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Life Cycle Assessment of Lithium-ion Battery Pack: Implications of Second-life and Changes in Charging Electricity

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Abstract* — The *impact of battery electric vehicles (BEV) on global warming is influenced by their battery size and charging electricity source. Therefore, Life Cycle Assessment (LCA) studies of BEV may consider changes in the energy sources for charging and the end-of-life management of used batteries. This study conducts an LCA of a BEV battery pack considering the influences of the charging electricity mix and repurposing the used battery. A cradle-to-grave system is considered to assess the environmental impacts of a Lithium-ion battery (LIB) weighing 290 kg and a pack energy density of 188.3 Wh/kg. The LIB cells were repurposed at their first end-of-life, considering a 50% cell conversion rate (CCR) for 5 years second-life. LCA results show a 6% reduction in GWP impact when the share of renewable sources in the charging electricity mix is considered. Considering recycling, an 11% reduction in GWP is found and less than 1% reduction for repurposing the used LIB cells. The sensitivity analysis found marginal benefits for a longer second-life and higher CCR values (>50%). The parameter with the most influence in the results is the source of electricity to charge the repurposed LIB. Thus, the potential benefits of second-life batteries strongly depend on the source of charging electricity followed by a longer second lifetime (>5 years).

Keywords — Life cycle assessment (LCA), second-life batteries, electric vehicles, li-ion battery

I. INTRODUCTION

Mitigating climate change impacts require efforts from all economic sectors to reduce anthropogenic greenhouse gas (GHG) emissions [1]. In 2018, carbon dioxide (CO_2) emissions from the transport sector reached 8.2 Gt CO_2-eq and were responsible for about 24% of energy-related CO_2 emissions [2]. In this same year, road vehicles contributed to around 75% of CO_2 emissions of this sector, underlining the need to further abate transport emissions. In this context, the transport sector is transitioning to low-carbon technologies, such as battery electric vehicles (BEV), to improve its environmental performance. However, Life Cycle Assessment (LCA) studies have shown that impacts of BEV production are still higher than conventional cars [3], [4].

The main difference in production impacts of the BEV in comparison to conventional cars is the added burden of battery production in BEV [4]. In addition to this, the potential of BEVs to mitigate climate change strongly depends on the source of electricity used to charge its battery during the use stage [3], [5]. In light of this, there are several initiatives to improve the environmental performance of BEV batteries, such as their second use in less demanding applications [6], [7]. After their first use in BEV, around 60% to 80% of the initial battery capacity remains making them suitable for a second use in such applications, while avoiding the production of new batteries [6], [7].

To this end, this paper aims to perform an LCA of a Nickel Manganese Cobalt (NMC) Li-ion battery (LIB) for BEV application and assess the implications of extending its lifetime for a second use in less demanding applications. Furthermore, the study also considers changes in the electricity sector that could directly influence the life cycle environmental impacts of BEV and their batteries – the increase in the share of renewable energy sources (RES). Thus, an added objective of the paper is to examine the impact of changes in the electricity sector on the environmental performance of BEV batteries.

II. MATERIAL AND METHODS

A cradle-to-grave LCA was performed based on the ISO standards [8], [9]. The goal was to assess the environmental impacts of a BEV battery pack, considering the influences of the charging electricity mix and repurposing the used battery. The functional unit was one battery pack of 54.6 kWh for a B-segment BEV, sufficient for charge cycles between 3,000 and 5,000 at 80% depth of discharge (DoD), driven for at least 160,000 km over a lifetime of 10 years (2019 – 2028). The system boundary covers the production, use, and end-of-life (EoL) of the entire LIB (Figure 1), weighing 290 kg and has a pack energy density of 188.3 Wh/kg. The LCA was performed considering the reference, dynamic, and repurposed scenarios. An extended system boundary to avoid allocation between first and second use was considered, allowing the inclusion of an equivalent LIB (hereafter "avoided LIB") that the repurposed LIB might replace.

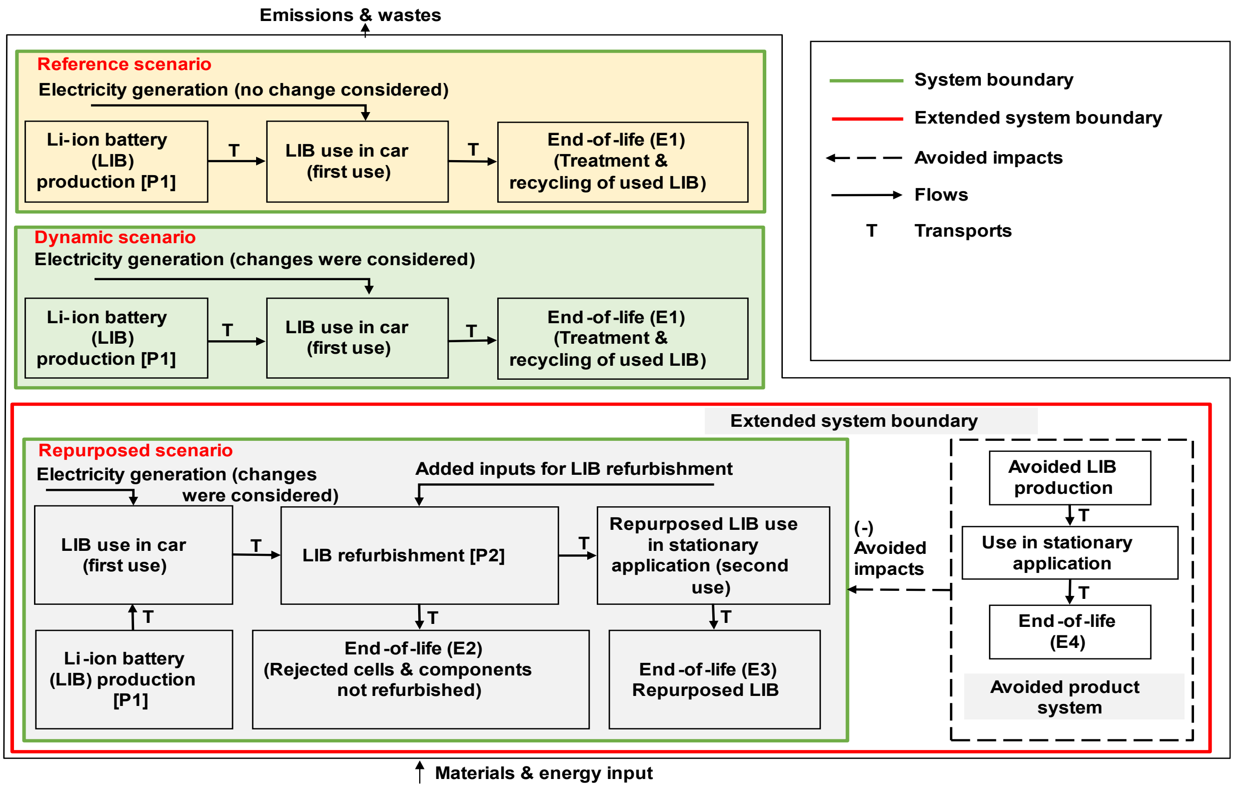

Figure 1:System boundaries and scenarios in this study.

The first use of the LIB pack in a BEV was modelled based on previous studies as the electricity losses due to the internal battery efficiency and the extra energy required to carry the weight of the battery through its lifetime [10], [11]. LIB cell production was considered to occur in Asia as over 88% of LIB cell manufacturing capacity is currently located in this region [12]. The LIB pack assembly, the use phase, and the EoL stages were assumed to occur in Europe. The production of the LIB cells and the battery pack components (consisting of battery packaging, cooling system, and battery management system) were modelled based on secondary data in references [13]–[15].

Transportation of the LIB pack from the manufacturer to the car assembly plant was also included. It was assumed that about 30% of energy use in the BEV could be linked to transporting the LIB pack (WE_{ratio}) [10]. Likewise, 95% and 80% of roundtrip efficiencies were assumed at the battery start-of-life and end-of-life, respectively. The energy efficiency fade was assumed to degrade linearly with a constant degradation of 4.62E-5 [11]. Electricity losses due to the LIB efficiency (E_{loss}) and the extra electricity needed to carry the LIB pack (E_{mass}) were calculated using Eq. 1 and Eq. 2, respectively. Table 1 presents the description of the parameters in Eq. 1 and Eq. 2 and the assumed values.

$$E_{loss} = \sum_{t}^{(l_{BEV} * d_{BEV})} \left(\left(\frac{D_{BEV}}{(D_{BEV} * d_{BEV})}\right) * (1 - \eta_t) * C_{BEV}\right) / \eta_t \quad (1)$$

$$E_{mass} = (W_{batt}/W_{BEV}) * WE_{ratio} * D_{BEV} * \left(\frac{C_{BEV}}{\eta_c}\right) \quad (2)$$

Table 1: Parameters to model the use phase of a Lithium-ion (LIB) pack in a battery electric vehicle (BEV).

Parameter	Assumed values	Reference or comments
l_{BEV} = LIB pack service life (year)	10	Based on car manufacturers warranty [16], [17]
C_{BEV}= BEV consumption (kWh/km)	0.19	Estimated using WLTP [18]
η_c = Charging efficiency (%)	90	Based on [19]
d_{BEV} = # of days of BEV use per year	365	Authors' estimate
η_t = LIB pack efficiency at day t of its use (%)	95% at start-of-life to 80% at end-of-life	Based on [6]
W_{BEV} = Mass of BEV (kg)	1541	[20]
WE_{ratio} = Weight-energy relationship (%)	30	[10]
D_{BEV} = Lifetime mileage of BEV (km)	160000	Based on car manufacturers warranty [16], [17]
W_{BEV} = Mass of LIB pack (kg)	290	[13]–[15]
Depth of discharge of repurposed LIB	Range 50% to 60%	Based on [19]

Transport, road (tkm)	71.4	[11]
Transport, water (tkm)	248.2	[11]

In the dynamic and repurposed scenarios, the LIB pack use phase was modelled considering the temporal aspect of the CO_2 content of the charging electricity mix. The average EU electricity mix for each operational year was based on the "Stated Policies Scenarios" for the EU, which proposed implementing existing and announced plans/policies without introducing new policies [4].

The secondary use phase was modelled considering transportation (0.22 tonne-km/kg) of the repurposed LIB to its user and the electricity losses due to its battery efficiency (80% at the start of second life to 60% at the end of second life) [6]. Electricity losses due to the repurposed LIB efficiency (E_{Rloss}) was calculated using Eq. (3). The electricity losses (E) due to the use phase of the avoided LIB was estimated using Eq. (4).

$$E_{R_{loss}} = \sum_{t}^{l_c}(LIB_{cap} * LIB_{\%\,res.cap_{Eol}} * CC * LIB_{\%\,res.cap_k} * (1-\eta_k) * DoD_k)/\eta_k \qquad (3)$$

$$E_{A_{loss}} = \sum_{t}^{l_c}(LIB_{cap} * LIB_{\%\,res.cap_k} * (1-\eta_k) * DoD_k)/\eta_k \qquad (4)$$

Where LIB_{cap} = initial energy storage capacity of the BEV battery/avoided LIB (kWh); $LIB_{\%\,res.cap_{Eol}}$ = residual capacity of the BEV battery at first EoL (%); CCR = cell conversation rate; $LIB_{\%\,res.cap_k}$ = residual capacity of the repurposed/avoided LIB at of a given cycle k (%); η_k = battery efficiency of the repurposed/avoided LIB at cycle k; DoD_k = depth-of-discharge of repurposed /avoided LIB at cycle k (%); and l_c = cycle life of repurposed /avoided LIB cells in secondary use (days).

Inventory data for the LIB pack EoL treatment and recycling were based on Ecoinvent v3.6 [21] and Cusenza et al. [22], respectively. LIB refurbishment was modelled according to [11], considering the impacts of transportation and the state of health. The avoided LIB and the replacement of broken components in the repurposed LIB were modelled based on literature [13]–[15]. It was assumed that 50% of the used LIB cells were viable for second use [11].

The life cycle impact assessment considered all impact categories of the ReCiPe 2016 method [23]. However, the main focus of the discussion was on the impacts on climate change, represented by the impact category Global Warming Potential (GWP). In addition, the sensitivity of the results was tested considering 10% and 100% cell conversion rate (CCR), depth of discharge (DoD) of 30% to 40%, charging electricity for stationary LIB, and extent of the second lifetime of 1, 5, and 10 years.

III. RESULTS AND DISCUSSION

A. Life cycle environmental impacts - Contribution analysis

Figure 2 shows the life cycle environmental impact (as per defined FU) of the Li-ion battery pack for all impact categories of the ReCiPe 2016 LCIA method. The contribution of each life cycle stage is expressed as a percentage of the total contribution to each impact category. Negative contributions express benefits from recycling, changes in electricity, and second-life benefits.

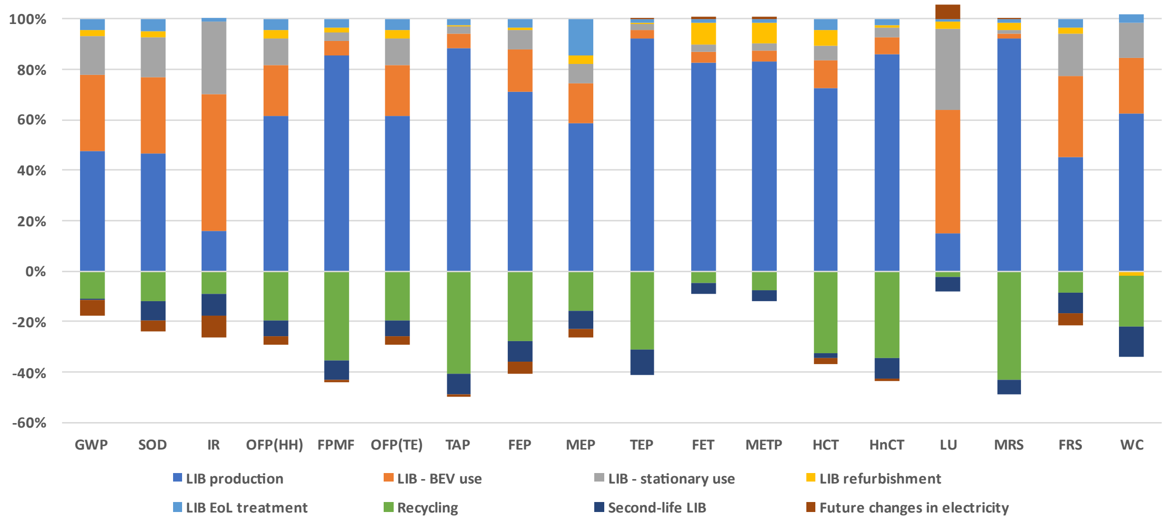

Figure 2: Contribution analysis - Life cycle environmental impacts of LIB pack as per defined FU. Impact categories: Legend: GWP: Global warming potential; OFP(HH): Ozone formation, Human health; SOD: Stratospheric ozone depletion; IR: Ionizing radiation; FPMF: Fine particulate matter formation; OFP(TE): Ozone formation, Terrestrial ecosystems; FRS: Fossil resource scarcity; TAP: Terrestrial acidification potential; FEP: Freshwater eutrophication potential; MEP: Marine eutrophication potential; TEP: Terrestrial ecotoxicity potential; FET: Freshwater ecotoxicity potential; METP: Marine ecotoxicity potential; HcTP: Human carcinogenic toxicity; HnCTP: Human non-carcinogenic toxicity; LU: Land use; WC: Water consumption; MRS: Mineral resource scarcity.

LIB production contributes about 60% to most impact categories, except for GWP (48%), stratospheric ozone depletion (SOD) (47%), ionizing radiation (IR) (16%), land use (LU) (15%), and fossil resource scarcity (FRS) (45%). This trend is consistent with existing LCA studies on LIB for vehicle application [10], [22]. The use of the LIB in BEV has high impacts on IR (54%) and LU (49%). It also exhibits between 30% and 32% for GWP, SOD, and FRS. The contribution of LIB use is around 20% or less in the remaining impact categories. A similar pattern is observed for secondary use in a stationary application.

LIB recycling has its highest reduction in environmental impacts on mineral resource scarcity (MRS) (-43%). This result is expected as recycling materials in manufacturing can reduce or delay the use of virgin materials, thus mitigating material depletion. In addition, LIB recycling shows a 30% reduction in fine particulate matter, terrestrial acidification, terrestrial ecotoxicity, human non-carcinogenic toxicity (HnCTP), and human carcinogenic toxicity (HcTP) impact categories. These results confirm the suggested environmental benefits of LIB recycling.

The potential environmental benefits of integrating more RES in the electricity sector are more relevant for IR (-8%) and GWP (-6%), followed by a 5% reduction in SOD, freshwater eutrophication (FEP), and FRS. However, a 6% increase is observed for LU, and less than 1% in MRS, water consumption, and toxicity impact categories. Impact on land use is mainly linked to bioenergy production and the choice of technology for wind (onshore) and solar (ground-mount) electricity. This implies a negative impact for LU due to the increase of renewable energy production at a local scale. Regulations for the appropriate setting of RES can help mitigate its impacts on ecosystem services and other competing land-based developments. Likewise, the potential increase in the other impact categories highlights the importance of assessing a wide range of impact categories.

The impact of second life LIB is more relevant for the water consumption impact category, with about 12% reduction. Its contribution to other impact categories is greater than 5% reduction, except for GWP (-0,5%), FEP (-4%), marine eutrophication (MEP) (-4%), and HnCTP (-2%).

B. Global warming potential (GWP)

The GWP impacts are detailed in Figure 3. The total GWP impacts of the LIB park without recycling is 6.73E+03 kg-CO_2-eq (red line in Figure 3). LIB recycling at the EoL stage reduces GHG emissions by 11%. LIB production (3.89E+03 kg-CO_2-eq) followed by its first use in BEV (2.48E+03 kg-CO_2-eq) contribute the most to GWP impact (Figure 3). This trend differs from earlier studies. For example, [11] found a higher GWP impact for first use in BEV, but our result is more consistent with recent studies, e.g. [24]. The difference in trend could be linked to the demand for bigger battery sizes in the current BEV market. In addition to this, the carbon content of the charging electricity has reduced over the years, thus mitigating more GWP impacts during the BEV use phase. Overall, the GWP impact per kWh of the battery production is estimated as 71 kg-CO_2-eq/kWh.

When temporal aspects in the CO_2 content of the charging electricity mix are considered (Dynamic scenario), a further 6% reduction in total GWP is achieved. This confirms that the total GWP impact of a BEV will change with the emission profile of its charging electricity mix [25]. Therefore, it is essential to consider the expected changes in the charging electricity mix to reflect the BEV performance in real life since the carbon content of the electricity mix will vary throughout its lifetime. This suggestion follows the efforts to increase the share of RES in the EU energy system as proposed in the European Green Deal by 2050 [26].

The use phase GWP impact of the LIB pack in the BEV is dominated by electricity losses due to the internal battery efficiency - contributing over 70%. This suggests that LIB manufacturers may consider improvements along with this parameter. The remaining GWP impact is shared between electricity losses due to battery mass (28%) and transportation of the LIB pack to the car assembly plant (<1%).

The impact of repurposing 50% of the LIB cells for 5 years in the second lifetime represents less than 1% reduction in total GWP (difference between the grey line and the net GWP (green bar) in Figure 3). Thus, the results show that the potential environmental benefits for second-life batteries are minimal compared to LIB recycling. In this context, the second life of the battery does not present a major contribution to reduce impacts on climate change. On the other hand, its impact on GWP could change depending on the secondary application type and when assessed from a system perspective. Overall, a cumulative decrease of 17.5% in total GWP is achieved under the main assumptions in this study.

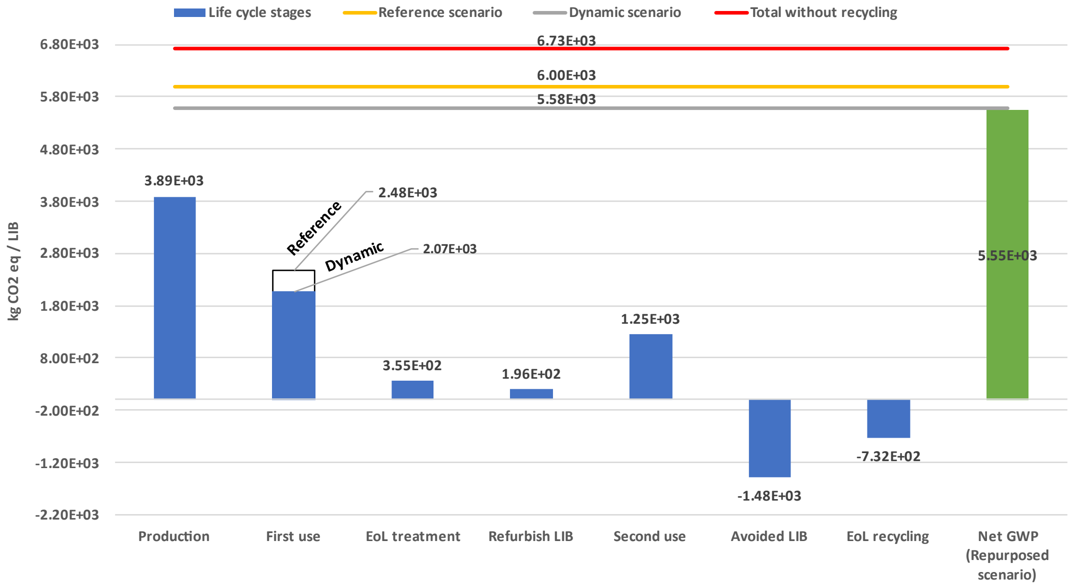

Figure 3: Global Warming Potential (GWP) impacts of a BEV li-ion battery considering secondary use (50% cell conversion rate for 5 years second lifetime) and temporal aspects in the CO_2 content of charging electricity.

C. *Sensitivity analysis*

The sensitivity analysis (Table 2) shows that the benefits of second-life batteries depend on the electricity source used for charging the repurposed LIB, followed by its second life span. This suggests that efforts to integrate RES and improve the internal battery efficiency are critical to mitigate GWP impacts, as electricity losses due to LIB internal efficiency drives GWP impacts in the use phase. For a longer second-life span (10 years), GWP reductions occur across all parameters, except when coal-based electricity is used to charge the repurposed LIB. Thus, from an environmental standpoint, the source of charging electricity is the most critical parameter for second-life batteries.

Table 2:Sensitivity analysis – GWP. Note: negative percentages mean reduction in GWP relative to the total. Sections marked red shows increase in climate change impacts.

	50% CCR		**10% CCR**		**100% CCR**	
Second-life / DoD	**50-60%**	**30-40%**	**50-60%**	**30-40%**	**50-60%**	**30-40%**
1 year	2.6%	1.1%	0.9%	0.6%	5.3%	2.4%
5 years	-0.5%	-7.2%	0.3%	-1.1%	1.7%	-11.8%
10 years	-7.1%	-17.1%	-1.2%	-3.2%	-9.7%	-29.7%
	50% CCR			**10% CCR**		
Second-life / electricity	**Wind**	**Solar PV**	**Coal**	**Wind**	**Solar PV**	**Coal**
1 year	1.4%	1.9%	6.6%	0.6%	0.7%	1.6%
5 years	-4.6%	-2.9%	15.6%	-0.8%	-0.5%	3.3%
10 years	-12.3%	-10.0%	14.6%	-2.6%	-2.2%	2.9%
	100% CCR					
Second-life / electricity	**Wind**	**Solar PV**	**Coal**			
1 year	2.5%	3.4%	13.0%			
5 years	-9.3%	-5.8%	31.7%			
10 years	-24.4%	-19.8%	30.4%			

IV. CONCLUSION

The impacts of LIB production on climate change are higher than the use phase in BEV. These results are driven by the need for a bigger battery size in the current BEV market. However, GWP impacts during the use phase (for both first and second use) are dominated by electricity losses due to the LIB internal battery efficiency. It is therefore essential for battery manufacturers to consider improvements in this parameter. Increasing the share of RES in the electricity sector can reduce the GWP impacts of BEV batteries by 6% through their lifetime. The results suggest that LCA practitioners may consider such improvements in the future LCA of electric vehicles.

Similarly, the potential benefits of second-life batteries strongly depend on the source of charging electricity. Therefore, a greater share of RES would result in a significant reduction of impacts on climate change. However, a higher share of RES may worsen other impact categories (e.g., LU). Therefore, a holistic and integrated approach to land use and energy planning is suggested. Furthermore, the increase in the total second lifetime can also increase the climate mitigation potential of second-life batteries. Therefore, an energy mix with a higher share of RES will maximise the environmental benefits of BEV and second-life batteries.

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