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Data Article

ESCAPE approach for the sustainability evaluation of spent lithium-ion batteries recovery: Dataset of 33 available technologies

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LCA
Cobalt
Lithium

A B S T R A C T

Recovering critical raw materials from end-of-life batteries is mandatory to limit the need of virgin resources in the long-term. However, most of the recycling of lithium-ion batteries (LIBs) technologies are still in an infancy stage. As a result, to date, only few studies focus on Life Cycle Assessment (LCA) of the proposed processes, presenting limited results.
This paper reports the methodology and data resulting from sustainability evaluation of 33 different technologies for spent LIBs recovery, on the basis of the availability of information, identified in literature. The ESCAPE (standing for Evaluation of Sustainability of material substitution using CArbon footPrint by a simplified approach) method is based on the use of only two parameters: the embodied energy and the carbon footprint. These parameters are calculated for all the process steps of each technology. Using the ESCAPE approach, the data about energies and emissions associated with the electricity consumption for thermal and mechanical treatments and chemicals and water use are calculated for

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all the 33 selected technologies, referring to a recent work (Fahimi et a., 2022), which only presents the results.
In addition, ESCAPE tool is used to evaluate and discuss the parameters that can affect the technologies sustainability, to better highlight the most onerous and impactful steps of each technology. Then, this paper also shows that ESCAPE approach allows to propose some strategies to improve the recovery processes, with the aim to support eco-design.

Specifications Table

Subject	Environmental science (General)
Specific subject area	Sustainability evaluation of raw materials recovery from spent lithium-ion batteries, based on embodied energy and carbon footprint
Type of data	Table Figure
How the data were acquired	Data were elaborated using the approach presented in this paper
Data format	Analyzed
Description of data collection	Referring to laboratory scale, 33 available technologies for LIBs recovery were analyzed. Every process was divided in single steps (considering chemicals, water, thermal and mechanical treatments) to calculate embodied energy and carbon footprint and, if possible, compared to reference material (extracted from virgin source). Data were referred to 1 kg cathode.
Data source location	Data evaluated following the procedures reported in ref [1]. are availbale in this work.
Data accessibility	With the article
Related research article	A. Fahimi, S. Ducoli, S. Federici, G. Ye, E. Mousa, P. Frontera, E. Bontempi, Evaluation of the sustainability of technologies to recycle spent lithium-ion batteries, based on embodied energy and carbon footprint, J. Clean. Prod, 338 (2022) 130493. https://doi.org/10.1016/j.jclepro.2022.130493

Value of the Data

- Several studies have proposed the possibility to recover a variety of materials from LIBs, even if the processes are developed only at the lab-scale.
- The ESCAPE approach is presented and applied to evaluate the available strategies to recover materials from LIBs.
- Following this approach, the data about energy consumption and emissions are calculated for all the steps of the 33 selected literature processes, proposed for LIBs recovery.
- The calculated data are used to evaluate the sustainability of selected technologies, allowing to provide an instrument to support the most suitable activities able to extract materials from waste acting in substitution of natural resources use.
- The parameters evaluated in the ESCAPE approach (embodied energy and carbon footprint) can be potentially integrated and/or compared with Life Cycle Assessment (LCA) study, giving an initial overview of a process even if developed at low technology readiness level.
- ESCAPE approach allows also to propose eco-design strategies for reducing environmental impact. For example, this work shows that water usage must be suitably managed (for example, limiting the use of ultrapure water) to improve the sustainability of LIBs recycling technologies.

1. Data Description

Table 1 reports conditions and parameters used for the evaluation of the embodied energy and the carbon footprint of the processes. They include also hypotheses whenever it is required to set missing information in the referring literature source (e.g. washing step described without mentioning any volume and type of water).

Table 2 reports the average power rating of laboratory instruments used for laboratory scale processes for treating 1 kg of material.

Table 3 reports the embodied energy and the carbon footprint values of chemicals used in this work and extracted from CES Selector (https://grantadesign.com/it/industry/products/ces-selector/) or Ecoinvent database (https://ecoinvent.org/).

Table 4 reports the embodied energy and the carbon footprint referred to a power rating of 1 W and for 60 s of usage, considered as global "World factors", as average value of all world countries. The data were calculated by considering the reports of the International Energy Agency (IEA) [2,3,5].

Table 5 reports the detailed values of the embodied energy and the carbon footprint evaluated for all the steps of each considered process (see also Ref [1]), divided into four categories: thermal treatments, mechanical treatments, chemicals, and water use. The data were calculated considering the processes as exactly described by the authors.

Table 6 reports the detailed values of the embodied energy and the carbon footprint evaluated for all the steps of each considered process (see Ref. also [1]), divided into four categories: thermal treatments, mechanical treatments, chemicals, and water use. The data were calculated considering the use of distilled water instead of ultrapure water or deionized water for chemicals dilution. In addition, for the products washing, only tap water was considered.

Table 1
Conditions and parameters used for the evaluation of embodied energy and carbon footprint of the recycling processes for spent lithium-ion batteries.

1	1 kg raw material (cathode of batteries) was considered for all the processes. Its embodied energy and carbon footprint are assumed to be equal to zero, since recycling spent LIB is originally considered a waste.
2	For thermal and mechanical processes, all the available information (about time and temperature) were found in the reference article.
3	To account the quantities of chemicals, their amount (reported in the reference papers) was adjusted to 1 kg of starting raw material.
4	For drying processes (made at around 100 °C), a power value of 400 W was used. Time, if not specified, was set to one hour.
5	For thermal processes at elevated temperature (activation, pyrolysis, carbonization, etc.) a power value of 2500 W was used.
6	If the reference articles proposed several synthesis conditions, the optimal condition was considered, otherwise if not mentioned, the lowest values of times and/or temperatures were considered (to have the lowest embodied energy and carbon footprint).
7	In thermal treatments, the additional time required to reach the working temperature (reported only from some authors) has not been considered in the calculations.
8	When a flow of nitrogen or argon was coupled to the heating, these elements were evaluated as mass of reagent added to the process, and the mass was obtained from their input flow data indicated by the reference article
9	For mechanical processes, time was set on 5 min, if not specified in the article.
10	Filtration was considered performed by the operator, without the use of instrument. In any cases this process is expected to have low embodied energy and carbon footprint.
11	The water used to prepare the solutions of chemicals used in the synthesis was considered distilled.
12	The water used for washing has been always considered as tap water even if distilled water was expressly indicated.
13	For each washing step, 10 l of water were considered for 1 kg of starting raw material.
14	Liquid CO_2 was evaluated as additional reagent, and whenever not mentioned its flow input, we assumed it to be equal to 5 l/min
15	For technologies exploiting water leaching, the "leaching" water was considered as tap water.
16	In case of mechanical/thermal/chemical treatment previous to eventual chemical analysis (e.g. ICP-MS), these were not considered in the calculation.
17	For drying steps, if temperature not mentioned, we assume it is done under room conditions.
18	Volume of NaCl (5%) solution for discharging step of batteries was assumed to be 10 l of solution for 1 kg of material.
19	The efficiency of the processes was not considered in the calculation since in several articles they were not indicated.

Table 2
List of power rating for thermal and mechanical laboratory processes considered in the work.

	Process	Power (W)
Thermal processes	Drying (low temperature ≈ 100°C)	400
	Heating (high temperature)	2500
	Heating and mixing	630
	Laboratory scale autoclave	3700
	Laboratory scale arc furnace	2880
	Pilot scale vacuum furnace	12,000
Mechanical processes	Centrifugation	500
	Crushing	1100
	Cutting/Shredding	1000
	Grinding	250
	Milling	1800
	Sieving	480
	Stirring	270
	Sonicating	200
	Vacuuming	550

Table 3
List of embodied energy and carbon footprint of chemicals used in this work and Ref [1].

Chemical	Embodied energy (MJ/kg)	Carbon footprint ($kgCO_{2\text{-}eq}$/kg)
Citric acid	74.4	3.1
Distilled water	0.0135	0.00082
dH_2O (double deionized water)	19.1	0
Tap water	0.005	0.0003
Hydrogen peroxide	12.94	0.01
Gypsum	0.05	0
Hydrochloric acid	17.5	0.9
Isopropyl alcohol	1.69	1.85
Nitrogen (gas)	4.3	0.25
Industrial grade Phosphoric acid	27.2	0.5
Fertilizers grade Phosphoric acid	18.2	1
Sodium bicarbonate	7.53	0.61
Sodium hydroxide	12.54	3.2
Sulfuric acid	7,36	0,21
LiOH	62.9	5.7
Dimethyl carbonate (DMC)	54.1	2.3
Liquid Argon	32.07	2.33
Sodium percarbonate	18.1	1.26
Liquid carbon dioxide	8.24	0.9
Lignite	9.5	0.036
Silica	33.1	3.2
Calcium oxide	3.7	1.2
Dimethyl acetamide (DMAC)	88.8	3.4
Lithium carbonate	27.24	2.06
NaCl	2.4	0.18
EDTA	78.2	4.24
NaCl	2.4	0.18
Ammonium sulphate	6.2	0.5
Nitric acid (50%)	12.54	3.2

Table 4
EE and CF referred to a power rating of 1 W and for 1 min of usage, considered as global "World factors", as average value of all world countries. The data were calculated by considering the reports of the International Energy Agency (IEA) [2,3].

Electric_to_Thermal (1 W; 60 s)		Electric_to_Mechanical (1 W; 60 s)	
EE factor (MJ/kg)	CF factor (kg/kg)	EE factor (MJ/kg)	CF factor (kg/kg)
0.00012153	0.00000714	0.00013656	0.00000802

Table 5
Detailed values of embodied energy (EE) and carbon footprint (CF) resulted for all the steps of each considered process (see Ref [1]), divided into four categories: thermal treatments, mechanical treatments, chemicals, and water use. (A) hydrometallurgical processes; (B) pyrometallurgical processes; (C) direct recycling processes. The data were calculated considering the processes as exactly described by the authors.

A: HYDROMETALLURGICAL METHOD								
1			2			3		
https://doi.org/10.1016/j.matchemphys.2017.01.003			DOI: 10.1016/j.jhazmat.2009.11.026			https://doi.org/10.1021/acssuschemeng.7b00571		
Photocatalytic properties of Co3O4/LiCoO2 recycled from spent lithium-ion batteries using citric acid as leaching agent	EE (MJ/kg)	CF (kgCO2/kg)	*Recovery of cobalt and lithium from spent lithium ion batteries using organic citric acid as leachant*	EE (MJ/kg)	CF (kgCO2/kg)	*Sustainable Recovery of Cathode Materials from Spent Lithium-Ion Batteries Using Lactic Acid Leaching System*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**2336,5**	**69,7**	**Total**	**1899,8**	**48,4**	**Total**	**1456,6**	**43,3**
Thermal treatment	160,4	9,4	Thermal treatment	168,0	9,9	Thermal treatment	165,6	9,7
Mechanical treatment	0	0	Mechanical treatment	4,1	0,2	Mechanical treatment	1,2	0,1
Chemical treatment	1441,6	60,3	Chemical treatment	910,7	38,2	Chemical treatment	439,3	33,5
Use of water (washing steps and solutions)	734,5	0,0	Use of water (washing steps and solutions)	816,9	0,0	Use of water (washing steps and solutions)	850,5	0,0
4			5			6		
https://doi.org/10.1016/j.wasman.2017.03.037			https://doi.org/10.1016/j.jpowsour.2012.06.068			https://doi.org/10.1016/j.cej.2015.06.071		
Recovery of lithium and cobalt from spent lithium-ion batteries using organic acids: Process optimization and kinetic aspects	EE (MJ/kg)	CF (kgCO2/kg)	*Ascorbic-acid-assisted recovery of cobalt and lithium from spent Li-ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)	*Hydrometallurgical processing of spent lithium ion batteries (LIBs) in the presence of a reducing agent with emphasis on kinetics of leaching*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**1578,5**	**47,7**	**Total**	**1075,7**	**28,0**	**Total**	**1018,7**	**9,3**
Thermal treatment	118,6	7,0	Thermal treatment	19,8	1,2	Thermal treatment	97,5	5,7
Mechanical treatment	0,6	0,0	Mechanical treatment	1,5	0,1	Mechanical treatment	0,8	0,0
Chemical treatment	969,2	40,7	Chemical treatment	392,3	27,8	Chemical treatment	118,2	3,6

(continued on next page)

Table 5 (*continued*)

Use of water (washing steps and solutions)	490,0	0,0	Use of water (washing steps and solutions)	662,7	0,0	Use of water (washing steps and solutions)	802,2	0,0
7			**8**			**9**		
https://doi.org/10.1016/j.jpowsour.2013.08.128			https://doi.org/10.1016/j.jhazmat.2016.03.062			https://doi.org/10.1016/j.wasman.2016.03.006		
Hydrometallurgical process for the recovery of high value metals from spent lithium nickel cobalt aluminum oxide based lithium-ion batteries	EE (MJ/kg)	CF (kgCO2/kg)	*Recycling of spent lithium-ion battery cathode materials by ammoniacal leaching*	EE (MJ/kg)	CF (kgCO2/kg)	*An environmental benign process for cobalt and lithium recovery from spent lithium-ion batteries by mechanochemical approach*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**527,2**	**11,3**	**Total**	**2179,4**	**23,5**	**Total**	**512,5**	**27,8**
Thermal treatment	155,6	9,1	Thermal treatment	7,5	0,4	Thermal treatment	36,5	2,1
Mechanical treatment	1,6	0,1	Mechanical treatment	1,6	0,1	Mechanical treatment	75,7	4,4
Chemical treatment	34,4	2,0	Chemical treatment (only the binary ammonia + ammonium sulfite)	336,7	22,9	Chemical treatment	390,8	21,2
Use of water (washing steps and solutions)	335,6	0,0	Use of water (washing steps and solutions)	1833,6	0,0	Use of water (washing steps and solutions)	9,6	0,0
10			**11**			**12**		
https://doi.org/10.1016/j.wasman.2017.05.013			https://doi.org/10.1016/j.wasman.2016.09.039			https://doi.org/10.1016/j.jclepro.2015.10.132		
Recycling of spent lithium-ion battery with polyvinyl chloride by mechanochemical process	EE (MJ/kg)	CF (kgCO2/kg)	*Green and facile method for the recovery of spent Lithium Nickel Manganese Cobalt Oxide (NMC) based Lithium ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)	*An atom-economic process for the recovery of high value-added metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**451,8**	**13,6**	**Total**	**196,3**	**1,0**	**Total**	**587,9**	**11,0**
Thermal treatment	42,3	2,5	Thermal treatment	9,8	0,6	Thermal treatment	45,6	2,7
Mechanical treatment	147,6	8,7	Mechanical treatment	1,9	0,1	Mechanical treatment	0,9	0,1
Chemical treatment	70,4	2,4	Chemical treatment	4,7	0,3	Chemical treatment	180,9	8,3
Use of water (washing steps and	191,5	0,0	Use of water (washing steps and	180,0	0,0	Use of water (washing	359,	0,0

(continued on next page)

Table 5 (*continued*)

solutions)			solutions)			steps and solutions)	8	
13			**14**			**15**		
https://doi.org/10.1016/j.wasman.2016.03.009			https://doi.org/10.1016/j.seppur.2017.08.049			https://doi.org/10.1016/j.jhazmat.2011.07.114		
Recovery of cobalt from spent lithium-ion batteries using supercritical carbon dioxide extraction	EE (MJ/kg)	CF (kgCO2/kg)	*A promising physical method for recovery of LiCoO2 and graphite from spent lithium-ion batteries: Grinding flotation*	EE (MJ/kg)	CF (kgCO2/kg)	*Vacuum pyrolysis and hydrometallurgical process for the recovery of valuable metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**589,4**	**2,4**	**Total**	**195,7**	**0,9**	**Total**	**414,2**	**3,4**
Thermal treatment	13,8	0,8	Thermal treatment	0,0	0,0	Thermal treatment	13,7	0,8
Mechanical treatment	1,1	0,1	Mechanical treatment	11,7	0,7	Mechanical treatment	3,0	0,2
Chemical treatment	52,5	1,5	Chemical treatment	2,6	0,2	Chemical treatment	56,1	2,4
Use of water (washing steps and solutions)	522,0	0,0	Use of water (washing steps and solutions)	181,5	0,0	Use of water (washing steps and solutions)	341,1	0,0
16			**17**			**18**		
https://doi.org/10.1016/j.jhazmat.2015.09.050			https://doi.org/10.1016/j.hydromet.2015.09.025			https://doi.org/10.1016/j.jhazmat.2017.05.024		
Environmentally-friendly oxygen-free roasting/wet magnetic separation technology for in situ recycling cobalt, lithium carbonate and graphite from spent LiCoO2/graphite lithium batteries	EE (MJ/kg)	CF (kgCO2/kg)	*Thermal treatment process for the recovery of valuable metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)	*Recycling metals from lithium ion battery by mechanical separation and vacuum metallurgy*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**144,7**	**7,9**	**Total**	**183,8**	**3,0**	**Total**	**30,6**	**1,5**
Thermal treatment	9,1	0,5	Thermal treatment	14,3	0,8	Thermal treatment	21,1	1,2
Mechanical treatment	120,7	7,1	Mechanical treatment	0,7	0,0	Mechanical treatment	4,5	0,3
Chemical treatment	4,9	0,3	Chemical treatment	48,7	2,1	Chemical treatment	0,0	0,0
Use of water (washing steps and solutions)	10,0	0,0	Use of water (washing steps and solutions)	120,1	0,0	Use of water (washing steps and solutions)	5,0	0,0

(*continued on next page*)

Table 5 (*continued*)

B: PYROMETALLURGICAL METHOD								
1			**2**			**3**		
https://doi.org/10.1016/j.susmat.2019.e00139			https://doi.org/10.1016/j.susmat.2019.e00139			https://doi.org/10.1021/acssuschemeng.9b04175		
Recovery of lithium and cobalt from waste lithium-ion batteries through a selective isolation-suspension approach	EE (MJ/kg)	CF (kgCO_2/kg)	*Recovery of lithium and cobalt from waste lithium-ion batteries through a selective isolation-suspension approach*	EE (MJ/kg)	CF (kgCO_2/kg)	*Alkali Metal Salt Catalyzed Carbothermic Reduction for Sustainable Recovery of $LiCoO_2$: Accurately Controlled Reduction and Efficient Water Leaching*	EE (MJ/kg)	CF (kgCO_2/kg)
Total	**259,3**	**4,2**	**Total**	**583,1**	**11,3**	**Total**	**196,8**	**12,2**
Thermal treatment	30,3	1,8	Thermal treatment	30,3	1,8	Thermal treatment	144,9	8,5
Mechanical treatment	10,5	0,6	Mechanical treatment	3,2	0,2	Mechanical treatment	1,6	0,1
Chemical treatment	34,1	1,8	Chemical treatment	189,6	8,9	Chemical treatment	49,3	3,6
Use of water (washing steps and solutions)	184,3	0,0	Use of water (washing steps and solutions)	352,7	0,0	Use of water (washing steps and solutions)	1,0	0,0
4			**5**			**6**		
https://doi.org/10.1021/acssuschemeng.9b01564			https://doi.org/10.1016/j.mineng.2018.06.023			https://doi.org/10.1016/j.jpowsour.2019.01.072		
A Simplified Process for Recovery of Li and Co from Spent $LiCoO_2$ Cathode Using Al Foil As the in Situ Reductant	EE (MJ/kg)	CF (kgCO_2/kg)	*Separation of Li and Co from the active mass of spent Li-ion batteries by selective sulfating roasting with sodium bisulfate and water leaching*	EE (MJ/kg)	CF (kgCO_2/kg)	*Selective extraction of lithium (Li) and preparation of battery grade lithium carbonate (Li_2CO_3) from spent Li-ion batteries in nitrate system*	EE (MJ/kg)	CF (kgCO_2/kg)
Total	**576,5**	**14,9**	**Total**	**97,0**	**5,2**	**Total**	**742,3**	**11,1**
Thermal treatment	36,4	2,1	Thermal treatment	52,9	3,1	Thermal treatment	48,5	2,8
Mechanical treatment	2,0	0,1	Mechanical treatment	2,2	0,1	Mechanical treatment	7,5	0,4

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Table 5 (*continued*)

Chemical treatment	84,4	12,6	Chemical treatment	41,0	2,0	Chemical treatment	38,9	7,8
Use of water (washing steps and solutions)	454,4	0,0	Use of water (washing steps and solutions)	1,0	0,0	Use of water (washing steps and solutions)	647,4	0,0
7			**8**			**9**		
https://doi.org/10.1002/cite.201500066			https://doi.org/10.1016/j.jpowsour.2017.03.093			https://doi.org/10.1016/j.jpowsour.2012.01.152		
Recovery Concept of Value Metals from Automotive Lithium-Ion Batteries	EE (MJ/kg)	CF (kgCO2/kg)	*A promising approach for the recovery of high value-added metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)	*Development of a recycling process for Li-ion batteries*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**241,1**	**14,2**	**Total**	**335,5**	**9,2**	**Total**	**136,3**	**8,7**
Thermal treatment	215,1	12,6	Thermal treatment	72,5	4,3	Thermal treatment	105,7	6,2
Mechanical treatment	21,1	1,2	Mechanical treatment	19,7	1,2	Mechanical treatment	7,2	0,4
Chemical treatment	4,9	0,3	Chemical treatment	54,5	3,8	Chemical treatment	23,4	2,1
Use of water (washing steps and solutions)	0,0	0,0	Use of water (washing steps and solutions)	188,8	0,0	Use of water (washing steps and solutions)	0,0	0,0
C: DIRECT RECYCLING METHOD								
1			**2**			**3**		
https://doi.org/10.1016/j.joule.2020.10.008			https://doi.org/10.1039/C5GC02650D			https://doi.org/10.1039/C6RA27210J		
Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing	EE (MJ/kg)	CF (kgCO2/kg)	*Environmentally friendly recycling and effective repairing of cathode powders from spent LiFePO4 batteries†*	EE (MJ/kg)	CF (kgCO2/kg)	*Direct regeneration of cathode materials from spent lithium iron phosphate batteries using a solid phase sintering method*	EE (MJ/kg)	CF (kgCO2/kg)
Total	**717,3**	**32,5**	**Total**	**178,871**	**5,706**	**Total**	**606,692**	**65,672**
Thermal treatment	41,1	2,4	Thermal treatment	32,0	1,9	Thermal	220,4	12,9

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Table 5 (*continued*)

						treatment		
Mechanical treatment	1,9	0,1	Mechanical treatment	1,8	0,1	Mechanical treatment	1,9	0,1
Chemical treatment	670,3	30,0	Chemical treatment	51,8	3,7	Chemical treatment	2,4	0,1
Use of water (washing steps and solutions)	4,2	0,0	Use of water (washing steps and solutions)	93,3	0,0	Use of water (washing steps and solutions)	382,0	0,0
4			**5**			**6**		
https://doi.org/10.1016/j.susmat.2020.e00152			DOI: 10.1039/c7gc02831h			DOI: 10.1039/c7gc02831h		
A direct recycling case study from a lithium-ion battery recall	EE (MJ/kg)	CF (kgCO2/kg)	*Effective regeneration of LiCoO2 from spent lithium-ion batteries: a direct approach towards high-performance active particles*†	EE (MJ/kg)	CF (kgCO2/kg)	*Effective regeneration of LiCoO2 from spent lithium-ion batteries: a direct approach towards high-performance active particles*†	EE (MJ/kg)	CF (kgCO2/kg)
Total	**812,1**	**39,9**	**Total**	**403,610**	**18,864**	**Total**	**676,675**	**28,162**
Thermal treatment	164,1	9,6	Thermal treatment	107,9	6,3	Thermal treatment	266,2	15,6
Mechanical treatment	270,1	15,9	Mechanical treatment	2,3	0,1	Mechanical treatment	2,3	0,1
Chemical treatment	174,7	14,4	Chemical treatment	290,4	12,4	Chemical treatment	405,2	12,4
Use of water (washing steps and solutions)	203,3	0,0	Use of water (washing steps and solutions)	3,1	0,0	Use of water (washing steps and solutions)	3,1	0,0

Table 6
Detailed values of embodied energy (EE) and carbon footprint (CF) resulted for all the steps of each considered process (see Ref [1]), divided into four categories: thermal treatments, mechanical treatments, chemicals, and water use. (A) hydrometallurgical processes; (B) pyrometallurgical processes; (C) direct recycling processes. The data were calculated considering the use of distilled water instead of ultrapure water or deionized water for chemicals dilution. In addition, for the products washing, only tap water was considered.

H: HYDROMETALLURGICAL METHOD								
1			**2**			**3**		
https://doi.org/10.1016/j.matchemphys.2017.01.003			DOI: 10.1016/j.jhazmat.2009.11.026			https://doi.org/10.1021/acssuschemeng.7b00571		
Photocatalytic properties of Co3O4/LiCoO2 recycled from spent lithium-ion batteries using citric acid as leaching agent	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Recovery of cobalt and lithium from spent lithium-ion batteries using organic citric acid as leachant*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Sustainable Recovery of Cathode Materials from Spent Lithium-Ion Batteries Using Lactic Acid Leaching System*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**1602,6**	**69,7**	**Total**	**1083,4**	**48,4**	**Total**	**606,7**	**43,4**
Thermal treatment	160,4	9,4	Thermal treatment	168,0	9,9	Thermal treatment	165,6	9,7
Mechanical treatment	0	0	Mechanical treatment	4,1	0,2	Mechanical treatment	1,2	0,1
Chemical treatment	1441,6	60,3	Chemical treatment	910,7	38,2	Chemical treatment	439,3	33,5
Use of water (washing steps and solutions)	0,6	0,0	Use of water (washing steps and solutions)	0,6	0,0	Use of water (washing steps and solutions)	0,7	0,0
4			**5**			**6**		
https://doi.org/10.1016/j.wasman.2017.03.037			https://doi.org/10.1016/j.jpowsour.2012.06.068			https://doi.org/10.1016/j.cej.2015.06.071		
Recovery of lithium and cobalt from spent lithium-ion batteries using organic acids: Process optimization and kinetic aspects	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Ascorbic-acid-assisted recovery of cobalt and lithium from spent Li-ion batteries*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Hydrometallurgical processing of spent lithium-ion batteries (LIBs) in the presence of a reducing agent with emphasis on kinetics of leaching*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**1088,8**	**47,7**	**Total**	**414,0**	**29,1**	**Total**	**217,1**	**9,4**
Thermal treatment	118,6	7,0	Thermal treatment	19,8	1,2	Thermal treatment	97,5	5,73
Mechanical treatment	0,6	0,0	Mechanical treatment	1,5	0,1	Mechanical treatment	0,8	0,0
Chemical treatment	969,2	40,7	Chemical treatment	392,3	27,8	Chemical treatment	118,2	3,56
Use of water (washing steps and solutions)	0,4	0,0	Use of water (washing steps and solutions)	0,5	0,0	Use of water (washing steps and solutions)	0,6	0,03

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Table 6 (*continued*)

7			8			9		
https://doi.org/10.1016/j.jpowsour.2013.08.128			https://doi.org/10.1016/j.jhazmat.2016.03.062			https://doi.org/10.1016/j.wasman.2016.03.006		
Hydrometallurgical process for the recovery of high value metals from spent lithium nickel cobalt aluminium oxide based lithium-ion batteries	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Recycling of spent lithium-ion battery cathode materials by ammoniacal leaching*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*An environmental benign process for cobalt and lithium recovery from spent lithium-ion batteries by mechanochemical approach*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**191,9**	**11,3**	**Total**	**347,1**	**23,5**	**Total**	**503,0**	**27,8**
Thermal treatment	155,6	9,1	Thermal treatment	7,5	0,4	Thermal treatment	36,5	2,1
Mechanical treatment	1,6	0,1	Mechanical treatment	1,6	0,1	Mechanical treatment	75,7	4,4
Chemical treatment	34,4	2,0	Chemical treatment (only the binary ammonia + ammonium sulfite)	336,7	22,9	Chemical treatment	390,8	21,2
Use of water (washing steps and solutions)	0,2	0,0	Use of water (washing steps and solutions)	1,3	0,1	Use of water (washing steps and solutions)	0,0	0,0
10			**11**			**12**		
https://doi.org/10.1016/j.wasman.2017.05.013			https://doi.org/10.1016/j.wasman.2016.09.039			https://doi.org/10.1016/j.jclepro.2015.10.132		
Recycling of spent lithium-ion battery with polyvinyl chloride by mechanochemical process	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Green and facile method for the recovery of spent Lithium Nickel Manganese Cobalt Oxide (NMC) based Lithium-ion batteries*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*An atom-economic process for the recovery of high value-added metals from spent lithium-ion batteries*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**260,5**	**13,6**	**Total**	**16,5**	**1,0**	**Total**	**227,7**	**11,0**
Thermal treatment	42,3	2,5	Thermal treatment	9,8	0,6	Thermal treatment	45,6	2,7
Mechanical treatment	147,6	8,7	Mechanical treatment	1,9	0,1	Mechanical treatment	0,9	0,1
Chemical treatment	70,4	2,4	Chemical treatment	4,7	0,3	Chemical treatment	180,9	8,3

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Table 6 (*continued*)

Use of water (washing steps and solutions)	0,2	0,0	Use of water (washing steps and solutions)	0,2	0,0	Use of water (washing steps and solutions)	0,3	0,0
13			**14**			**15**		
https://doi.org/10.1016/j.wasman.2016.03.009			https://doi.org/10.1016/j.seppur.2017.08.049			https://doi.org/10.1016/j.jhazmat.2011.07.114		
Recovery of cobalt from spent lithium-ion batteries using supercritical carbon dioxide extraction	EE (MJ/kg)	CF (kgCO_2/kg)	*A promising physical method for recovery of LiCoO2 and graphite from spent lithium-ion batteries: Grinding flotation*	EE (MJ/kg)	CF (kgCO_2/kg)	*Vacuum pyrolysis and hydrometallurgical process for the recovery of valuable metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO_2/kg)
Total	**67,8**	**2,4**	**Total**	**14,4**	**0,9**	**Total**	**73,0**	**3,4**
Thermal treatment	13,8	0,8	Thermal treatment	0,0	0,0	Thermal treatment	13,7	0,8
Mechanical treatment	1,1	0,1	Mechanical treatment	11,7	0,7	Mechanical treatment	3,0	0,2
Chemical treatment	52,5	1,5	Chemical treatment	2,6	0,2	Chemical treatment	56,1	2,4
Use of water (washing steps and solutions)	0,4	0,0	Use of water (washing steps and solutions)	0,1	0,0	Use of water (washing steps and solutions)	0,2	0,0
16			**17**			**18**		
https://doi.org/10.1016/j.jhazmat.2015.09.050			https://doi.org/10.1016/j.hydromet.2015.09.025			https://doi.org/10.1016/j.jhazmat.2017.05.024		
Environmentally friendly oxygen-free roasting/wet magnetic separation technology for in situ recycling cobalt, lithium carbonate and graphite from spent LiCoO2/graphite lithium batteries	EE (MJ/kg)	CF (kgCO_2/kg)	*Thermal treatment process for the recovery of valuable metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO_2/kg)	*Recycling metals from lithium-ion battery by mechanical separation and vacuum metallurgy*	EE (MJ/kg)	CF (kgCO_2/kg)
Total	**137,4**	**8,1**	**Total**	**63,8**	**3,0**	**Total**	**27,0**	**1,6**
Thermal treatment	9,1	0,5	Thermal treatment	14,3	0,8	Thermal treatment	21,1	1,2
Mechanical treatment	120,7	7,1	Mechanical treatment	0,7	0,0	Mechanical treatment	4,5	0,3
Chemical treatment	4,9	0,3	Chemical treatment	48,7	2,1	Chemical treatment	0,0	0,0

(*continued on next page*)

Table 6 (*continued*)

Use of water (washing steps and solutions)	2,7	0,2	Use of water (washing steps and solutions)	0,1	0,0	Use of water (washing steps and solutions)	1,4	0,1

P: PYROMETALLURGICAL METHOD								
1			2			3		
https://doi.org/10.1016/j.susmat.2019.e00139			https://doi.org/10.1016/j.susmat.2019.e00139			https://doi.org/10.1021/acssuschemeng.9b04175		
Recovery of lithium and cobalt from waste lithium-ion batteries through a selective isolation-suspension approach	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Recovery of lithium and cobalt from waste lithium-ion batteries through a selective isolation-suspension approach*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Alkali Metal Salt Catalyzed Carbothermic Reduction for Sustainable Recovery of LiCoO2: Accurately Controlled Reduction and Efficient Water Leaching*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**75,1**	**4,2**	**Total**	**223,4**	**10,9**	**Total**	**195,9**	**12,2**
Thermal treatment	30,3	1,8	Thermal treatment	30,3	1,8	Thermal treatment	144,9	8,5
Mechanical treatment	10,5	0,6	Mechanical treatment	3,2	0,2	Mechanical treatment	1,6	0,1
Chemical treatment	34,1	1,8	Chemical treatment	189,6	8,9	Chemical treatment	49,3	3,6
Use of water (washing steps and solutions)	0,2	0,0	Use of water (washing steps and solutions)	0,3	0,0	Use of water (washing steps and solutions)	0,1	0,0
4			5			6		
https://doi.org/10.1021/acssuschemeng.9b01564			https://doi.org/10.1016/j.mineng.2018.06.023			https://doi.org/10.1016/j.jpowsour.2019.01.072		
A Simplified Process for Recovery of Li and Co from Spent LiCoO2 Cathode Using Al Foil As the in Situ Reductant	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Separation of Li and Co from the active mass of spent Li-ion batteries by selective sulfating roasting with sodium bisulfate and water leaching*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Selective extraction of lithium (Li) and preparation of battery grade lithium carbonate (Li2CO3) from spent Li-ion batteries in nitrate system*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**123,2**	**14,9**	**Total**	**96,1**	**5,2**	**Total**	**95,4**	**11,1**
Thermal treatment	36,4	2,1	Thermal treatment	52,9	3,1	Thermal treatment	48,5	2,8
Mechanical treatment	2,0	0,1	Mechanical treatment	2,2	0,1	Mechanical treatment	7,5	0,4
Chemical treatment	84,4	12,6	Chemical treatment	41,0	2,0	Chemical treatment	38,9	7,8

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Table 6 (*continued*)

Use of water (washing steps and solutions)	0,4	0,0	Use of water (washing steps and solutions)	0,1	0,0	Use of water (washing steps and solutions)	0,6	0,0
7			8			9		
https://doi.org/10.1002/cite.201500066			https://doi.org/10.1016/j.jpowsour.2017.03.093			https://doi.org/10.1016/j.jpowsour.2012.01.152		
Recovery Concept of Value Metals from Automotive Lithium-Ion Batteries	EE (MJ/kg)	CF (kgCO$_2$/kg)	*A promising approach for the recovery of high value-added metals from spent lithium-ion batteries*	EE (MJ/kg)	CF (kgCO$_2$/kg)	*Development of a recycling process for Li-ion batteries*	EE (MJ/kg)	CF (kgCO$_2$/kg)
Total	**241,1**	**14,2**	**Total**	**146,8**	**9,2**	**Total**	**136,3**	**8,7**
Thermal treatment	215,1	12,6	Thermal treatment	72,5	4,3	Thermal treatment	105,7	6,2
Mechanical treatment	21,1	1,2	Mechanical treatment	19,7	1,2	Mechanical treatment	7,2	0,4
Chemical treatment	4,9	0,3	Chemical treatment	54,5	3,8	Chemical treatment	23,4	2,1
Use of water (washing steps and solutions)	0,0	0,0	Use of water (washing steps and solutions)	0,2	0,0	Use of water (washing steps and solutions)	0,0	0,0

D: DIRECT RECYCLING METHOD								
1			2			3		
https://doi.org/10.1016/j.joule.2020.10.008			https://doi.org/10.1039/C5GC02650D			https://doi.org/10.1039/C6RA27210J		
Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing	EE (MJ/kg)	CF (kgCO$_2$/kg)	*Environmentally friendly recycling and effective repairing of cathode powders from spent LiFePO4 batteries†*	EE (MJ/kg)	CF (kgCO$_2$/kg)	*Direct regeneration of cathode materials from spent lithium iron phosphate batteries using a solid phase sintering method*	EE (MJ/kg)	CF (kgCO$_2$/kg)
Total	**713,2**	**32,5**	**Total**	**85,661**	**5,713**	**Total**	**224,963**	**13,217**
Thermal treatment	41,1	2,4	Thermal treatment	32,0	1,9	Thermal treatment	220,4	12,9

(continued on next page)

Table 6 (*continued*)

Mechanical treatment	1,9	0,1	Mechanical treatment	1,8	0,1	Mechanical treatment	1,9	0,1
Chemical treatment	670,3	30,0	Chemical treatment	51,8	3,7	Chemical treatment	2,4	0,1
Use of water (washing steps and solutions)	0,0	0,0	Use of water (washing steps and solutions)	0,1	0,0	Use of water (washing steps and solutions)	0,3	0,0
4			5			6		
https://doi.org/10.1016/j.susmat.2020.e00152			DOI: 10.1039/c7gc02831h			DOI: 10.1039/c7gc02831h		
A direct recycling case study from a lithium-ion battery recall	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Effective regeneration of LiCoO2 from spent lithium-ion batteries: a direct approach towards high-performance active particles†*	EE (MJ/kg)	CF ($kgCO_2/kg$)	*Effective regeneration of LiCoO2 from spent lithium-ion batteries: a direct approach towards high-performance active particles†*	EE (MJ/kg)	CF ($kgCO_2/kg$)
Total	**609,1**	**39,9**	**Total**	**400,556**	**18,864**	**Total**	**673,621**	**28,162**
Thermal treatment	164,1	9,6	Thermal treatment	107,9	6,3	Thermal treatment	266,2	15,6
Mechanical treatment	270,1	15,9	Mechanical treatment	2,3	0,1	Mechanical treatment	2,3	0,1
Chemical treatment	174,7	14,4	Chemical treatment	290,4	12,4	Chemical treatment	405,2	12,4
Use of water (washing steps and solutions)	0,2	0,0	Use of water (washing steps and solutions)	0,0	0,0	Use of water (washing steps and solutions)	0,0	0,0

Fig. 1 reports the relative (A and B) and absolute (C and D) values of embodied energy and carbon footprint, for the 33 considered LIBs recover technologies, evaluated for 1 kg of cathode. The numerical data of absolute values are reported in Table 5.

2. Experimental Design, Materials and Methods

Several recycling technologies have been proposed to recover the valuable materials in spent LIBs. All the processes have been basically classified into three categories: hydrometallurgy, pyrometallurgy and direct recycling [1]. They generally consist of multiple steps, involving chemical, mechanical, and thermal treatments, with also products washing. However, the sustainability evaluation of the global proposed processes is lacking.

ESCAPE method, presented in [1] for the evaluation of materials and/or processes sustainability, considers CO_2 (or carbon) footprint and embodied energy as the only two parameters to be accounted for sustainability analysis. This approach was developed to support design decisions of technologies at low TRL (3–5) or at pilot-scale (TRL 6–8), when a full and exhaustive LCA cannot be realised. In particular, embodied energy of a product refers to all the energies necessary to extract raw materials from minerals and ores, plus the energies used for the final product manufacturing. Carbon footprint corresponds to the greenhouse gases (GHG) generated in material production [4,11].

These parameters, which can be understood by most of the public, were selected on the premise that global warming potential and energy consumption are two of the main LCA impact parameters and that they can be calculated for all life cycle phases of a product/process.

They depend on the selected materials and on the energy for their manufacturing (for example mechanical and/or thermal energy). Since the ESCAPE approach generally refers to laboratory scale processes, electricity is always used to supply energy for both thermal and mechanical treatments. The evaluation of embodied energy and carbon footprint need calculation of the equivalence factors, depending on the fuels input used by countries to produce electricity and the type of energy into which electricity is converted by laboratory instruments [4].

To calculate the equivalence factors, three steps were used:

1. *Calculation of the proportion of electricity obtained from fossil fuels, and nuclear and renewable sources.*

Information on the quantities of electricity produced by the different fuels in the all world countries are available on the reports of the International Energy Agency (IEA) [1,2].

For each country, the proportion of electricity produced from fossil fuels, nuclear power, and renewable sources were calculated by dividing the individual quantities by the total electricity produced. For fossil fuels derived energy, electricity produced from hard coal, brown coal, peat, oil shale and oil sands, coal gases, oil products and natural gas was considered. For renewable sources derived energy, electricity produced from hydroelectric plants, geothermal, solar, wind, tide power and other sources, biofuels, and wastes (including wood waste, other solid waste, and industrial and municipal waste) was considered.

Average energy proportions for all the world have also been calculated, considering the global electricity production. This was considered in the present work.

2. *Calculation of the conversion efficiency of fossil fuels into electricity.*

The second step concerns the calculation of the energy efficiency to generate electricity from fossil fuels, based on the IEA methodology [3]. Data on fuel inputs to public electricity plants and combined heat and power plants, and electricity and heat outputs from these plants were derived from IEA statistics documents. The conversion efficiency of electricity production from fossil fuels can be calculate as [6]:

$$\eta = \frac{E + (Hx\beta)}{F} \tag{1}$$

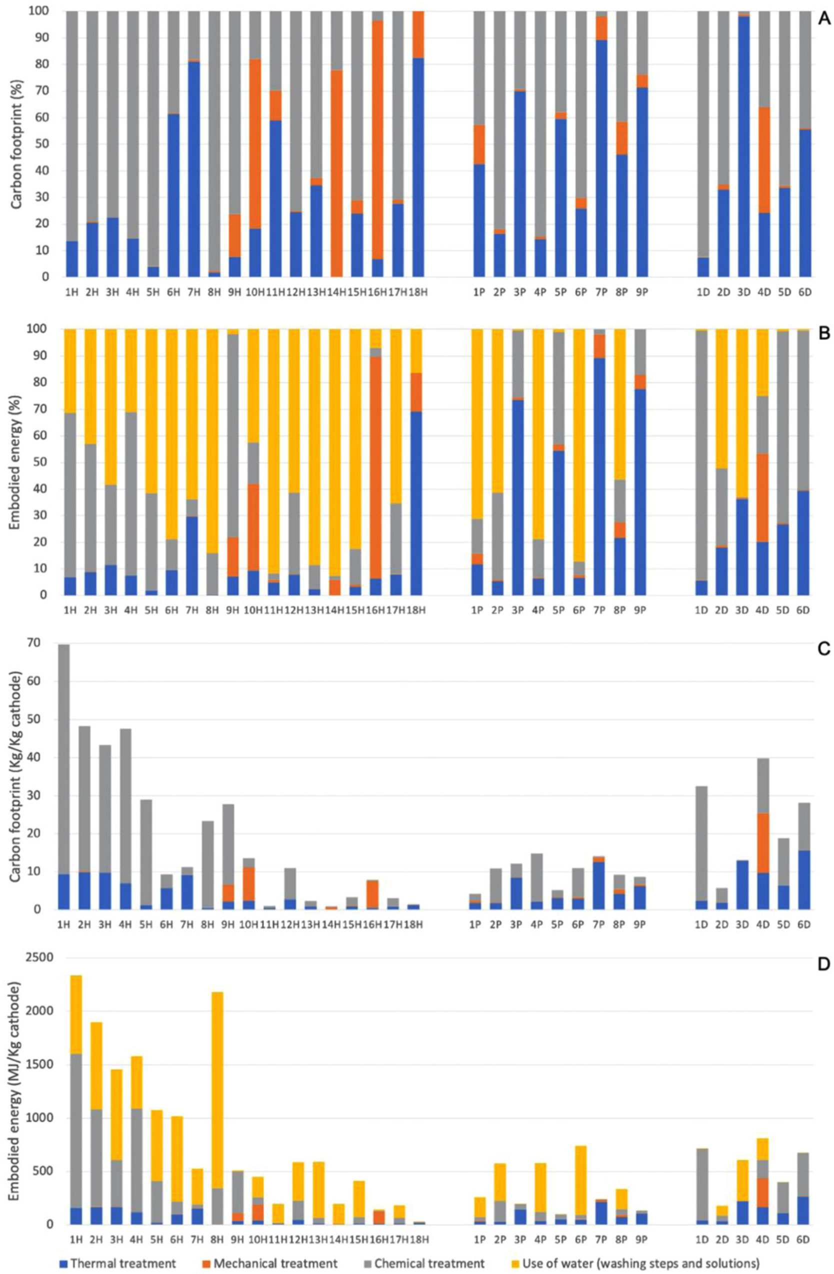

Fig. 1. Relative (A and B) and absolute (C and D) values of EE and CF, for the 33 considered LIBs recover technologies (for the data see Table 5), evaluated for 1 kg of cathode. H stands for hydrometallurgical method; P stands for pyrometallurgical method; D stands for direct recycling.

were,

η = conversion efficiency of electricity production by fossil fuels;

E = electricity production from public electricity plants and public combined heat and power plants;

H = heat output from public combined heat and power plants;

β = loss coefficient. It is expressed as the loss of electricity generation per unit of extracted heat. Its value is assumed to be 0.175 [3];

F = fossil fuel input for public electricity plants and public combined heat and power plants.

3. *Calculation of the Country equivalence factors.*

Using electricity proportion values between the various fuels and the conversion efficiency calculated previously, for each country the indices of "Energy equivalence (MJ / MJ)" and "CO_2 footprint equivalence (kg / MJ)" were calculated as follows [7]:

$$Energy\ equivalence\left(\frac{MJ}{MJ}\right) = \frac{Fossil\ fuel\ proportion}{\eta} + Nuclear\ proportion + Renewables\ proportion \tag{2}$$

$$CO_2\ footprint\ equivalence\left(\frac{Kg}{MJ}\right) = \frac{Fossil\ fuel\ proportion}{\eta}\ x\ CO_2\ conversion\ factor \tag{3}$$

where:

$CO_2\ conversion\ factor = 0.071$ kg/MJ [8]

Once calculated, the equivalence factors are used to evaluate the EE and CF.

To calculate embodied energy and carbon footprint involved in each procedure, it is necessary to know:

- The type of energy generated during the process being studied (like thermal energy in a furnace or mechanical energy in a mixer);
- The instrument operating power;
- The instrument running time (the time of the instrument use).

Then, embodied energy (EE) and carbon footprint (CF) were calculated as follows:

$$EE(J) = Power\ rating\ (W)\ x\ Running\ time\ (s)\ x\ \frac{Energy\ equivalence}{Product\ efficiency} \tag{4}$$

$$CF\ (Kg) = \frac{Power\ rating\ (W)\ x\ Running\ time\ (s)}{1\ x\ 10^6}\ x\ \frac{CO_2\ footprint\ equivalence}{Product\ efficiency} \tag{5}$$

The product efficiency depends on the energy that is used:

- For electric to thermal conversion the product efficiency = 1;
- For electric to mechanical (electric motors) conversion the product efficiency = 0.89 [9]

The embodied energy and the carbon footprint (referred to world mean values [2]) calculated for a power rating of 1 W and for a usage of 60 s, considering the global world factors, are shown in Table 4.

In this work the ESCAPE approach is used to evaluate the sustainability of 33 literature processes, proposed for LIBs recovery (see Tables 5 or 6 for the list) [1]. They were selected on the basis of the availability of all the information about the technological steps, in the publication of the methodology sections, to evaluate the embodied energy and the carbon footprint of all the single process. They were calculated using Eqs. (4) and (5). The lists of the parameters used in this work, with corresponding power rating, are reported in Tables 1 and 2.

Along with laboratory procedures, all the reagents employed in the synthesis were considered. The corresponding embodied energy and the carbon footprint are listed in Table 3. Also the water contribution was accounted. On the contrary, for the waste-derived raw materials these parameters were putted equal to zero, because they origin from other processes as by-products, then it is realistic to neglect emissions and energies associated to their purchase.

The embodied energy and the carbon footprint due to mechanical and/or thermal steps were calculated in accord to the reported procedure. In particular, ESCAPE approach was applied even if several of these technologies were developed only at laboratory scale, at the publication time.

Fig. 1 shows the resulting embodied energy and the carbon footprint evaluated for all the steps of the 33 selected technologies [1], using the ESCAPE approach. The data were calculated considering the processes as exactly described by authors, and they are reported considering separately chemicals, water, mechanical and thermal treatments (see Table 5 for all the data). In particular, in literature, chemicals are often diluted using ultrapure water (dH_2O), that has a high energy impact (EE=19.1 MJ/kg(dH_2O)). Ultrapure water is also sometimes used for washing the final obtained products, contributing to increase the energy impact of the proposed technology. This is extremely evident considering Fig. 1 (data are in Table 5), that shows that the water usage can reach an energy contribution higher than 90% of all process.

It is evident that it is necessary to promote technological improvements able to reduce the environmental impacts, and the ESCAPE approach, allowing to highlight the most onerous steps of a technology, can contribute to provide eco-design strategies. Indeed, the tool allows to rapidly explore alternatives to guide decision-making.

As an example, it is possible to propose the substitution of ultrapure water or deionized water (EE= 0.24 MJ/kg(water)) with distilled water (EE=0.01354 MJ/kg(water)) for chemicals dilution, for all the considered technologies. In addition, for the products washing, only tap water (EE=0.005 MJ/kg(tap water)) can be considered. The resulting embodied energy and carbon footprint data are reported in Table 6 (they are also reported and discussed in Fig. 4 of Ref [1]). Comparing Tables 5 and 6, it results evident that the choice to use less onerous water typologies is fundamental to reduce the energy impact of the processes (considering the original technologies, using dH_2O, embodied energy can reach values till 1800 MJ/Kg(cathode), as in the technology 8H). These results are in accord with literature: LCA data concerning industrial technologies involving chemicals, show similar results, highlighting the high energy involved in ultrapure water usage, and the necessity to replace it with industrial water (tap water) [10]. However, comparing data reported in Table 6, that are obtained by changing only some process steps, with data reported in Table 5, it is possible to highlight that ESCAPE approach allows to rapidly check technological alternatives and support materials selection strategies.

Moreover, being based on only two parameters, the data reported in this paper may be also used by other authors and compared with other approaches developed to evaluate environmental impact. Then it is possible to conclude that ESCAPE tool cannot only be considered as a simple pre-screening methodology, designed for a preliminary sustainability evaluation, but it can also be identified as an eco-design strategy, that can be very useful to guide the decision-making process for a design and/or redesign of a product/technology.

Ethics Statements

This work involves neither human nor animal subjects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Tables 5 and 6 (Original data) (Mendeley Data).

CRediT Author Statement

Serena Ducoli: Investigation, Methodology, Data curation, Writing – review & editing; **Ario Fahimi:** Investigation, Methodology, Writing – original draft; **Elsayed Mousa:** Investigation, Writing – review & editing; **Guozhu Ye:** Writing – review & editing; **Stefania Federici:** Writing – review & editing; **Patrizia Frontera:** Writing – review & editing; **Elza Bontempi:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

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References

[1] A. Fahimi, S. Ducoli, S. Federici, G. Ye, E. Mousa, P. Frontera, E. Bontempi, Evaluation of the sustainability of technologies to recycle spent lithium-ion batteries, based on embodied energy and carbon footprint, J. Clean. Prod. 338 (2022) 130493, doi:10.1016/j.jclepro.2022.130493.
[2] IEA, Electricity information, IEA Stat. (2018) www.iea.org/t&c/.
[3] IEA (2019), World Energy Balances 2019, OECD Publishing, Paris, doi:10.1787/3a876031-en.
[4] A. MF, Materials and the Environment, Eco-Informed Material Choice, 3rd ed., Elsevier, 2021, doi:10.1016/B978-0-12-821521-0.00004-9.
[5] IEA, Worldwide Trends in Energy Use and Efficiency, IEA, 2008.
[6] European Commission, COMBINED HEAT AND POWER (CHP) GENERATIONDirective 2012/27/EU of the European Parliament and of the Council Commission Decision 2008/952/EC, Eurostat Energy statistics, 2017.
[7] M.F. Ashby, Case studies: eco-audits, Mater. Environ. (2013) 193–225 ISBN 9780123859716, doi:10.1016/B978-0-12-385971-6.00008-7.
[8] R. Stone, Introduction to Internal Combustion Engines, 4th ed., R. Stone, 2012.
[9] Office of Energy Efficiency and Renewable Energy, Premium Efficiency Motor Selection and Application Guide-A Handbook for Industry, Office of Energy Efficiency and Renewable Energy, 2014.
[10] X. Zhao, Y. Zhang, Y. Cheng, S. Bai, C. Li, Identifying environmental hotspots and improvement strategies of vanillin production with life cycle assessment, Sci. Total Environ. 769 (2021) Article number 144771, doi:10.1016/j.scitotenv.2020.144771.
[11] A Fahimi, S Federici, L Depero, B Valentim, I Vassura, F Ceruti, L Cutaia, Elza Bontempi, Evaluation of the sustainability of technologies to recover phosphorus from sewage sludge ash based on embodied energy and CO_2 footprint, Journal of Cleaner Production 289 (2021), doi:10.1016/j.jclepro.2020.125762.