Societal impacts of batteries in transportation frameworks

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***Abstract*—This article focuses on the societal impact of lead-acid and lithium batteries, differentiating between five chemistries. This impact is broken down into three factors: social vulnerability, land use, and impact on local populations. By first studying the mass composition of the modules and then examining the societal impact of the materials that compose them, the overall societal impact is determined. The lithium iron phosphate battery proves to be the least impactful, and the lithium titanate oxide battery the most impactful. These results must be complemented by considering their uncertainties, as well as the energy density and current recyclability of batteries.**

***Keywords*—societal impacts, lithium batteries, mass composition, energy transition metals**

I. Introduction

The energy transition is a major challenge facing our society, aimed at reducing our dependence on fossil fuels and promoting renewable energy. Batteries are one of the pillars of this transition, used in a variety of applications ranging from electric vehicles to home energy storage systems. Although their environmental impact is already known [1], the use of materials such as cobalt, lithium, iron, and aluminum in battery production raises concerns about their societal impact [2].

For example, cobalt is often extracted under dangerous working conditions and with unsustainable mining practices, resulting in negative impacts on workers and local communities [3]. Similarly, lithium is also extracted intensively, often in environmentally sensitive regions such as salt flats, which can have adverse consequences on local flora and fauna [4].

Therefore, understand and consider the societal impacts of these metals in the energy transition when choosing a battery chemistry is crucial. This article focuses on battery chemistries used in the transportation sector, including lead-acid (PbA), lithium iron phosphate (LFP), nickel manganese cobalt (NMC), nickel cobalt aluminum (NCA), lithium manganese oxide (LMO), and lithium titanium oxide (LTO) batteries [5], [6].

To link these impacts with different battery technologies, the mass composition of batteries is firstly described in this paper. Subsequently, maps listing the societal impacts of mines are used to assess risks on these metals. Societal impacts are here divided into three factors: social vulnerability, land use, and mine impacts on local populations. Social vulnerability take into account parameters such as the level of poverty, the inequalities present in the country, land use primarily concerns soil pollution and detriment, and mine impacts on local populations are related to health. These three impacts are measured on a scale ranging from 1 to 5, with 1 being the weakest impact and 5 the strongest. These results are complemented by the calculation of their uncertainty.

II. Battery mass composition

The mass composition of lithium batteries varies depending on their chemistry. To understand how their material content can impact society, knowing the weight distribution of these chemical elements inside the batteries is essential. Despite the differences in mass composition between these technologies, the general structure of a battery remains the same.

A. *Battery architecture*

In the field of batteries, differentiation between a cell, a module, and a battery pack is important. A cell is considered as a fundamental building block of the battery, as it provides energy. A module is a combination of several cells connected together, usually in series. A battery pack is a combination of several modules and is used to power higher-powered devices. The battery management system (BMS) and cooling circuit are usually placed in the battery pack [7].

The inside of a cell is composed of electrodes, an electrolyte, and a separator. The active materials, which are responsible for the electrochemical reaction, are in the positive electrode. The negative electrode is mainly made up of graphite. At each of these positive and negative interfaces, current collectors are placed. On the outside of the cell is a casing, consisting mainly of plastic and steel (Fig. 1).

The assumption made regarding the different chemistries studied is that regardless of the chosen technology, the BMS, housing, and cooling circuit are identical. This article, therefore, focuses on the mass composition of the modules.

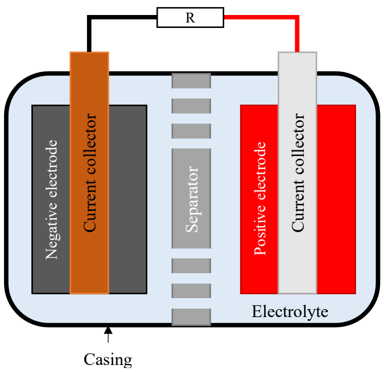

Fig. 1. Battery architecture

B. Mass composition for each battery chemistry

The mass composition of batteries is studied in relation to the different components mentioned in the diagram. Two main battery technologies are addressed in this article: lead-acid batteries and lithium batteries.

1) Lead-acid battery

Lead-acid batteries use a chemical reaction between lead and sulfuric acid. These batteries have been widely used in the automotive industry since World War II. They remain a dominant technology in automotive applications due to their low cost and reliability [8].

In the studied mass distribution, the electrode represents 62% of the mass compared to only 9% for the casing. Lead alone represents nearly 61% of the mass [9] (TABLE I). Plastic refers to polyethylene and polypropylene, and oxygen can be associated with the vacuum present in the battery.

TABLE I. MASS COMPOSITION OF A LEAD-ACID BATTERY

Elements	Mass composition [%]
Antimony	0.71
Arsenic	0.03
Lead	60.69
Glass	0.02
Oxygen	2.26
Plastic	8.55
Sulphuric acid	10.33
Water (unsalted)	16.93

2) Lithium batteries

Lithium batteries have a high energy density, long lifespan, and low self-discharge, making them an efficient source of energy for electric vehicles.

They contain an electrolyte, which is usually a lithium salt dissolved in an organic solvent. The cathodes are typically composed of a metal oxide-based material, while the anodes are often made up of graphite or metallic lithium with respective current collectors of aluminum and copper. The electrode generally represents 57% of the module's mass, compared to 24% for the casing. The rest of the mass is divided between the electrolyte, separator, and other volatile components [7].

Among all the batteries chemistry described in this study, steel accounts for an average of 4.27% of the total mass, while plastic represents 13.30%. Aluminum ranges between 11 and 18% of the mass. More specifically, for LTO, NMC, and NCA technologies, cobalt makes up an average of 2.78% of the total mass. Lithium is present in less than 1% of LMO batteries, between 1 and 2% for LFP, NMC, and NCA batteries, and equal to 2.49% for LTO batteries [10]. The breakdown of the mass composition of the active materials comes from the supplier for LFP, NMC, NCA, and LMO batteries and from the reference for LTO batteries [11] (TABLE II). The chemistry used for the NMC battery is chemistry 622: its electrode consists of 60% nickel, 20% manganese and 20% cobalt.

TABLE II. MASS COMPOSITION OF LITHIUM BATTERIES

Elements	Mass composition [%]				
	LFP [a]	***NMC*** [b]	***NCA*** [c]	***LTO***	***LMO*** [d]
Aluminum	11.38	12.77	14.15	13.61	17.88
Carbonate ethylene	11.90	11.50	11.50	5.34	11.63
Cobalt		2.97	1.76	3.62	
Copper	9.01	16.08	13.58	2.91	17.80
Fluoride	4.74	3.76	3.30	23.43	2.51
Graphite	13.47	12.03	15.26	2.51	15.00
Iron	9.90	0.12	0.0004	0.15	0.003
Lead	0.003				
Lithium	1.26	1.80	1.43	2.49	0.52
Manganese	0.09	2.85		3.62	8.40
Nickel		8.56	9.57	10.86	0.02
Others	2.97	4.17	3.65	4.01	3.34
Oxygen	12.28	5.84	6.63	7.41	5.63
Phosphorus	5.62				
Plastic	12.99	13.00	13.12	14.33	13.04
Steel	4.40	4.40	4.40	3.76	4.40
Titanium				1.74	

[a] msesupplies.com , [b] electrodesandmore.com , [c] mtixtl.com, [d] samaterials.com

III. SOCIETAL IMPACTS OF MATERIALS

Considering the societal impact of the materials used in battery manufacturing is imperative. In fact, the extraction of these materials often results in significant socio-economic consequences for local population, with the most vulnerable communities often being the most affected. Additionally, the loss of agricultural land and the deterioration of local ecosystems have long-term consequences for surrounding communities [12].

The energy transition metals include copper, graphite, iron, nickel, lithium, aluminum, manganese, and cobalt. The societal impact of these metals is already known through the references [2], [13]. However, the societal impact of carbonate ethylene, fluoride, lead, plastic, phosphorus, sulfuric acid, steel and titanium remains to be determined. This determination is made by associating maps listing the various societal impacts with the production sites of the materials [2].

A. Societal impacts of energy transition metals

In [2] the societal impacts for lithium, iron, copper, nickel, aluminum, platinum, and cobalt can be found. The societal impact of rare elements is also given, but titanium is not included in this type of element. In [13], societal impacts is given for graphite, lithium, nickel, cobalt, and manganese. The global societal impact is the arithmetic mean of the three factors: social vulnerability, land use, and impact on local populations. In both references, societal impacts are given at different scales: although they are complementary in terms of the materials studied, the scales need to be standardized.

The impacts are given on a scale of 0 to 5, with 5 being the factor with the strongest societal impact [2]. A color scale is also assigned, ranging from red for the highest value to green for the lowest value (Fig. 2). The societal impacts of these materials are illustrated in TABLE III.

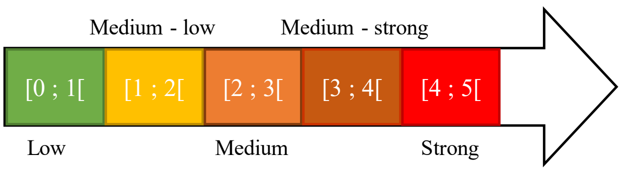

Fig. 3. Color scale for societal impacts

TABLE III. ENERGY TRANSITION METALS SOCIETAL IMPACTS

Elements	Social vulnerability	Land uses	Impacts on community	Global societal impact
Lithium [e, f]	1.00	1.00	2.00	1.33
Copper [e]	1.00	2.00	4.00	2.33
Nickel [e, f]	2.00	3.00	2.00	2.33
Graphite [f]	1.67	3.33	3.33	2.78
Iron [e]	2.00	4.00	2.00	2.67
Aluminum [e]	3.00	4.00	1.00	2.67
Manganese [e, f]	1.67	3.33	3.33	2.78
Cobalt [e, f]	5.00	5.00	5.00	5.00

[e] [2], [f] [13]

Of all the societal impacts presented, lithium is the metal with the least risk from a societal point of view. Even though usage conflicts exist in lithium mines, notably in Argentina and Chile, there are no artisanal mines. Nevertheless, lithium has unknown toxic effects. Cobalt is the metal with the greatest societal impact. Although artisanal mining represents a small share of total extracted tonnages, these mines face phenomena of corruption, forced labor, and child labor. In addition, cobalt mines transmit numerous respiratory and dermatological diseases to local populations [13].

B. Societal impacts of carbonate ethylene, fluoride, lead, plastic, phosphorus, sulfuric acid, steel and titanium

The geographic distribution of societal risks is provided in the supplementary information of the reference [2]. Maps are presented for factors of social vulnerability, land use, and impact on local populations. Fig. 2 uses one of the maps presented in the reference and illustrates the global distribution of impacts on local populations.

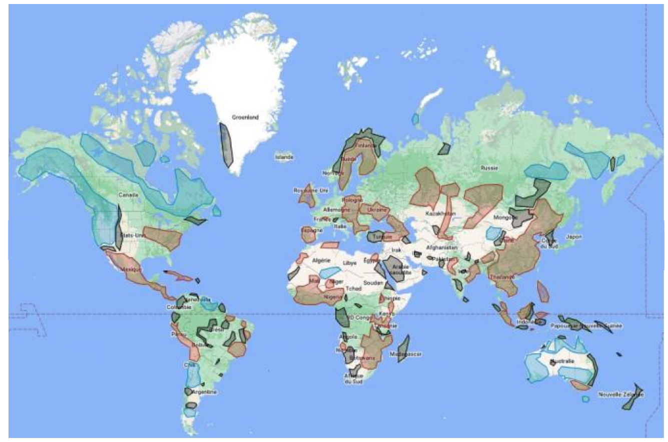

Fig. 2. Worldwide distribution of impacts on community

A weighting ranging from 1 to 3 is applied to each production site: 1 representing an insignificant impact from mining, 3 representing the strongest impact. These maps are divided into six regions: Africa, Asia, Europe, North America, South America, and Oceania. In addition to these maps, the production distribution by country for lead, plastic, sulfuric acid, fluoride, phosphorus, titanium, and carbonate has been extracted from the Observatory of Economic Complexity website. By combining the maps with the production countries, the societal impact by material and for each country is found.

To find the societal impact of each material F, the societal impact per region f is first calculated:

$$f_{j,i} = \frac{1}{k}\sum_{s=1}^{k} x_{j,i,s} \quad (1)$$

f represents the arithmetic mean of all the weights x applied to the production sites s. In (1), i represents the production sites, k represents the number of production sites, and j represents the factor under study (social vulnerability, impact on local populations, and land use).

TABLE IV presents the value of each factor f by region and for each element. These factors were not determined for steel. Indeed, since steel is composed of more than 98% iron, its societal impacts are considered similar to those of iron. As for determining the societal impacts of plastic, the production of propylene and polyethylene was differentiated initially. Once the various societal factors were attributed to these two sub-elements, the societal impacts of plastic were defined by multiplying the societal impacts of propylene and polyethylene by their production distribution. Generally, the social vulnerability factor is high in Africa and the American continent. The primary cause for Africa is poverty, with a lack of access to basic needs such as clean water, food, and education. In the American continent, the increase in this factor is mainly due to significant disparities in wealth distribution and, consequently, access to healthcare. In Europe, the high impact on community is due to conflict in Spain, Portugal, eastern Germany, and the Balkans [14].

TABLE IV. SOCIETAL IMPACTS BY REGION, FOR EACH ELEMENT

Region	Social vulnerability	Land uses	Impacts on community
Element: Carbonate ethylene			
Africa	4.86	2.50	3.54
Asia	2.67	2.03	2.91
Europe	1.15	1.92	4.55
North America	4.52	3.81	3.57
Oceania	1.25	2.08	1.25
South America	4.00	3.25	1.25
Element: Plastic			
Africa	5.00	3.03	3.91
Asia	2.62	2.20	2.89
Europe	1.14	2.14	4.55
North America	4.46	3.52	2.70
Oceania	0.27	0.82	0.27
South America	3.92	3.41	1.15
Element: Lead			
Africa	4.83	2.07	3.19
Asia	2.50	2.26	2.56
Europe	1.25	1.94	4.51
North America	4.50	4.75	4.75
Oceania	0.63	1.25	0.63
South America	3.89	3.06	1.39
Element: Sulfuric acid			
Africa	4.75	2.50	3.63
Asia	3.15	1.85	3.04
Europe	1.36	2.00	4.36
North America	4.32	3.86	3.41
Oceania	1.25	1.25	1.25
South America	3.33	3.75	1.67
Element: Titanium			
Africa	5.00	1.83	3.00
Asia	2.76	1.05	2.76
Europe	1.30	1.90	4.30
North America	3.13	3.75	2.50
Oceania	1.25	1.25	1.25
South America	5.00	4.00	1.00
Element: Fluoride			
Africa	5.00	3.33	1.67
Asia	3.38	1.47	3.09
Europe	1.41	1.85	4.24
North America	3.33	4.17	3.33
Oceania	2.50	2.50	2.50
South America	0.00	2.50	2.50
Element: Phosphorus			
Africa	4.72	2.92	3.75
Asia	2.33	1.72	2.76
Europe	1.29	2.10	4.60
North America	4.29	3.21	2.86
Oceania	0.83	1.67	0.83
South America	4.00	4.00	1.00

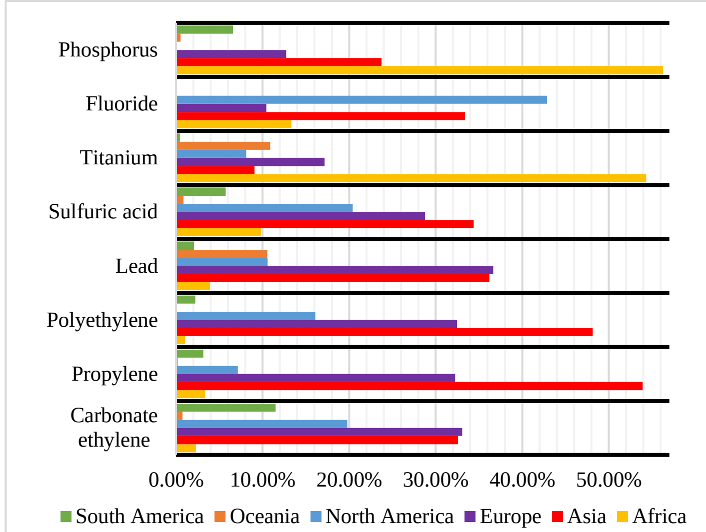

Fig. 4. Worldwide production of the materials studied

Fig. 4 provides the production distribution for the studied materials. These production rates, referred to as τ, are used to calculate the societal impacts for each material. The societal impact of each material F represents the sum of the product of the societal impact by region and its production rate τ. In (2), n represents the number of regions.

$$F_j = \sum_{n=1}^{i} \tau_i . f_{j,i} \qquad (2)$$

The initially found societal impact ranges from 1 to 3 depending on the weighting applied. The result is then normalized between 0 and 1 to match the data found in III.A Results are presented in TABLE V.

TABLE V. SOCIETAL IMPACTS OF OTHER METALS

Elements	Social vulnerability	Land uses	Impacts on community	Global societal impact
Steel	2.00	4.00	2.00	2.67
Carbonate ethylene	2.73	2.50	3.39	2.87
Plastic	1.98	3.15	3.73	2.95
Lead	2.17	3.30	4.05	3.17
Sulfuric acid	2.21	3.47	3.98	3.22
Titanium	3.95	3.10	3.55	3.53
Fluoride	3.95	3.63	3.78	3.79
Phosphorus	4.15	3.47	4.00	3.87

The societal impact of steel is similar to that of iron, as steel is mainly composed of iron. Among the elements presented in the table, the societal impact of phosphorus is the highest: a large portion of its production sites are located in areas with high social vulnerability and significant impact on local populations.

IV. Results and discussions

A. Uncertainties about the societal impacts of materials

When attributing societal factors to material production sites, some of them are located in undefined areas. For these sites, the chosen societal factor corresponds to that of the nearest neighboring zone. Thus, the ratio between the number of production sites belonging to an undefined zone and the number of production sites in a defined zone constitutes an uncertainty ΔF. This uncertainty is calculated for each material and for each factor.

$$\Delta F_j = \frac{s_{unknown,j}}{s_{total,j}} \quad (3)$$

$s_{unknown}$ represents the undefined areas, s_{total} the total number of production sites and j represents the factor under study. The global uncertainty ΔF is the arithmetic mean of uncertainties in these three factors.

TABLE VI. Uncertainties on societal impacts, for each material

Elements	Social vulnerability	Land uses	Impacts on community	ΔF
Carbonate ethylene	28.39%	36.77%	30.97%	32.04%
Plastic	26.39%	22.46%	28.78%	25.88%
Lead	24.81%	27.13%	31.01%	27.65%
Sulfuric acid	14.43%	24.74%	27.84%	22.34%
Titanium	20.00%	25.71%	18.57%	21.43%
Fluoride	26.53%	26.53%	24.49%	25.85%
Phosphorus	26.88%	24.73%	20.43%	24.01%
Other elements	0.00%	0.00%	0.00%	0.00%

TABLE VI presents the uncertainties found for the studied materials. The average uncertainty across all these materials (excluding steel) is 25.6%: approximately one-fourth of the production sites fall outside the areas where societal factors are defined.

The societal impacts of lithium, copper, nickel, graphite, iron, aluminum, manganese, and cobalt, as given in references [2] and [13], have an estimated uncertainty of 0.00%. The same uncertainty is found for steel, as the societal impacts of steel are estimated to be similar to those of iron.

B. Uncertainties about the societal impacts of batteries

The uncertainty regarding the societal impact of batteries ΔF_b consists of the uncertainty related to the societal impacts of materials ΔF. This uncertainty ΔF_b depends on the mass composition of the studied battery. ΔF_b represents the sum of uncertainties related to the materials multiplied by their mass fractions w in the studied battery.

$$\Delta F_b = \sum_{n=1}^{m} w_m . \Delta F_m \quad (4)$$

With m representing the number of elements composing the battery.

The second uncertainty to be considered in the calculation of the total uncertainty is the uncertainty related to the mass composition Δm. Δm arises from the "other" category in the mass distribution of batteries (TABLE II). For the lead-acid battery, the uncertainty related to the mass composition corresponds to the sum of the mass fractions of Arsenic, Antimony, and glass. The societal impacts of these materials have not been calculated due to their low quantity in this battery chemistry (TABLE I).

The final uncertainty Δ on the societal impact for each battery is calculated as follows:

$$\Delta = \sqrt{\Delta F_b^2 + \Delta m^2} \quad (5)$$

TABLE VII. Uncertainties of societal impact and mass composition

Battery	*Societal impact* ΔF_b	*Mass composition* Δm	*Total* Δ
LMO	8.00%	3.34%	9.97%
NMC	8.38%	4.17%	10.00%
NCA	8.37%	3.65%	10.24%
LFP	10.05%	2.97%	11.28%
LTO	12.37%	4.01%	13.04%
PbA	21.40%	0.76%	21.56%

In addition, societal impacts are calculated based on data available in 2023. As the societal conditions of the production sites studied can vary very rapidly, the data used to calculate the societal impacts need to be updated frequently. Add an additional degree of uncertainty to the one theoretically calculated is necessary, depending on the year in which this article is read.

C. Results

Fig. 5 presents the overall societal impacts of each battery, taking uncertainties into account. These results are overlaid on the color scale.

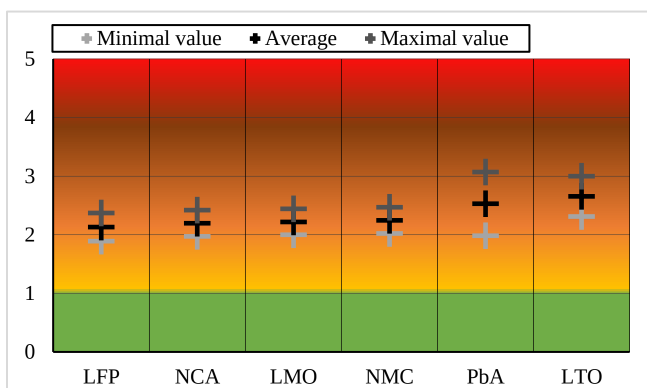

Fig. 5. Batteries societal impacts and results uncertainties

Considering only the average values, LFP batteries have the lowest societal impact, while LTO batteries have the highest. However, their average values are within the same range. Across all batteries studied in this article, the societal impact is medium. However, these results should be viewed with caution. Indeed, taking uncertainty into account reveals the variation of the societal impact throughout the scale. Thus, considering the minimum values of the societal impact, LFP, NCA, and PbA batteries have a medium-low societal impact. Considering the maximum values, PbA and LTO batteries have a medium-strong societal impact.

To make the most informed choice on battery technology, it is necessary to separately consider their societal impacts according to the three categories studied: social vulnerability, impact on local populations, and land use. Fig. 6 shows the values of these three factor categories for each battery chemistry.

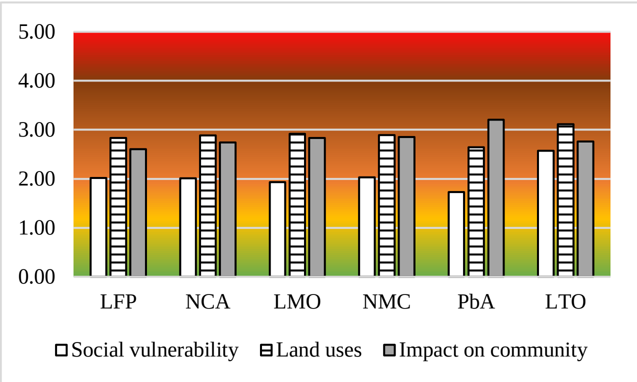

Fig. 6. Breakdown of societal impacts for each battery chemistry

By analyzing the societal impacts with a decomposition into sub-factors, the PbA battery proves to be the least socially vulnerable but the most impactful on local populations. This is mainly due to a well-known and controlled lead extraction process but with still significant impacts on the health of local communities. The LTO battery exhibits the highest impact on land use. This result is caused by the high fluoride content of this battery. Across all lithium batteries, the impact on local populations is relatively similar : regardless of the extracted materials, the damages to the health of local communities are comparable. The LTO battery has the highest social vulnerability factor.

The societal impact given in this article is calculated with respect to mass distribution. Once again, to make a fair comparison between battery chemistries, energy density must be taken into account. For the same energy need, about four times more PbA batteries are required than NMC batteries, thus requiring four times more material extraction. Moreover, significant technological advancements are expected in the chemical composition of batteries. The introduction of all-solid-state batteries or the replacement of graphite with silicon could alter the results presented in this article.

Finally, battery recycling must also complement these studies: the higher the battery technology's recycling rate, the lower its societal impact will be, as its proportion of virgin materials will decrease dramatically.

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