one unit of the product *j*. Equation (S3) can also be expressed as:

$$x_{ij} = a_{ij} \cdot X_j \quad \text{(S3)}$$

If Equation (S3) is substituted in Equation (S1), the total production of a sector is defined as:

$$X_1 = a_{11} \cdot X_1 + a_{12} \cdot X_2 + a_{13} \cdot X_3 + \cdots + a_{1n} \cdot X_n + y_1 \quad \text{(S4)}$$

If Equation (S4) is expanded to the different industry sectors:

$$X_1 = a_{11} \cdot X_1 + a_{12} \cdot X_2 + \cdots + a_{1n} \cdot X_n + y_1$$
$$X_2 = a_{21} \cdot X_1 + a_{22} \cdot X_2 + \cdots + a_{2n} \cdot X_n + y_2$$
$$X_n = a_{n1} \cdot X_1 + a_{n2} \cdot X_2 + \cdots + a_{nn} \cdot X_n + y_n$$

Defining the matrix of technical coefficients A which contains all the terms a_{ij}:

$$\begin{pmatrix} X_1 \\ X_2 \\ \dots \\ X_n \end{pmatrix} = \begin{pmatrix} a_{11} a_{12} \dots a_{1n} \\ a_{21} a_{22} \dots a_{2n} \\ \dots \dots \dots \dots \\ a_{n1} a_{n2} \cdots a_{nn} \end{pmatrix} \cdot \begin{pmatrix} X_1 \\ X_2 \\ \dots \\ X_n \end{pmatrix} + \begin{pmatrix} y_1 \\ y_2 \\ \dots \\ y_n \end{pmatrix} \rightarrow X = A \cdot X + Y \quad \text{(S5)}$$

By definition A is a non-negative matrix with $a_{ij} \geq 0$ for all *i* and *j* ($A \geq 0$), and each of the column sums is less than one ($\sum_{i=1}^{n} a_{ij} < 1$ for all j) [2].

If we bring all X terms to the left,

$$X_1 - a_{11} \cdot X_1 - a_{12} \cdot X_2 - \cdots - a_{1n} \cdot X_n = y_1$$
$$X_2 - a_{21} \cdot X_1 - a_{22} \cdot X_2 - \cdots - a_{2n} \cdot X_n = y_2$$
$$X_n - a_{n1} \cdot X_1 - a_{n2} \cdot X_2 - \cdots - a_{nn} \cdot X_n = y_n$$

and grouping the X_1 together in the first equation, the X_2 in the second equation, and so on, the final demand can be expressed for the different sectors:

$$(1 - a_{11}) \cdot X_1 - a_{12} \cdot X_2 - \cdots - a_{1n} \cdot X_n = y_1 \quad \text{(S6)}$$
$$-a_{21} \cdot X_1 + (1 - a_{22}) \cdot X_2 - \cdots - a_{2n} \cdot X_n = y_2$$
$$-a_{n1} \cdot X_1 - a_{n2} \cdot X_2 - \cdots + (1 - a_{nn}) \cdot X_n = y_n$$

Being I the identity matrix *n x n* and considering the technical coefficient matrix A:

$$I = \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix} \quad \text{so then } (I - A) = \begin{pmatrix} (1 - a_{11}) & -a_{12} & \dots & -a_{1n} \\ -a_{21} & (1 - a_{22}) & \dots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \dots & (1 - a_{nn}) \end{pmatrix}$$

Then

$$(I - A) \cdot X = Y$$
$$\text{thus } X = (I - A)^{-1} \cdot Y \quad \text{(S7)}$$

which represents the required economic purchases, direct and indirect, of a country or region to cover a final demand. The term $(I\text{-}A)^{-1}$ is the Leontief inverse matrix which represents all the direct and

indirect requirements in the supply chain. For input-output coefficient matrix (A) with the two characteristics mentioned above ($a_{ij} \geq 0$ and $\sum_{i=1}^{n} a_{ij} < 1$ for all j) Equation (S7) can also be expressed by:

$$X = (I - A)^{-1} \cdot Y = (I + A + A^2 + A^3 + \cdots) \cdot Y \quad \text{(S8)}$$

The different terms of Equation (S8) represents the production of the desired output or final demand (I·Y), the contributions from the first suppliers level (A·Y), the second indirect suppliers level (A^2·Y), etc. [3]. The term $(I-A)^{-1}$ is the Leontief inverse matrix that describes the direct and indirect requirements of the supply chain required to satisfy one unit of final demand Y.

Table S5. List of economic activity sectors included in the WIOD and its code.

Code	Economic Activity Sector
AtB	Agriculture, Hunting, Forestry and Fishing
C	Mining and Quarrying
15t16	Food, Beverages and Tobacco
17t18	Textiles and Textile Products
19	Leather, Leather and Footwear
20	Wood and Products of Wood and Cork
21t22	Pulp, Paper, Paper , Printing and Publishing
23	Coke, Refined Petroleum and Nuclear Fuel
24	Chemicals and Chemical Products
25	Rubber and Plastics
26	Other Non-Metallic Mineral
27t28	Basic Metals and Fabricated Metal
29	Machinery, Nec
30t33	Electrical and Optical Equipment
34t35	Transport Equipment
36t37	Manufacturing, Nec; Recycling
E	Electricity, Gas and Water Supply
F	Construction
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
H	Hotels and Restaurants
60	Inland Transport
61	Water Transport
62	Air Transport
63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
64	Post and Telecommunications
J	Financial Intermediation
70	Real Estate Activities
71t74	Renting of M&Eq and Other Business Activities
L	Public Admin and Defence; Compulsory Social Security
M	Education
N	Health and Social Work
O	Other Community, Social and Personal Services
P	Private Households with Employed Persons

Table S6. Assignation of inventory components to industrial sectors in the manufacturing of cells.

Component		Activity sector		
	Name	**Code**	**Name**	**Country**
Anode	Graphite	C	Mining and Quarrying	FN
	Conductive additive	C	Mining and Quarrying	FN
	Binder	25	Rubber and Plastics	FN
	Solvent	24	Chemicals and Chemical Products	FN
	Negative substrate	27t28	Basic Metals and Fabricated Metal	FN
Cathode	LiFePO4	24	Chemicals and Chemical Products	FN
	Conductive additive	C	Mining and Quarrying	FN
	Binder	25	Rubber and Plastics	FN
	Solvent	24	Chemicals and Chemical Products	FN
	Positive substrate	27t28	Basic Metals and Fabricated Metal	FN
	Separator	25	Rubber and Plastics	FN
Elect.	LPF6	24	Chemicals and Chemical Products	FN
	Solvent	24	Chemicals and Chemical Products	FN
Cell container	Aluminium tab	27t28	Basic Metals and Fabricated Metal	FN
	Copper tab	27t29	Basic Metals and Fabricated Metal	FN
	Aluminium	27t28	Basic Metals and Fabricated Metal	FN
	PETP	25	Rubber and Plastics	FN
	Oriented nylon	25	Rubber and Plastics	FN
	Polypropylene	25	Rubber and Plastics	FN
	Packaging film	25	Rubber and Plastics	FN
	Electricity	E	Electricity, Gas and Water Supply	FN
	Transport by rail	60	Inland Transport	FN
	Transport by road	60	Inland Transport	FN

Table S6. Assignation inventory components to industrial sectors in the manufacturing of BCU.

Component		Activity sector		
	Name	**Code**	**Name**	**Country**
BMS	Circuit board	30t33	Electrical and Optical Equipment	FR
	Copper	27t28	Basic Metals and Fabricated Metal	FR
	Steel	27t28	Basic Metals and Fabricated Metal	FR
DC/DC converter	Inverter board	30t33	Electrical and Optical Equipment	FR
	Capacitor	30t33	Electrical and Optical Equipment	FR
	Rectifier board	30t33	Electrical and Optical Equipment	FR
	Transformer	30t33	Electrical and Optical Equipment	FR
	Inductance (self)	30t33	Electrical and Optical Equipment	FR
	Wires	30t33	Electrical and Optical Equipment	FR
	Aluminium plate	27t28	Basic Metals and Fabricated Metal	FR
	Electricity	E	Electricity, Gas and Water Supply	FR
	Transport by rail	60	Inland Transport	FR
	Transport by road	60	Inland Transport	FR

Table S7. Assignation inventory components to industrial sectors in the manufacturing of the modules.

Component		Activity sector		
	Name	**Code**	**Name**	**Country**
Module case	Adhesive	20	Manufacture of chemicals and chemical products	BE
	Connection	26	Manufacture of computer, electronic and optical products	BE
	Cooling plate	24	Manufacture of basic metals	BE
	Cover frame	22	Manufacture of rubber and plastic products	BE
	Foam (EPDM)	22	Manufacture of rubber and plastic products	BE
	Foam (PUR)	22	Manufacture of rubber and plastic products	BE
	Frame	22	Manufacture of rubber and plastic products	BE
	Plate	24	Manufacture of basic metals	BE
	Plate_pres	24	Manufacture of basic metals	BE
	Protection cap	22	Manufacture of rubber and plastic products	BE
	Slide bar	22	Manufacture of rubber and plastic products	BE
	Tie rod	24	Manufacture of basic metals	BE
	Cap	22	Manufacture of rubber and plastic products	BE
	Washers	24	Manufacture of basic metals	BE
	Bolts	24	Manufacture of basic metals	BE
	Pin	24	Manufacture of basic metals	BE
	Nuts	24	Manufacture of basic metals	BE
	Thread insert	24	Manufacture of basic metals	BE
	Electricity	35	Electricity, gas, steam and air conditioning supply	BE
	Transport by rail	49	Land transport and transport via pipelines	BE
	Transport by road	49	Land transport and transport via pipelines	BE

Table S8. Assignation inventory components to industrial sectors in the recycling stage.

Component		Activity sector		
	Name	Code	Name	Country
Inputs	Reagent	20	Manufacture of chemicals and chemical products	BE
	Industrial water	36	Water collection, treatment and supply	BE
	H2SO4 (92%)	20	Manufacture of chemicals and chemical products	BE
	Lime	20	Manufacture of chemicals and chemical products	BE
Outputs	Lithium salt (LiCO3)	20	Manufacture of chemicals and chemical products	BE
	Steel	24	Manufacture of basic metals	BE
	Aluminium	24	Manufacture of basic metals	BE
	Copper	24	Manufacture of basic metals	BE
	Water to sewer	37-39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	BE
	Plastic	22	Manufacture of rubber and plastic products	BE
	Residue	37-39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	BE
	Gypsum (CaSO4, H2O)	37-39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	BE
	Electricity	35	Electricity, gas, steam and air conditioning supply	BE
	Transport by road	49	Land transport and transport via pipelines	BE

Table S9. Top 5 economic activity sectors contributing to each of the total impacts assessed. The list of codes with the corresponding economic activity sector is included in Table S1.

Global Warming Potential [g CO2 eq / km]

Manufacturing			Use			Recycling			Total		
Sector	Impact	%	Sector	Impact	%	Sector	Impact	%	Sector	Impact	%
E	15.07	36.73	E	30.81	89.48	27t28	-5.66	31.58	E	42.41	73.70
24	8.37	20.40	C	1.40	4.07	C	-3.84	21.43	24	6.52	11.34
C	5.76	14.03	23	0.39	1.14	E	-3.47	19.39	C	3.32	5.77
27t28	5.17	12.61	27t28	0.34	0.99	24	-1.98	11.05	23	1.45	2.52
60	1.58	3.86	60	0.33	0.96	60	-0.60	3.33	60	1.32	2.30

Terrestral Acidification [g SO2 eq / km]

Manufacturing			Use			Recycling			Total		
Sector	Impact	%	Sector	Impact	%	Sector	Impact	%	Sector	Impact	%
E	0.037	32.93	E	0.044	80.47	E	-0.017	30.82	E	0.064	57.12
24	0.024	21.05	AtB	0.003	5.11	27t28	-0.013	24.66	24	0.020	17.55
AtB	0.011	10.17	23	0.002	2.92	AtB	-0.006	11.39	AtB	0.008	7.12
27t28	0.011	9.69	C	0.001	2.62	24	-0.004	7.75	C	0.006	5.27
C	0.009	7.70	60	0.001	2.31	C	-0.004	7.60	60	0.005	4.14

Photochemical Oxidation Formation [g NMVOC / km]

Manufacturing			Use			Recycling			Total		
Sector	Impact	%	Sector	Impact	%	Sector	Impact	%	Sector	Impact	%
23	0.054	27.11	E	0.035	55.78	27t28	-0.024	27.77	E	0.059	33.48
24	0.046	22.94	23	0.014	21.65	23	-0.018	20.75	23	0.050	28.24
E	0.030	15.14	C	0.003	4.87	24	-0.012	13.85	24	0.035	19.83
C	0.018	9.03	60	0.003	4.36	C	-0.008	9.29	C	0.013	7.41
27t28	0.015	7.39	27t28	0.001	2.22	E	-0.006	7.49	60	0.010	5.90

Particulate Matter [g PM10 eq / km]

Manufacturing			Use			Recycling			Total		
Sector	Impact	%	Sector	Impact	%	Sector	Impact	%	Sector	Impact	%
E	9.8E-03	33.61	E	1.2E-02	81.18	E	-3.9E-03	28.70	E	1.8E-02	58.90
24	5.6E-03	19.23	AtB	5.0E-04	3.39	27t28	-3.6E-03	26.06	24	4.7E-03	15.40
27t28	2.7E-03	9.36	60	4.9E-04	3.35	AtB	-1.1E-03	7.97	60	1.8E-03	6.01
C	2.4E-03	8.24	23	3.8E-04	2.57	24	-1.1E-03	7.82	C	1.8E-03	5.95
60	2.3E-03	7.71	C	3.5E-04	2.37	C	-9.6E-04	7.00	AtB	1.4E-03	4.62

Economic Impact [€/km]

Manufacturing			Use			Recycling			Total		
Sector	Impact	%	Sector	Impact	%	Sector	Impact	%	Sector	Impact	%
24	1.9E-02	23.82	E	1.6E-02	57.58	27t28	-1.9E-02	44.67	E	2.1E-02	30.34
27t28	1.4E-02	17.48	71t74	2.8E-03	9.81	24	-5.3E-03	12.51	24	1.4E-02	21.28
C	9.0E-03	10.99	F	1.1E-03	3.99	71t74	-2.9E-03	6.72	C	7.6E-03	11.19
71t74	5.4E-03	6.59	C	9.4E-04	3.28	C	-2.3E-03	5.48	71t74	5.3E-03	7.87
E	5.0E-03	6.09	27t28	8.4E-04	2.92	51	-2.0E-03	4.64	25	2.8E-03	4.13

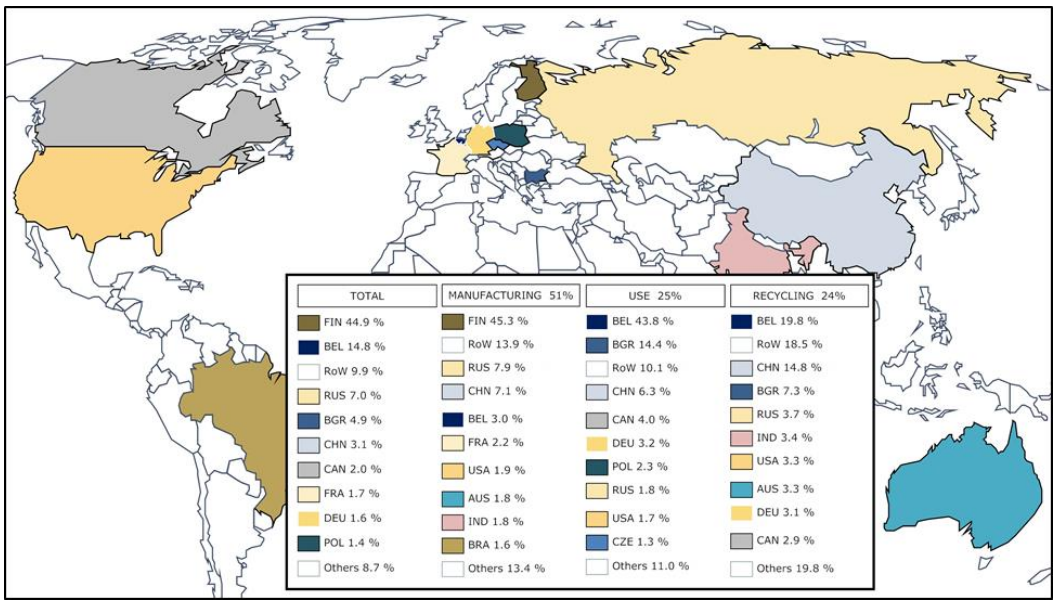

Figure S1. Geographical resolution and country contribution to Terrestrial Acidification of the life cycle stages of the ESS.

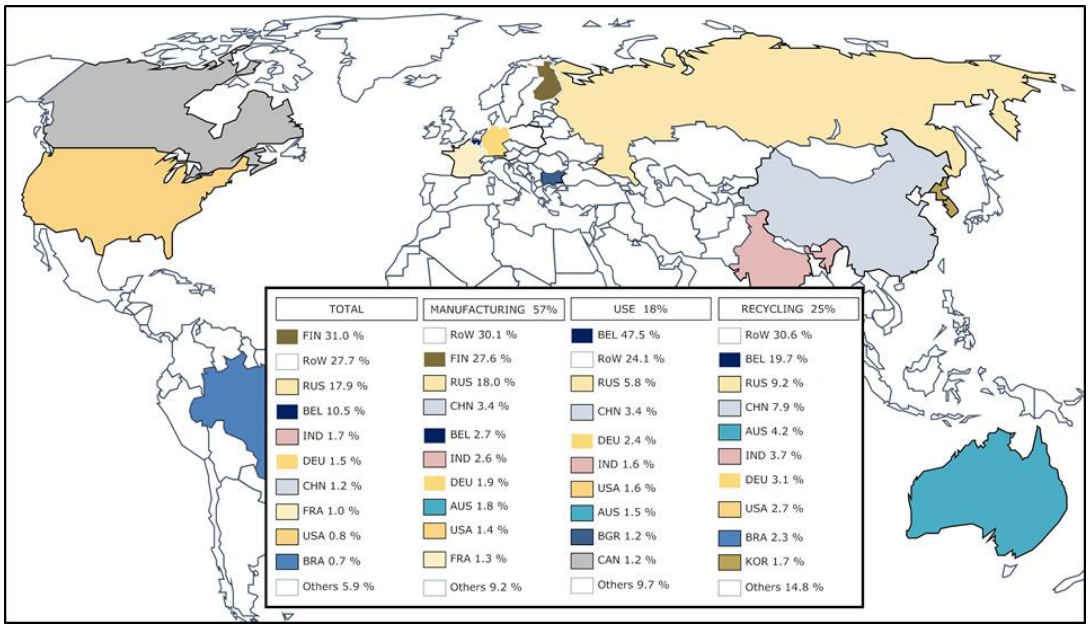

Figure S2. Geographical resolution and country contribution to Photochemical Oxidation Formation of the life cycle stages of the ESS.

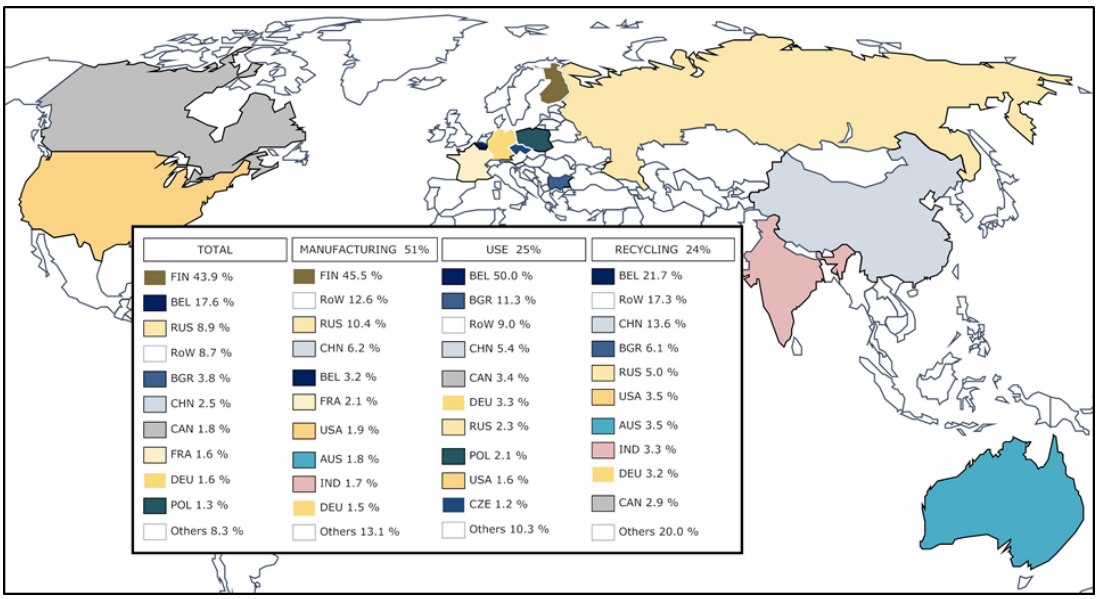

Figure S3. Geographical resolution and country contribution to Particulate Matter Formation of the life cycle stages of the ESS.

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