Evaluation of Environmental impacts of a perovskite solar cell prototype with a p-i-n meso – superstructured architecture trough life cycle assessment

Camilo Andrés Valderrama Benítez[1, *], Francisco José Molina Péreza[1, §,], , Juan Felipe Montoya Arango[2,3], Diana Catalina Rodríguez[4] , Aída Luz Villa[5], Jaume-Adrià Alberola-Borràs[6]

[1]Grupo de Investigación en Gestión y Modelación Ambiental (GAIA), Facultad de ingeniería, Escuela ambiental, Universidad de Antioquia, Calle 70 No. 52-21, Medellín, Colombia, 050010.

[2]Grupo Centro de Investigación, Innovación y Desarrollo de Materiales (CIDEMAT), Facultad de ingeniería, Departamento de ingeniería de materiales, Universidad de Antioquia, Medellín, Calle 70 No. 52-21, Medellín, Colombia, 050010.

[3]Grupo de Catalizadores y Adsorbentes (CATALAD), Instituto de Química, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia UdeA, Medellín 500001, Colombia

[4]Grupo Diagnóstico y Control de la Contaminación (GDCON), Facultad de ingeniería, Escuela ambiental, Universidad de Antioquia, Calle 70 No. 52-21, Medellín, Colombia, 050010.

[5]Grupo Catálisis Ambiental, Facultad de ingeniería, Departamento de ingeniería de química, Universidad de Antioquia, Calle 70 No. 52-21, Medellín, Colombia, 050010.

[6]Institute of Advanced Materials (INAM), Universitat Jaume I, Av. Vicent Sos Baynat, s/n, Castelló de la Plana, 12071 Spain

*Corresponding author. E-mail: candres.valderrama@udea.edu.co; francisco.molina@udea.edu.co

Supporting material.

The supporting material comprises a total of 13 pages with 7 tables.

This document includes:

- Supplementary methods.
- Complementary results.
- Supplementary references

Supplementary Information S1: Life Cycle Analysis Methodology

Life cycle analysis is an objective process that assesses the environmental burdens associated with a product, activity, or process by identifying the energy, materials used, and emissions released into the environment. This allows for comparison and evaluation of opportunities for environmental improvements, all defined under the International Organization for Standardization (ISO) standards, ISO 14040 and ISO 14044.

The compared perovskite solar cells have the following characteristics:

The prototype by Ramirez *et al*.[1] features an architecture comprising a glass coated with indium tin oxide (ITO) as the front electrode layer, a nickel oxide (NiOx) layer as the hole transport layer, a mesoporous aluminum oxide (Al_2O_3) support layer, a perovskite layer (methylammonium lead halide), a PCBM layer coated with rhodamine 101 as the electron transport layer, and finally, a silver electrode layer as the back electrode. This perovskite solar cell (PSC) was designated as C1.

The information for the second, third, fourth, and fifth PSCs was taken from Alberola *et al*.[2], which consisted of standard layers. For the front electrode layer, fluorine-doped tin oxide (FTO) coated glass was used; titanium dioxide (TiO_2) was used for the electron transport layer; Spiro-MeOTAD was used for the hole transport layer; and a gold cathode was used for the back electrode layer. However, although the halide perovskite absorber layer was used, it varied in each cell according to the deposition method used.

The technical specifications considered for the PSCs are shown in the following table:

Table S1. Specifications of the studied perovskite solar cells

Variable	Unit	C1	C2	C3	C4	C5
Insolation constant	kWh /m^2 – year			1700		
Cell efficiency	%	15	11.4	10.4	15	12.3
Module performance ratio (PR)	%			75		
Lifetime (LT)	years			5		
Configuration		Mesoporous	Planar	Planar	Planar	Mesoporous
Architecture		PIN			NIP	

The parameters considered were active area, conversion efficiency, lifespan, and module performance ratio, as reported in the literature. [3,4] The lifetime was set at 5 years, as this is the minimum number of years required for 1 cm² of PSCs to produce 1 kWh. This was calculated as reported by Monteiro *et al*.[5]:

$$A = \frac{\varepsilon}{I \times n \times PR \times LT} \quad (1)$$

Where:

ε : required energy (1 kWh).

I : Insolation constant (kWh /m^2 – año).

n : Module efficiency (%).

PR: Module performance ratio (%).

LT: Lifetime of photovoltaic technology (year)

A: Area (≤ 0.001 m^2).

Supplementary Information S2: Life Cycle Analysis Inventory

For the C1 cell inventory, primary information was provided by the CIDEMAT laboratory at the Universidad de Antioquia. The entire production process was taken from Ramírez *et al*.[1]. who fabricated solar cells on glass substrates with indium tin oxide (ITO, Naranjo substrates) films. The substrates underwent selective ITO removal via laser (P1), allowing for the fabrication of devices with active areas ranging from 0.09 to 2 cm². For this work, the material and energy inventory were considered for cells with an active area of 1 cm². The cell fabrication begins with cleaning the ITO substrates with neutral soap and sequential immersion in an ultrasonic bath in deionized water, acetone, and isopropanol for five minutes each, totaling 15 minutes. Then, a surface treatment with ultraviolet ozone was performed for 15 minutes at 100 °C. The hole transport layer (HTL) consists of NiOx nanoparticles synthesized using the chemical precipitation method reported by Ciro *et al*.[6] and Zhang *et al*.[7]. The NiOx nanoparticles (5 nm) were dispersed in deionized water at a concentration of 23 mg/mL, and sequentially subjected to high-speed mechanical stirring and ultrasound for 5 minutes each. Finally, NiOx films were deposited by spin-coating at 3000 rpm for 30 seconds. The mesoporous Al_2O_3 support layer was deposited by spin-coating a commercial dispersion of alumina nanoparticles (Aldrich). The dispersion was diluted in isopropanol (IPA) in a volume ratio of 1:3 (dispersion:IPA) to produce 100 nm films (this substance was not considered in the inventory for this layer in this study). The Al_2O_3 layers were deposited by dynamic spin-coating at 4000 rpm for 30 seconds using 100 µL of dispersion. These films were dried overnight under ambient conditions. To obtain a hybrid perovskite layer of 240 ± 10 nm, a precursor solution of methylammonium lead iodide ($CH_3NH_3PbI_3$) at a concentration of 27% by weight was deposited. The solution was prepared from $CH_3NH_3PbI_3$ perovskite powder previously prepared from a mixture of methylammonium iodide (Dyesol, code MS101000) and lead iodide (PbI2, Alfa Aesar, ref. 12724) in acetonitrile. The CH3NH3PbI3 perovskite ink was obtained by dispersing the powder in a solvent mixture of methylamine and acetonitrile at a concentration of 27% by weight of solids. The layers were deposited by spin-coating at 4000 rpm for 30 seconds. Subsequently, the films were thermally treated at 100 °C for 10 minutes. The PCBM (1-Material) was deposited by dynamic spin-coating a solution of 20 mg/mL in chlorobenzene (CB) at 2000 rpm for 30 seconds. Subsequently, a thermal treatment was performed at 65 °C for 5 minutes. Rhodamine 101 was deposited on top of the PCBM layer by dynamic spin-coating a 0.5 mg/mL solution in anhydrous ethanol at 4000 rpm for 30 seconds (this was not considered in the inventory). Finally, to complete the PSC, 80 nm silver electrodes were thermally evaporated under vacuum (≈10^{-6} mbar) at a deposition rate of around ≈0.1 nm/s.

In the case of the required energy, direct measurements of consumption could not be made. However, it was calculated using the information provided by the manufacturers of the equipment used in the PSC synthesis process, such as current and voltage. Additionally, the equipment's operation time and the usage factor, defined as the volume of manufacturing material required for a device of 1 cm² divided by the equipment's maximum capacity, were considered, as outlined in various studies.[8,9,10] The values taken are shown in **Table S2**. Primary information is marked with a superscript symbol (*). If this information could not be obtained, literature information was used, with the superscript corresponding to the respective research: García-Valverde *et al*.[8], ϰ; Zhang *et al*. [10, ɣ]; Alberola-Borràs *et al*. [2,ϙ].

Table S2. Equipment and Energy Use for the Synthesis of the 1 cm² Perovskite Solar Cell Developed by Ramirez *et al*.[1],

Deposition Layer	Process - Method	Equipment	Voltage (Volts)	Current (Amps)	Time (min)	Usage Factor for 1 cm² (%)	Energy (kWh)
FEL / ITO	Laser Patterning	20W Triumph MOPA fiber laser	-	-	2	-	4.17E-05*
	Ultraviolet Ozonation	OES -1000D – OZONE elimination system /novascan	220	5	15	0.19	5.20E-04*
	Ultrasonication	1510 Branson	120	2	15	0.714	4.29E-04*

Deposition Layer	Process - Method	Equipment	Voltage (Volts)	Current (Amps)	Time (min)	Usage Factor for 1 cm² (%)	Energy (kWh)
HTL / NiOx	Magnetic Stirrer	Benchmark - mixer	120	1.5	5	0.29	1.81E-06 [ϰ]
	Ultrasonication	1510 Branson	120	2	30	0.029	3.46E-05 [*]
	Spin Coating	Laurell: Model ws – 650 MZ – 8NPP 00	240	1	0.5	0.15	3.00E-06 [ϰ]
MSL/Al_2O_3	Spin Coating	Laurell: Model ws – 650 MZ – 8NPP 00	240	1	0.5	0.15	3.00E-06 [ϰ]
$PAL / CH_3NH_3PbI_3$	Spin Coating	Laurell: Model ws – 650 MZ – 8NPP 00	240	1	0.5	0.15	3.00E-06 [ϰ]
	Centrifuge	u-320 - Boeco	127	4	5	0.0253	1.07E-05 [*]
	Magnetic Stirrer	Benchmark - mixer	120	1.5	3	0.29	2.61E-05 [ɤ]
	Annealing	Hot Plate	120	1	10	0.39	7.81E-05 [ϰ]
ETL/ PC60BM	Dynamic Spin Coating	Laurell: Model ws – 650 MZ – 8NPP 00	240	1	0.5	0.15	3.00E-06 [ϰ]
	Annealing	Hot Plate	120	1	5	0.39	3.91E-05 [ϰ]
BEL/Ag	Thermal Evaporation under Vacuum	-	-	-	10	-	2.16E-02 [ɤ]
Glove Box			-				1.47E-03 [ƍ]

Table S3, provides a detailed overview of the materials, energy requirements in the processes, emissions, and waste generated for the fabrication of the perovskite solar cell prototype developed in Colombia by Ramirez *et al*.[1], designated as C1. To distinguish between the variables, the information is presented as done by Espinosa *et al*.[11], where each data point is labeled in the first column with the following letters:

Where:

I: Input.

P: Required Process.

W: Waste Treatment.

E: Emissions.

O: Material Output.

Table S3. Inventory compiled for the cradle-to-gate LCA of C1 prepared using SimaPro 9.5.0.2 software.

	Materials and Processes for 1 cm² of PSC	Quantity	Unit	Comments and References
	C1.1 Front electrode layer (ITO)	1	cm^2	Inventory for the Solar Cell Developed by the CIDEMAT Group
I	Isopropanol {GLO}| market for | Cut-off, S	0.000267	kg	
I	Acetone, liquid {GLO}| market for | Cut-off, S	0.000267	kg	
I	Water, deionised, from tap water, at user {GLO}| market for | Cut-off, S	0.107	kg	
I	Soap {GLO}| market for | Cut-off, S	0.0000166	kg	
I	Indium Tin Oxide coated glass	0.0001	m^2	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0000173100	kWh	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00051985	kWh	
W	Heat, waste	0.000337	MJ	
W	Waste water	0.107	Kg	
O	Electrodo frontal – Vidrio recubierto de óxido de indio y estaño	0.0005	kg	
»A01	Indium Tin Oxide coated glass	1	m^2	García-Valverde *et al.*[8]
I	Indium {GLO}| market for | Cut-off, S	0.00230	kg	
I	Tin {GLO}| market for | Cut-off, S	0.0002	kg	
I	Flat glass, uncoated {GLO}| market for | Cut-off, S	1.54	kg	

I	Argon, liquid {GLO}| market for | Cut-off, S	0.124	kg	
I	Oxygen, liquid {RoW}| market for | Cut-off, S	0.0001	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.225	kWh	
	C1.2 – Hole transport layer (NiO_x)	1	cm^2	Inventory for the solar cell developed by the CIDEMAT group. It was synthesized using the method of Ciro *et al*.[6] and Zhang *et al*.[7]
»A02	NiOx	0.000000368	kg	
I	Water, deionised, from tap water, at user {GLO}| market for | Cut-off, S	0.00001115	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00003	kWh	Spin - Coating
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.000625	kWh	Shaker
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00003462	kWh	Ultrasound
E	NiO_x	0.000000350	kg	
O	Capa de Transporte de Huecos (NiOx)	0.0000000184	kg	
w	Waste water	0.000011959	kg	
A02	NiOx	1	g	Information CIDEMAT
I	Nickel nitrate hexahydrate	0.0045	kg	
I	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S	0.001	kg	
I	Water, deionised, from tap water, at user {GLO}| market for | Cut-off, S	0.022	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0014062	kWh	Ultrasound
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.000625	kWh	Shaker
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0028125	kWh	Annealing
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0014062500	kWh	Annealing

E	Nickel compounds	0.0005448	kg	
E	Sodium compounds, unspecified	0.002125	kg	
E	Wastewater	0.022	kg	
	C1.3 Mesoporous Alumina Support Layer (Al_2O_3)	1	cm^2	
I	Aluminium oxide {GLO}| market for | Cut-off, S	0.00000100386	kg	
I	Hydrochloric acid, without water, in 30% solution state {GLO}| tetrafluoroethane production | Cut-off, S	0.000000592933	kg	
I	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S	0.00000200772	kg	
I	Water, deionised, from tap water, at user {GLO}| market for | Cut-off, S	0.0000028181	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00003	kWh	
w	Heat, waste	0.000340	MJ	
w	Wastewater	0.0000317271	kg	
O	Mesoporous layer of alumina- Al_2O_3	0.0000000593	kg	
	C1.4 Perovskite absorbing layer ($MAPbI_3$)	1	cm^2	
»A03	Lead iodide (PbI_2)	0.00000456	kg	
I	Methylamine {GLO}| market for | Cut-off, S	0.00000207	kg	
I	Acetonitrile {GLO}| market for | Cut-off, S	0.000077588	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00003	kWh	Spin - coating
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.000078125	kWh	anhealed
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00000496	kWh	
W	Heat, waste	0.00398	MJ	
W	Waste, organic	0.000085696400000000	kg	
O	Capa de perovskita	0.0000001	kg	
»A04	MAI (CH_3NH_3I)	0.00000157	kg	
A03	Lead iodide (PbI_2)	1	kg	Gong *et al.*[9]
I	Iodine {GLO}| market for | Cut-off, S	0.67	kg	
I	Potassium hydroxide {GLO}| market for | Cut-off, S	0.291	kg	

I	Lead {GLO}| market for | Cut-off, S	0.449	kg	
I	Nitric acid, without water, in 50% solution state {GLO}| market for | Cut-off, S	0.729	kg	
P	Heat, from steam, in chemical industry {RoW}| market for heat, from steam, in chemical industry | Cut-off, S	13.5	MJ	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.133	kWh	
W	Wastewater	0.160	kg	
O	Potassium nitrate {GLO}| market for | Cut-off, S	0.438	kg	
O	Nitric oxide {GLO}| market for nitric oxide | Cut-off, S	0.0434	kg	
A04	MAI (CH_3NH_3I)	1	kg	Gong *et al.*[9]
I	Hydrogen sulfide {GLO}| market for | Cut-off, S	0.139	kg	
I	Iodine {GLO}| market for | Cut-off, S	1.04	kg	
I	Methylamine {GLO}| market for | Cut-off, S	0.581	kg	
I	Ethanol, without water, in 99.7% solution state, from ethylene {GLO}| market for | Cut-off, S	7.31	kg	
I	Diethyl ether, without water, in 99.95% solution state {GLO}| market for | Cut-off, S	20.8	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	9.24	kWh	
P	Heat, from steam, in chemical industry {RoW}| steam production, as energy carrier, in chemical industry | Cut-off, S	8.30	MJ	
W	Wastewater	29.9	kg	
O	Sulfur {GLO}| market for | Cut-off, S	0.118	kg	
	C1.5 Electron transport layer (PCBM)	1	cm^2	
I	Monochlorobenzene {GLO}| market for | Cut-off, S	0.0000111	kg	
I	Ethanol, without water, in 99.7% solution state, from ethylene {GLO}| market for | Cut-off, S	0.00000789	kg	
»A05	PCBM	0.000000150	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.00003	kWh	

P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0000391	kWh	
W	Heat, waste	0.00000833	MJ	
W	Waste, organic	0.0000190	kg	
O	Electron transport layer	0.00000000652	kg	
A05	PCBM	1	kg	García-Valverde *et al.*[8]
I	Toluene, liquid {GLO}| market for | Cut-off, S	122.885	kg	
I	Oxygen, liquid {RoW}| market for | Cut-off, S	73.963	kg	
I	2-cyclopentone {GLO}| market for | Cut-off, S	0.850	kg	
I	Ammonia, liquid {RoW}| market for | Cut-off, S	0.788	kg	
I	Sodium hypochlorite, without water, in 15% solution state {GLO}| market for | Cut-off, S	0.344	kg	
I	Hydrochloric acid, without water, in 30% solution state {RoW}| market for | Cut-off, S	0.218	kg	
I	Sulfur trioxide {GLO}| market for | Cut-off, S	0.479	kg	
I	Tap water {RoW}| tap water production, conventional treatment | Cut-off, S	6141.187	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	252.44	kWh	
	C1.6 Back electrode layer (Ag)	1	cm^2	
I	Silver {GLO}| market for | Cut-off, S	0.000000127	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0216	kWh	Espinosa *et al.*[11]
O	Silver {GLO}| market for | Cut-off, S	0.0000001049	kg	
	Glove Box	1	cm^2	Alberola-Borràs *et al.*[2]
I	Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S System - Copied from ELCD	0.0098	kg	
P	Electricity, low voltage {CO}| market for electricity, low voltage | Cut-off, S	0.0533	MJ	
E	Nitrogen, atmospheric	0.00980	kg	

<u>Supplementary Information S3: Environmental Impact Assessment</u>

The environmental impacts studied through the life cycle were calculated using the methodology suggested by the International Life Cycle Data system (ILCD), which sets standards and ensures data quality and LCA results from its application. This method is highly recommended for evaluating the environmental impact of photovoltaic electricity generation systems, as it is used by multiple authors due to its ability to cover and consider inputs and emissions generated from raw material extraction, manufacturing, transportation, and use, i.e., from cradle to gate or midpoint. [2,9-13]

Due to incomplete information coverage required for a cradle-to-grave and/or endpoint study, making assumptions about the use phase and final disposal phase introduces greater uncertainty. Therefore, this study employs the midpoint method and selected impact categories shown in Table S4. Lastly, based on the environmental impact analysis results for each component, normalization and weighting were conducted using the global equivalent normalization set recommended by the European Commission - Joint Research Centre - Institute for Environment and Sustainability.[14]

According to the ILCD manual, this LCA study is categorized as situation A, as it involves comparing goods and services, specifically different Perovskite Solar Cells (PSCs). It aims to identify weaknesses in terms of the environmental impact of PSCs and provide quantitative life cycle data to verify the environmental performance of this technology, among other benefits.[15] The LCA was modeled using an attributional approach, which describes environmentally relevant physical flows of a life cycle and its subsystems. This approach assigns inputs and outputs of systems to a functional unit of a product or service system and describes its supply chain, whether specific or average.

According to the ILCD manual, the study falls under the attributional modeling, particularly in situation A, which involves comparing goods and services (p. 82). However, it has been stipulated that consequential LCA can also be used for situations A and B, where it reflects the consequences of decisions. [16] Nonetheless, studies like Espinosa *et al*.11 indicated that the Ecoinvent database, when modeled consequentially, is more suitable for situation B and may not fully align with situations A and C1, hence it was modeled under situation A and attributional.

The database used for this study was Ecoinvent 3.6, employing the cut-off approach, which is attributional and allows for defining multiple-product activities as single-product activities. Methodological rules for database calculation are based on the recycling content approach or cut-off approach, assigning responsibility to the producer. Moreover, waste by-products must be treated if they are not allocated to the activity producing them, thus identifying which activity or process is negatively linked in this study.[17]

Supplementary Information S4: Complementary Results

Table S4. Non-Standardized Environmental Impacts of the PSCs Studied (C1), with 1 cm^2 as the Functional Unit

Impact category	Unit	FEL	HTL	MSL	PAL	ETL	BEL	GB	total
Climate change	kg CO_2 eq	2.5E-03	2.1E-04	1.3E-05	6.0E-04	2.4E-04	6.5E-03	5.3E-03	1.5E-02
Human toxicity, non-cancer effects	CTUh	6.3E-10	4.2E-11	4.0E-12	1.7E-10	3.6E-11	1.3E-09	8.8E-10	3.1E-09
Human toxicity, cancer effects	CTUh	1.2E-10	8.6E-12	2.3E-12	2.4E-11	7.5E-12	2.7E-10	1.8E-10	6.1E-10
Particulate matter	kg PM2.5 eq	1.4E-06	9.4E-08	8.3E-09	3.9E-07	1.4E-07	2.7E-06	2.3E-06	7.0E-06
Terrestrial eutrophication	molc H+ eq	1.5E-05	1.6E-06	9.6E-08	4.2E-06	1.1E-06	4.6E-05	3.9E-05	1.1E-04
Freshwater eutrophication	kg P eq	8.1E-	4.5E-	4.1E-	1.6E-	4.8E-	1.4E-	9.4E-	3.4E-06

		07	08	09	07	08	06	07	
Freshwater ecotoxicity	CTUe	5.2E-02	8.6E-03	5.9E-04	7.1E-03	2.5E-03	2.7E-01	1.8E-01	5.2E-01
Land use	kg C deficit	1.8E-03	9.8E-05	9.3E-06	4.8E-04	2.0E-04	3.0E-03	2.0E-03	7.6E-03
Water resource depletion	m3 water eq	1.8E-03	9.8E-05	9.3E-06	4.8E-04	2.0E-04	3.0E-03	2.0E-03	7.6E-03
Mineral, fossil & ren resource depletion	kg Sb eq	2.3E-05	8.8E-08	9.6E-09	1.1E-06	4.5E-07	2.6E-06	2.1E-06	3.0E-05
DEA	MJ	6.0E-02	4.6E-03	2.6E-04	1.6E-02	5.0E-03	1.4E-01	1.2E-01	3.45E-01

Table S5. Results of the normalized environmental impacts applying the ILCD 2011 Midpoint+ V1.11 methodology/EC -JRC Global Normalization, assessed through the cradle-to-gate LCA of C1, using 1 cm2 as a functional unit.

Impact category	**Total**	**FEL**	**HTL**	**MSL**	**PAL**	**ETL**	**BEL**	**GB**
Climate change	2.17E-06	3.54E-07	2.95E-08	1.88E-09	8.43E-08	3.42E-08	9.18E-07	7.48E-07
Human toxicity. non-cancer effects	1.99E-05	4.08E-06	2.68E-07	2.58E-08	1.09E-06	2.35E-07	8.54E-06	5.67E-06
Human toxicity. cancer effects	4.93E-05	9.74E-06	6.97E-07	1.87E-07	1.90E-06	6.05E-07	2.15E-05	1.47E-05
Particulate matter	1.39E-06	2.66E-07	1.85E-08	1.64E-09	7.67E-08	2.80E-08	5.39E-07	4.56E-07
Terrestrial eutrophication	8.30E-07	1.44E-07	1.09E-08	8.23E-10	5.78E-08	1.03E-08	3.37E-07	2.69E-07
Freshwater eutrophication	5.21E-07	1.24E-07	6.86E-09	6.20E-10	2.38E-08	7.41E-09	2.15E-07	1.44E-07
Freshwater ecotoxicity	1.40E-04	1.40E-05	2.29E-06	1.57E-07	1.90E-06	6.57E-07	7.30E-05	4.81E-05
Land use	1.46E-09	3.42E-10	1.88E-11	1.79E-12	9.17E-11	3.81E-11	5.75E-10	3.90E-10
Water resource depletion	4.29E-07	3.37E-07	1.27E-09	1.39E-10	1.52E-08	6.55E-09	3.77E-08	3.12E-08
Mineral. fossil & ren resource depletion	5.02E-06	3.34E-06	1.02E-08	5.36E-09	7.18E-07	1.26E-08	7.28E-07	2.05E-07

Table S6*.* Results of the normalized environmental impacts applying the ReCiPe 2016 Midpoint (H) V1.04 / World (2010) H methodology. assessed through the cradle-to-gate LCA of C1, , using 1 cm2 as a functional unit.

Impact category	**Total**	**FEL**	**HTL**	**MSL**	**PAL**	**ETL**	**BEL**	**GB**
Global warming	2.003E-06	3.25E-	2.73E-	1.73E-	7.82E-	3.16E-	8.48E-	6.91E-

		07	08	09	08	08	07	07
Fine particulate matter formation	9.79448E-07	1.51E-07	1.43E-08	9.73E-10	3.55E-08	1.21E-08	4.15E-07	3.50E-07
Terrestrial acidification	1.84081E-06	2.56E-07	2.76E-08	1.63E-09	7.10E-08	1.86E-08	7.92E-07	6.73E-07
Freshwater eutrophication	5.24497E-06	1.25E-06	6.91E-08	6.24E-09	2.40E-07	7.46E-08	2.16E-06	1.45E-06
Terrestrial ecotoxicity	4.21924E-05	6.28E-06	6.37E-07	4.08E-08	2.04E-06	6.50E-07	1.92E-05	1.34E-05
Freshwater ecotoxicity	0.001294752	1.36E-04	2.10E-05	1.37E-06	1.92E-05	5.79E-06	6.70E-04	4.41E-04
Human carcinogenic toxicity	0.00016945	3.16E-05	2.44E-06	5.98E-07	5.95E-06	2.11E-06	7.53E-05	5.14E-05
Human non-carcinogenic toxicity	8.63801E-05	1.79E-05	1.18E-06	9.92E-08	4.31E-06	8.45E-07	3.78E-05	2.43E-05
Land use	2.07577E-08	1.23E-08	1.36E-10	1.92E-11	1.03E-09	2.52E-10	4.22E-09	2.78E-09
Mineral resource scarcity	1.00482E-09	4.79E-10	4.09E-12	9.32E-13	3.35E-10	1.68E-12	1.21E-10	6.38E-11
Fossil resource scarcity	4.44894E-06	1.07E-06	5.24E-08	3.34E-09	3.25E-07	1.01E-07	1.63E-06	1.27E-06
Water consumption	1.09668E-06	5.35E-07	9.51E-09	7.09E-10	3.69E-08	1.28E-08	2.93E-07	2.09E-07

Table S7. Results of the Cumulative Energy Demand from PSC Study, , using 1 cm2 as a functional unit.

Impact category	Unit	Total	FEL	HTL	MSL	PAL	ETL	BEL	GB
Renewable. water	MJ	1.31E-01	9.41E-03	2.23E-03	9.94E-05	5.44E-04	3.81E-04	6.97E-02	4.86E-02
Renewable. wind. solar. geothe	MJ	6.72E-04	9.51E-05	3.45E-06	8.81E-07	2.75E-05	8.29E-06	1.05E-04	4.31E-04
Renewable. biomass	MJ	1.09E-03	7.26E-04	4.73E-06	1.18E-06	9.90E-05	1.97E-05	1.40E-04	9.44E-05
Non-renewable. biomass	MJ	6.84E-05	6.80E-05	5.21E-09	1.35E-09	4.23E-08	1.58E-08	1.57E-07	1.06E-07
Non-renewable. nuclear	MJ	1.03E-02	1.88E-03	9.46E-06	6.38E-06	5.06E-04	1.16E-04	2.66E-04	7.52E-03
Non-renewable. fossil	MJ	2.02E-01	4.79E-02	2.35E-03	1.50E-04	1.46E-02	4.51E-03	7.30E-02	5.96E-02

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