Lithium Cells For Railway Rolling Stock: a Comparative Study in terms of equivalent Environmental Impact

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***Abstract*— For nonelectrified or partially electrified lines, Battery Electrical Multiple Unit (BEMU) trains are a feasible and sustainable alternative to diesel-propelled solutions, especially for local passenger services. Batteries are a fundamental component for this kind of train playing also a key role in terms of equivalent impact in terms of CO2 emissions.* Within the research activities carried out in the framework of the European project FP4 – Rail4EARTH, i*n this work authors focus their attention on the different impacts associated with widely diffused lithium chemistries like LTO, LiNMC, $LiFePO_4$, investigating how typical specifications of the railway sector substantially influence both performed technical choices and environmental impact in terms of equivalent CO_2 emissions, calculated according to* ISO 14044:2021.**

Keywords—BEMU, ROLLING STOCK, Lithium Cells, Railway, Environmental Impact.

I. INTRODUCTION

The field of application of this study is restricted to on-board traction batteries of BEMUs (Battery-Electric-Multiple Unit), a typology of rolling stock that is gathering an appreciable commercial success [1-8], promising a complete substitution of pre-existing diesel multiple unit (DMU) on partially electrified lines and the elimination of direct emissions during the use phase. The reason for this success is substantially described by the SWOT (Strength, Weakness, Opportunities, Threats) analysis of Table I. Most of this product shares the same (or a quite similar) layout, which is derived from standards concerning hybrid series trains[9]. Main Features of these commercial trains and market-ready prototypes of BEMUs have been used to produce a simplified operational scenario corresponding to simplified specifications of Table II.

TABLE I. BRIEF SWOT ANALYS OF BEMU TRAIN WITH RESPECT OF OTHE INNOVATIVE SOLUTIONS.

	HELPFUL	HARMFUL
INTERNAL	STRENGTH -Autonomy and performance of Battery-Operated Trains can be increased even using storage with relatively modest performances. -Dynamic recharge is performed with standard pantographs under conventional catenaries, the system can be interfaced with electrical infrastructures used in the railway sector. -Recharge is performed in Motion, no time is wasted for recharge	WEAKNESSES -If performances of batteries are modest, electrified sections should be quite extended (higher costs). -Aging of batteries due to fast recharge may reduce the life of the installed battery storage. -If traffic intensity increases costs of a fully electrified system should be cheaper than a partially electrified one with battery-operated trains.
EXTERNAL	OPPORTUNITIES -Performances and costs of Battery Storage Systems are improving thanks to the mass production of batteries for the automotive sector. -If the traffic increases, a partially electrified line can be converted into a fully electrified one. -A dynamic recharge of the train along intermediate sections of the line is compatible with the integration of the system in local grids sustained by renewable energy sources.	THREATS -Hydrogen-powered solution can be a more valid competitor. -Evolution of storage technologies should involve further interventions on the recharge infrastructure.

Preliminary evaluation of expected mission profiles has been done considering previous studies in which the same authors have investigated different application scenarios in which the proposed partially electrified lines have both small [10] or step slopes[11].

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TABLE II. TYPICAL FEATURES OF BEMUS [1-8].

Property	Mean Value or (Typical Range)
Max Speed	160[kmh] (140-180[kmh])
Mass	180[tons] (160-200[tons])
Traction Power	1.5[MW](1.1-1.9[MW])
Installed Battery Size	650[kWh] (350-950[kWh])
Expected Storage Weight	9[tons] (5-13[tons])
Expected autonomy	100[km] (50-150)
Expected life (mileage)	$2.4*10^6$[km] ($1.6-3.2*10^6$[km])
Expected life (years)	20[years] (15-25[years])
*including DC-DC	

In some of these studies, authors have also compared the expected life of different lithium chemistries for a near-realistic mission profile [10], summing both the combined effects of cycle and calendar aging. These results lead to results and considerations that are substantially aligned to available technical literature[12]: lithium chemistries that can be adopted for battery-operated rolling stock are similar to their corresponding automotive counterparts, but different design specifications and specific exigencies of railway application should lead to choices that are radically different with respect to road vehicles. However, it's confirmed that batteries are a crucial component, also for the design of innovative, multimodal rolling stock. Battery performances are mostly defined at the level of cells, and the best candidates for vehicular applications are typically LiNMC (Lithium-Nickel-Manganese-Cobalt), $LiFePO_4$ (Lithium-Iron-Phosphate), LTO (Lithium Titanate), whose main features are described in Table III.

Despite the recognized importance of batteries for BEMUs, there is a substantial lack of scientific literature concerning the comparative sustainability of different lithium chemistries that can be adopted for railway traction systems. In this work authors introduce a preliminary analysis of the equivalent impact according to the LCA (Life Cycle Assessment) methodology [18][19].

II. PERFORMED LCA ANALYSIS

Performed analysis is focused on the main components that define a battery pack, as shown in Figure 1, assuming that the rest of the plant has limited differences with respect to adopted chemistry (an acceptable simplification introduced to circumscribe the analysis to the most significant components).

TABLE III. TYPICAL FEATURES OF DIFFERENT LITHIUM CHEMISTRIES.

Property	LiNMC[20][21]	$LiFePO_4$	LTO[24] [25]
Energy Density	~250 [Wh/kg]	~150 [Wh/kg]	~80-90 [Wh/kg]
Price/kWh [13] (*Cell*//Pack.)*	*60-100[$/kWh]* 100-140[$/kWh]	*50-80[$/kWh]* 90-120[$/kWh]	*100-250[$/kWh]* 150-300[$/kWh]
Nom/**Max**/*Min.* Voltage	3.7 /**4.2**/*3.0* [V]	3.2/**4.0**/*2.8* [V]	2.3/**2.8**/*1.8*[V]
Max *Charge*/Discharge (continuous)	*1C*/3C	*1C*/2C	At least *3C*/3C
Roundtrip.Eff. at 1C	93-95%	92-94%	96-98%
Exp. Life(Cycle Aging)	3000-4000 Cycles	3000-5000 Cycles	+15000 Cycles
Calendar Aging [14]	2-3%year*[15][16]	1-2% year*[15]	Extr.Low* (null or negl. For SOC<50%)[17]
Catode Material	$LiNi_xMn_yCo_zO_2$	$LiFePO_4$	**Various
Anode Material	Graphite	Graphite	$Li_4Ti_5O_{12}$***

*Calendar aging is largely dependent
**For LTO different kind of cathodes can be used in literature [26] LiFeP04 LiNMC or LCo cathodes are proprosed, higher energy densities are assured by most performing cathods (tendentially LiNMC is the considered choice in this paper)
*** sometimes LTO batteries incorporates also some Niobium (NTO-LTO)[27]

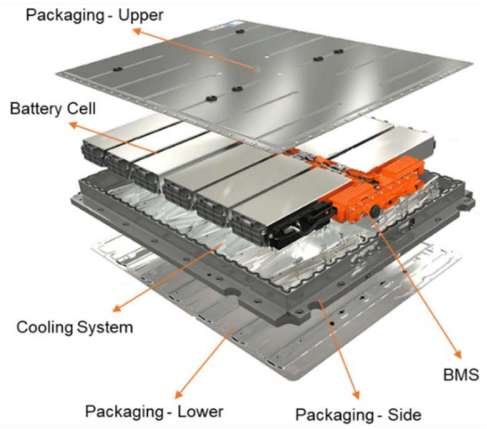

Fig. 1. List of Components that define a Battery Pack.

The analysis considers the entire life cycle of batteries, using a cradle-to-grave approach to compare the three technologies in their railway application according to the scheme of Figure 2, where the different phases of the product life are shown.

To perform the analysis, the so-called F.U. (Functional Unit) must be defined: F.U. is the reference unit that allows different solutions to be compared consistently in an LCA analysis.

For the proposed analysis, F.U. is defined according to (1) as the specific energy that the battery will deliver during its life expressed in *kWh-cycles/kg*:

$$E_{spec_life} = \frac{\overbrace{E_{battery}}^{Specific\ Energy\left[Wh/kg\right]}}{m_{battery}} \overbrace{n_{cycles}}^{Expected\ Life\left[cycles\right]} \quad (1)$$

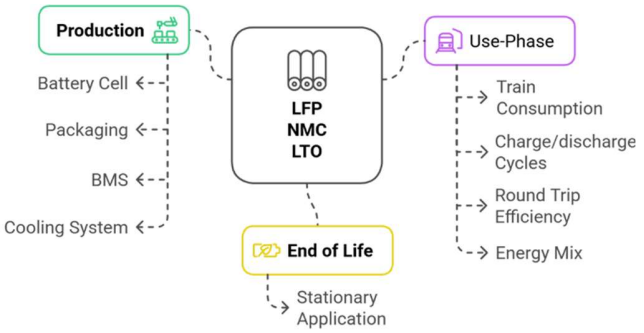

Fig. 2. Craddle to Grave Analysys (different phases of product life).

Chosen F.U. is quite an innovative contribution with respect to current literature [28] since it introduces in a single index a scaling of stored energy with respect to battery weight that takes into account also the expected life of the battery. This is a fundamental innovation for the study of railway systems, where the life of the vehicle can be equivalent or significantly longer with respect to the various chemistries that must be compared (an aspect that is often neglected for analyses that are mostly oriented to automotive or energy markets).

A. Analysis of the Production Phase

For the study of the production phase, it's considered a battery pack designed for a specific use case that was designed for a previous study of the same authors[10]. For the detailed sizing of sub-components and subsystem needed to generate a realistic of involved material and processes it was used the approaches proposed in a recent study of Innocenti [29].

Starting from the layer of Figure 1 that also defines system boundaries, it was possible to evaluate the B.O.M.s (Bill of Materials) for three different battery packs, one for each investigated chemistry.

Processes considered for the Production Phase are the following:

- Extraction, transportation, and processing of raw materials manufacture of battery pack components, divided into four sub-groups:
  - Battery cell;
  - Packaging;
  - BMS;
  - Cooling system;
  - Battery pack assembly.

The data was collected using Ecoinvent version 3.10.1, updated in November 2024, as the reference database. Regarding geographical boundaries, a mixed approach was adopted, combining data representative of the international context with data specific to a particular context, such as the grid mix of the countries considered. An effort was made to prioritize the global origin (GLO in Ecoinvent) of the data where possible, otherwise focusing on China (CN) for production and "rest of the world" (RoW) for assembly. Some results concerning the production impact of different batteries scaled with respect to the chosen functional unit are shown in Figure 3: the calculated impact of the LiNMC one is the highest, while the lowest one is the LFP one.

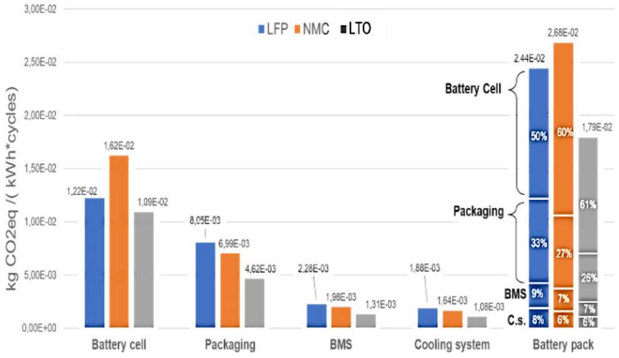

Fig. 3. Equivalent Production Impact of battery pack build with different chemistries (stored with respect chosen functional unit).

It's clear that most of the impact of the battery pack is related to the construction of cells. It's also interesting to notice that the reduced impact of LTO cells with respect to LiNMC is mainly caused by the chosen functional unit, which emphasizes the duration of the battery, which is much longer for LTO batteries. As shown in Figure 4, the impact associated with the construction of LTO batteries is much higher with respect to all the other chemistries if the evaluation is performed with respect of stored energy in kWh, since both adopted cathode and anode materials are the most impacting, and the energy density is the lower one. Also, the energy density of LTO is lower. But the proposed functional unit is the right choice for a railway application since required life of the system is very long so batteries with lower durations should be substituted many times, increasing their equivalent impact. This concept is

also clear if the impact of the five most impactful processes is compared with respect of the chose functional unit, as shown in Figure 5: the impact of the cathode construction for both chemistries are different (which is the same material for LiNMC and LTO batteries) since energy density and expected life are different.

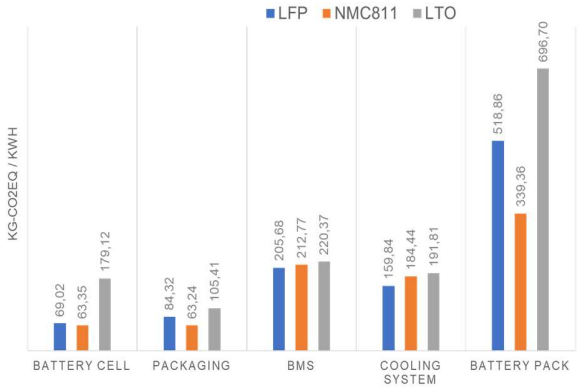

Fig. 4. Comparison of Equivalent Production Impact of battery pack scaled with respect to stored energy (kWh).

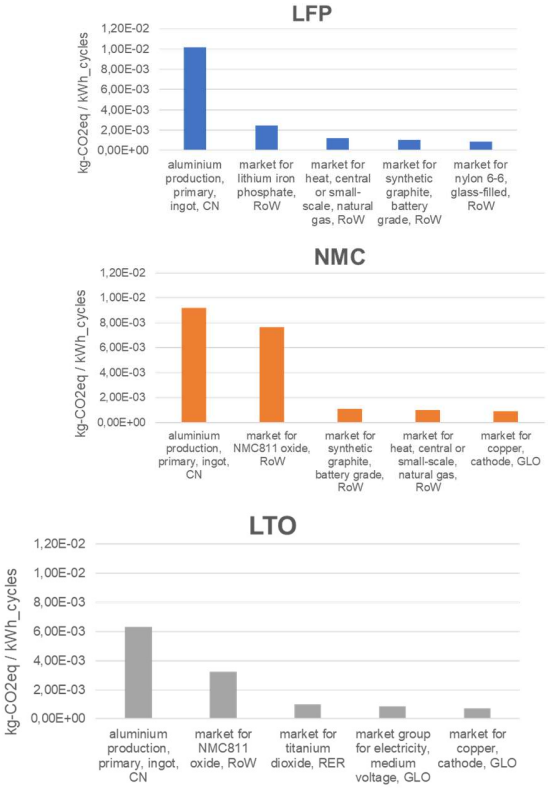

Fig. 5. Comparison of the five most impactful processes for each chemistry.

B. Analysis of the Use Phase

Analysis of the use phase of batteries is mainly focused on the energy consumption related to train operation with respect to the energy mix adopted in nine different countries listed in Table IV.

The energy required per kilometer travelled by train is calculated according to the methodology suggested by EN50591 standard[30] and then properly scaled with respect of chosen functional unit. The estimated train consumption, considered in this work, is equal to 4.36 kWh/km. Total consumed energy of batteries is then evaluated considering roundtrip efficiency of different chemistries. Some results in terms of equivalent impact with respect of the chosen functional unit are shown in Figure 6:

The impact for different chemistries considering both construction and use phases is compared considering different also different countries, France and Poland for which the equivalent impact of the adopted energy mix is completely different.

TABLE IV. EQUIVALENT CARBON INTEXITY OF DIFFERENT COUTRIES ACCORDING TO THE ADOPTED ENERGY MIX.

Country	Carbon Intensity [kg CO2eq/kWh]	Country	Carbon Intensity [kg CO2eq/kWh]
France	0,021	**Japan**	0,509
Denmark	0,082	**China**	0,555
Spain	0,128	**India**	0,58
Germany	0,225	**Poland**	0,619
Italy	0,294		

For countries like France, for which the adopted energy mix is highly sustainable, the impact of the use case is quite like the one of the construction phases. Otherwise, if the supposed energy mix is mostly derived from fossil sources (as in Poland), the impact of energy used is dramatically bigger (even 30-40 times higher). Also, in this case LTO battery is advantaged with respect to other chemistries, but this advantage is not due to the chosen functional unit, but by the extremely low internal impedance of LTO cells, which increases the round-trip efficiency, reducing energy losses.

Hybrid Diesel Trains, where a significant part of power stored by the battery is produced by Internal Combustion engines with limited efficiency, can also be studied with the same approach. Also, for this type of rolling stock the impact derived by the product use phase is quite dominant.

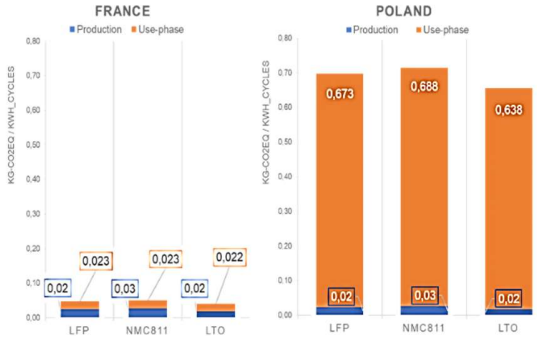

Fig. 6. Comparison of the five most impactful processes for each chemistry.

C. *End of Life-Second Life Application*

For this part of the study, the authors have also considered the possibility of a second-life reuse of the battery after the service. Typical reuse should be for static applications such as backup power storage for telecommunication systems[31], or peak shaving for reversible power stations along the line[32].

For what concerns chemistries that are more diffused, like LiNMC or $LiFePO_4$ there are some many references in literature[33][34] that can be useful to evaluate the improvement in terms of GWP100 (Global Warming Potential). For LTO, this estimation is much more difficult, since this kind of cells are much less diffused, and their very long life further contributes to reducing the availability of data concerning the behaviour of aged cells. For this work it is estimated a percentual improvement with respect to the construction phase is shown in Figure 7. These results also demonstrate the limited advantages for the proposed application since the use phase of the product is predominant in terms of impact, especially when energy is mostly produced with fossil fuels.

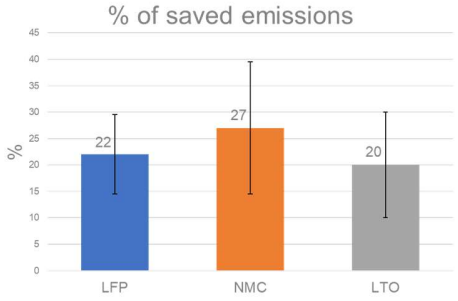

Fig. 7. Comparison of the five most impactful processes for each chemistry.

III. Conclusions and Future Developments

In this work authors performed a comparative sustainability analysis regarding the application to BEMU trains of lithium batteries with different chemistries. The results of this work clearly indicate that currently for BEMU trains, LTO cells present clearly advantages also in terms of sustainability, due to their long expected life, which substantially reduce the impact of the production phase, and their high round-trip efficiency, which assure a better efficiency during the use phase. Efficiency plays a key role in determining sustainability, but efficiency is strongly affected by the way in which powerflow across the battery is managed. So, authors are working to further extend the analysis in terms of sensitivity with respect of adopted recharge and use policies.

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