



CIRCULAR economy innovations for resilient, competitive and sustainable BATTERY technologies

D2.4 Environmental and Economic Impact Report

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List of acronyms

BC – Black carbon

CO₂ (w/ C in VOC & CO) – CO₂ emissions, including carbon from VOC and CO oxidation

Direct – Direct recycling

GHGs – Greenhouse gases

Hydro - Hydrometallurgical recycling

LCA – Life cycle assessment

LFP – LiFePO₄

NMC811 – LiNi_{0.8}Mn_{0.1}Co_{0.1}O₂

OC – Organic carbon

PM₁₀ – Particulate matter $\leq 10 \mu\text{m}$

PM_{2.5} – Particulate matter $\leq 2.5 \mu\text{m}$

Pyro – Pyrometallurgical recycling

SOH – State of health

VOC – Volatile organic compounds



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Executive Summary

The report describes the life cycle assessment of recycling evaluated for pyrometallurgical, hydrometallurgical and direct recycling technologies with environmental data and utility footprint in Poland and France to allow European comparison similar to the Life cycle cost analysis. Several metrics have been analysed being scale of operation, chemistry type, recycling method, country of recycling, starting from cell or pack which were fed by the energy mix in the country as of 2025.

In general, the NMC811 recycling process uses more energy and water compared to LFP recycling. The primary energy demand in France is lower than in Poland for all three analysed methods, at both pack and cell level. However, France's water usage is higher than Poland's. The greenhouse gas emissions per kg of feedstock is higher in Poland than in France, both at pack and cell level which is mainly due to the higher fossil fuel usage in Poland's electricity grid compared to large nuclear contribution in France.

The life cycle assessment shows that in general, CO₂ footprint in France is lower than in Poland as opposed to the cost analysis where cost are usually higher in France (D2.2) which shows the dilemma of Europe that CO₂ and cost are very independent factors in battery recycling and depend largely on the countries given cost, labour, energy mix and utilities.

1. Introduction

1.1. Overview and scope

A life cycle assessment (LCA) was performed using the EverBatt model developed by the Argonne National Laboratory¹. This model comprises six modules: battery manufacturing with virgin materials, battery collection and transportation, battery recycling, materials conversion, cathode powder production, and battery manufacturing with recycled materials. The battery recycling module was implemented for the purpose of the project to evaluate the environmental impact of open-loop recycling (Figure 1). The current analysis does not cover battery collection and transportation, disassembly, material conversion or cathode (re)production. The EverBatt model considers three recycling technologies/pathways: pyrometallurgical recycling, hydrometallurgical recycling, and direct recycling. A detailed process flow for each technology can be found in the EverBatt documentation¹.

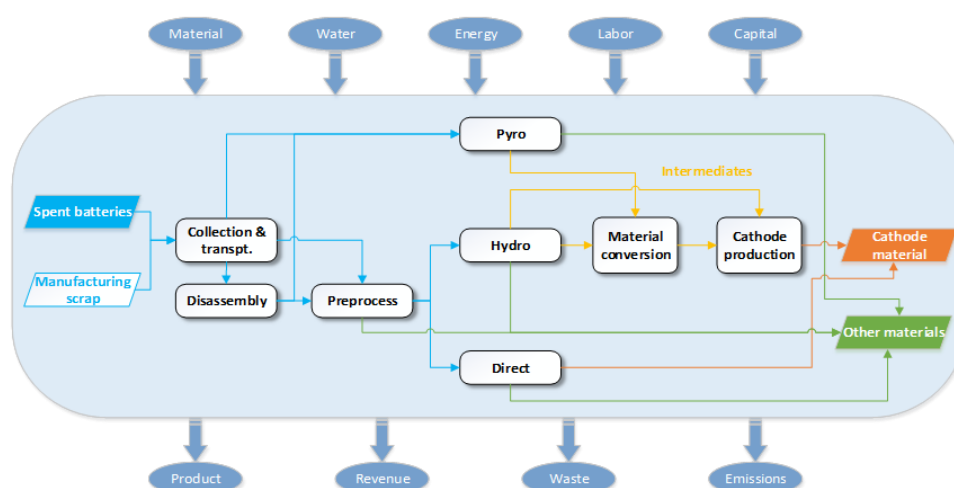


Figure 1. Schematic of the EverBatt recycle module.

1.2. Aim and objectives

The analysis aimed to study the life cycle assessment (LCA) of recycling spent batteries. The investigation was conducted in two European countries with different electricity production mixes: Poland and France (see Table 1) to allow comparison between a country with very nuclear energy mix and one with still high fossil fuel mix in the electricity production and allow comparison to D2.2 cost assessment. Two battery chemistries were studied, including NMC811 ($\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$) and LFP (LiFePO_4), at both the pack and cell levels.

As the feedstock input levels and materials cost do not influence LCA, these parameters were neglected in the analysis. However, the electricity mix has a significant impact on LCA and the electricity mix from 2025 was used². This data is used for the primary analysis in D2.3 here.

Table 1. Electricity generation PL/FR 2024².

Electricity source	Poland	France
Residual oil	4.45%	2.02%
Natural gas	12.17%	3.42%
Coal	53.54%	0.30%
Biomass	4.93%	1.75%
Nuclear	0.00%	68.04%
Hydro	1.36%	12.43%
Others	23.55%	12.04%

2. LCA of recycling in Poland and France

Methodology: The initial setting of cost, usage, energy density and material prices and footprint was already presented in D2.2 with all respective sources which is used here also exactly the same to allow direct comparison of cost and life cycle analysis. D2.2 data served as the setting for the life cycle assessment to analysis the three different recycling technologies (pyro-, hydrometallurgical and direct) for the two chemistries (LFP and NCM811) in France and Poland, respectively. The data was feed into the Everbatt model to allow a direct comparison between cost and life cycle data. Figure 2 and Table 2 show results of our calculations and its comparison of the energy and water consumption associated with NMC811 recycling in Poland and France. Hydrometallurgical NMC811 recycling is the technology that consumes the highest energy and water per kg of feedstock, followed by direct recycling and pyrometallurgy as the leaching step consumes lots of water but also energy during the roasting process. The primary energy demand in France is slightly lower than in Poland for all three analysed methods, at both pack and cell level due to cleaner and more efficient energy generation. On the other hand, water usage is higher in France than in Poland.

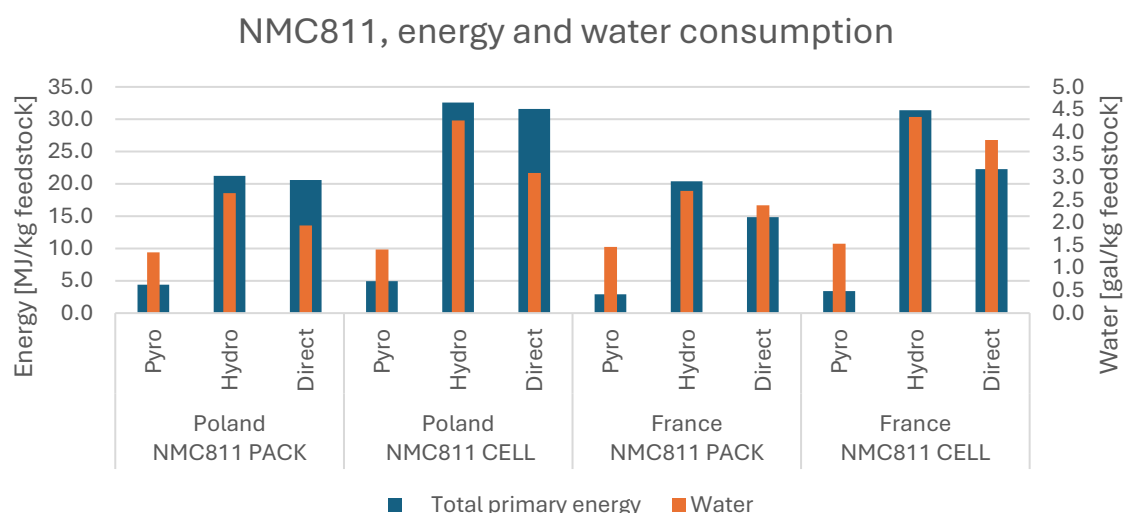


Figure 2. Energy and water consumption for NMC811 recycling.

Table 2. Energy and water consumption for NMC811 recycling.

	Poland					
	NMC811 Pack			NMC811 Cell		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	4.393	21.247	20.613	4.928	32.599	31.578
Water [gallon]	1.342	2.653	1.938	1.408	4.261	3.097
	France					
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	2.917	20.394	14.832	3.390	31.397	22.279
Water [gallon]	1.461	2.698	2.382	1.532	4.335	3.826
Δ Energy*	-34%	-4%	-28%	-31%	-4%	-29%
Δ Water**	9%	2%	23%	9%	2%	24%

* Δ =FR energy-PL energy/PL energy

** Δ =FR water-PL water/PL water

Figure 3 and Table 3 show comparison of the energy and water consumption associated with LFP recycling in Poland and France. Direct LFP recycling is the technology that consumes the highest energy per kg of feedstock, followed by hydrometallurgy and pyrometallurgy. The primary energy demand in France is lower than in Poland for all three analysed methods, at both pack and cell level. On the other hand, water usage is higher in France than in Poland as we also observed in NCM811 case before.

In general, direct recycling is much higher energy usage than pyro- and hydrometallurgical recycling compared to NCM811 where hydrometallurgical was also high due to leaching of many metals from NCM811.

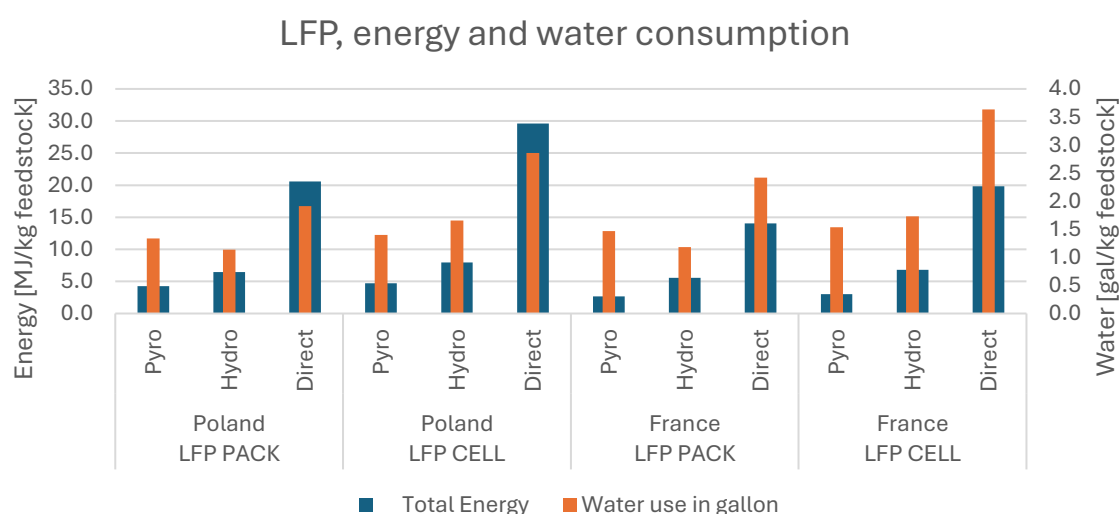


Figure 3. Energy and water consumption for LFP recycling.

Table 3. Energy and water consumption for NMC811 recycling.

	Poland					
	LFP Pack			LFP Cell		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	4.268	6.447	20.583	4.721	7.977	29.627
Water [gallon]	1.339	1.135	1.915	1.397	1.658	2.861
	France					
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	2.683	5.584	14.061	2.992	6.819	19.806
Water [gallon]	1.467	1.181	2.420	1.537	1.728	3.633
Δ Energy*	-37%	-13%	-32%	-37%	-15%	-33%
Δ Water**	10%	4%	26%	10%	4%	27%

* Δ =FR energy-PL energy/PL energy

** Δ =FR water-PL water/PL water

Figure 4 and Table 4 show comparison of the greenhouse gas emissions for recycling in Poland and France. In general, the greenhouse gas (GHG) emissions per kg of feedstock is higher in Poland than in France, both at pack and cell level which is mainly due to the different electricity mix of nuclear heavy vs fossil fuel heavy as shown in Table 1 as data feed for the model. Cell level recycling emits more GHGs per kg of feedstock compared to pack level as normalization per kg already takes the steel and aluminium components from the pack recycling out.

Moreover, NMC811 recycling results in higher GHGs emissions per kg of feedstock than LFP recycling although for directly recycling both cathode chemistries are quite similar due to the fact that recovery and recalcination are similar energy intensive for both cathode types. Detailed emissions breakdown for Poland and France can be found in Appendices 1 and 2, respectively.

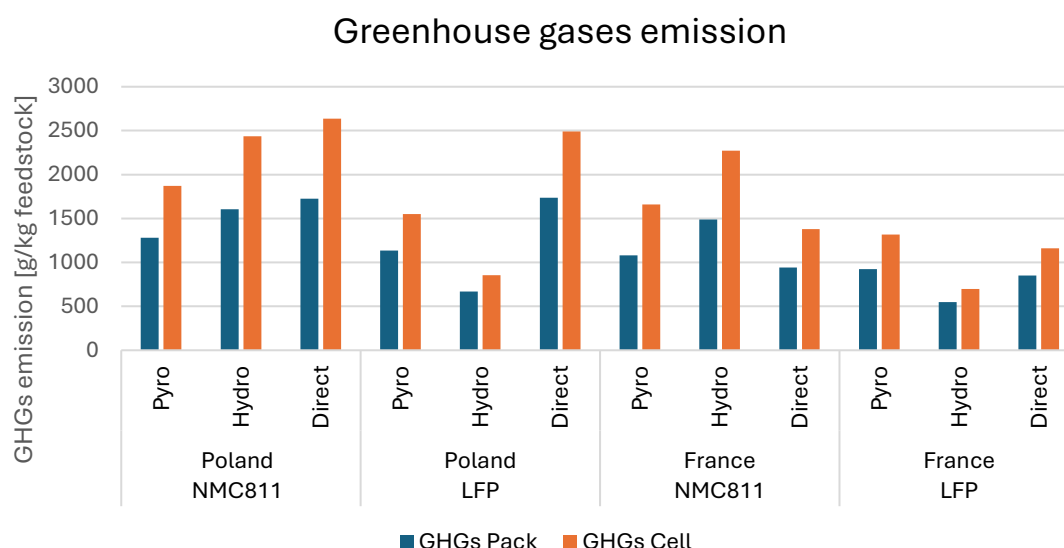


Figure 4. Greenhouse gas emissions comparison.

Table 4. Greenhouse gas emissions comparison.

	Poland					
	NMC811			LFP		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
GHGs Pack [g/kg feedstock]	1281.625	1605.432	1727.168	1136.859	666.8764	1734.884
GHGs Cell [g/kg feedstock]	1870.068	2436.700	2638.027	1551.988	854.3399	2490.075
	France					
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
GHGs Pack [g/kg feedstock]	1081.576	1489.829	943.6042	922.0134	549.850	851.008
GHGs Cell [g/kg feedstock]	1661.632	2273.756	1377.589	1317.603	697.4551	1158.953
Δ GHGs Pack*	-16%	-7%	-45%	-19%	-18%	-51%
Δ GHGs Cell**	-11%	-7%	-48%	-15%	-18%	-53%

* Δ =FR GHGs Pack-PL GHGs Pack/PL GHGs Pack

** Δ =FR GHGs Cell-PL GHGs Cell/PL GHGs Cell

3. LCA of battery reuse in Poland and France

Following the analysis of battery recycling processes and their associated environmental footprints, battery reuse represents an alternative circular economy pathway with distinct environmental implications³. While recycling focuses on material recovery and the avoidance of primary material extraction, reuse extends the operational lifetime of existing batteries, deferring both recycling activities and the need for new battery manufacturing. The environmental impact of reuse is primarily driven by the carbon intensity of the electricity used during the second-life operation.

The model simulates battery operations from initial state of health (SOH: 100% (new), 90%, 80%, 70%) down to 40% end-of-life, using 90% depth of discharge per cycle. Battery degradation follows empirical aging curves for NCM and LFP. Due to limited data for LFP, its curve from 56% to 40% SOH was extrapolated using a linear regression to allow comparison of both NCM811 and LFP batteries down to 40% remaining useful capacity.

The cumulative CO₂ emissions from second-life battery operations are calculated according to the following formula:

Equation 1. CO₂ emission formula.

$$CO_2 = \sum_{Cycle=1}^n SOH(Cycle) \cdot Q_{ini} \cdot CO_{2ele} \cdot E_{loss}$$

Where:

- $SOH(cycle)$ represents battery state of health (SOH) at each charge cycle. The SOH value at each cycle determines the effective capacity available for energy storage and therefore the amount of electricity that must be drawn from the grid to charge the battery.
- Q_{ini} is initial capacity of battery (values provided in the Table 5 chosen as 88Ah*3.7V for NCM811 cells and 79Ah*3.25V for LFP cell by Battronics),

Table 5. Initial battery capacity values.

C_0 [Wh]	NCM	LFP
Pack level	198.034	149.149
Cell level	326.984	228.728

- CO_{2ele} represents carbon intensity in grams per kWh of the electricity used for battery charging. This value captures emissions associated with generating the electricity used to charge the battery system and varies significantly by country depending on the electricity generation mix. The carbon intensity values used in this analysis are derived from the EverBatt life cycle assessment model², which provides values in g CO₂/mmBtu. The conversion from mmBtu to kWh is 1 mmBtu equals approximately 293.071 kWh. Values provided in the Table 6 presents CO_{2ele} values after conversion.

Table 6. Electricity carbon intensity CO_{2ele} for France and Poland².

	CO_{2ele} [g CO ₂ /kWh]
France	50.73
Poland	719.13

- E_{loss} represents the additional grid electricity required to compensate for energy losses during battery charge and discharge operations. These losses arise from internal resistance, which causes voltage drops and heat generation in both charge and discharge processes. The loss parameter is chemistry-dependent: NMC811 batteries exhibit 1.6% energy losses per complete charge-discharge cycle, while LFP batteries show 1.9% losses. In the emissions calculation, E_{loss} is applied as a fractional multiplier (0.016 for NMC811 and 0.019 for LFP) to account for the extra electricity drawn from the grid to overcome these resistive losses. Below are explained calculations for E_{loss} values:

Equation 2. Electricity loss calculation.

$$E_{loss} = \frac{\Delta U_{tot}}{U_{nom}}$$

- ΔU_{tot} – total voltage drop due to internal resistance over a complete charge-discharge cycle, assumed to be $2 \times 30 \text{ mV} = 60 \text{ mV}$,
- U_{nom} – nominal cell voltage, taken as 3.7 V for NMC811 and 3.2 V for LFP.

Poland's electricity generation relies heavily on coal-fired power plants, which dominate the country's energy mix with approximately 60% of generation coming from hard coal and lignite sources. The EverBatt model reports Poland's grid carbon intensity as 210,756 g CO₂/mmBtu. Converting this to standard energy units: $210.756 \text{ g CO}_2/\text{mmBtu} \div 293.071 \text{ kWh/mmBtu} = 719.13 \text{ g CO}_2/\text{kWh}$.

France presents a markedly different energy mix, with nuclear power, hydroelectricity, and other renewables together supplying roughly 90% of its electricity generation. France's extensive reliance on nuclear power results in one of the cleanest electricity grids in Europe. The EverBatt model reports France's grid carbon intensity as 14,868 g CO₂/mmBtu. Converting to standard units: $14,868 \text{ g CO}_2/\text{mmBtu} \div 293.071 \text{ kWh/mmBtu} = 50.73 \text{ g CO}_2/\text{kWh}$. This value is approximately 14 times lower than Poland's carbon intensity, representing a fundamental difference in environmental impact for identical battery operations.

3.1 Single Cycle Per Day Operation

3.1.1 CO₂ Footprint of Cell-Level Battery Reuse

Analysis of CO₂ emissions from French battery operations under single daily charge-discharge cycles reveals relatively modest environmental impacts due to the low grid carbon intensity, Figure 5. Cell-level NMC811 systems starting at 100% SOH accumulate approximately 379 grams of CO₂ emissions over their 1800-day operational lifetime when normalized per kilogram of battery material. This modest cumulative impact reflects both the short operational lifetime of NMC811 under daily cycling and France's exceptionally clean grid. As the SOH decreases to 90%, 80%, and 70%, the cumulative emissions at end-of-life also decrease proportionally, reaching approximately 256 grams, 137 grams, and 55 grams of CO₂ respectively, as batteries with lower initial SOH have reduced capacity requiring less charging energy per cycle.

LFP cell-level systems in France demonstrate substantially higher cumulative emissions due to their extended operational lifetimes under single-cycle daily use. Batteries at 100%

SOH operate for approximately 5735 cycles, accumulating roughly 870 grams of over their complete second-life service. The 90% SOH scenario, generates approximately 738 grams of CO₂ over its operational lifetime. Lower initial SOH values of 80% and 70% produce proportionally reduced cumulative emissions of approximately 440 and 420 grams respectively, reflecting both the reduced initial capacity and the somewhat shorter operational lifetimes due to faster degradation from the already-compromised starting condition.

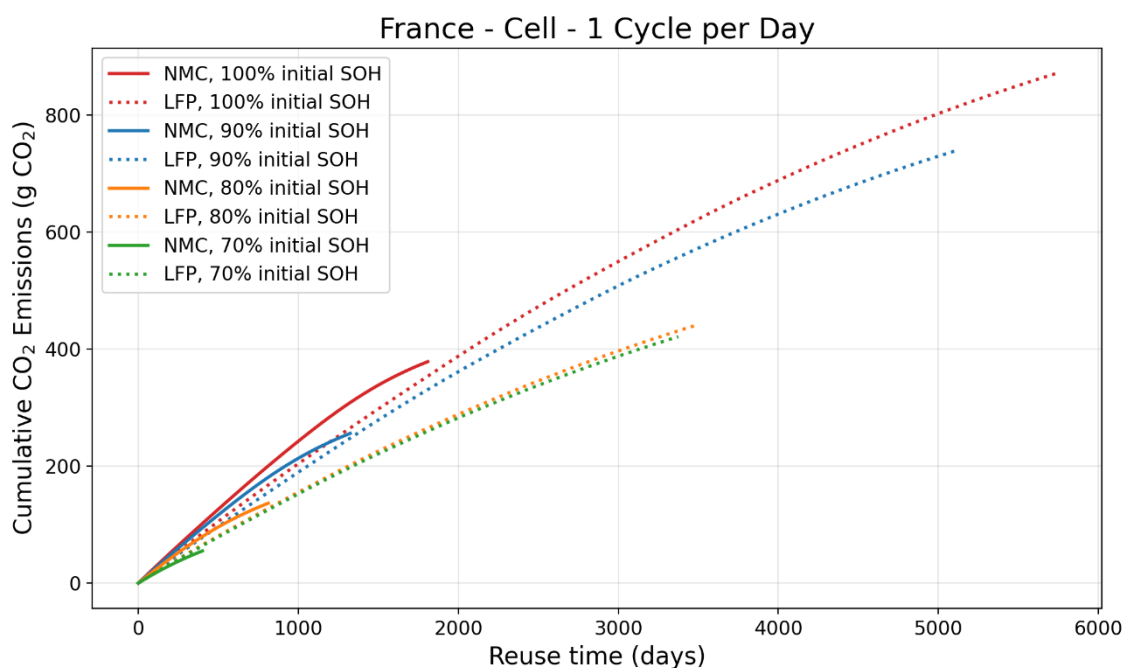


Figure 5. Cumulative CO₂ emissions of NMC and LFP battery cells under single-cycle-per-day reuse in France.

Figure 6 presents Polish battery operations under single-cycle daily use demonstrating dramatically higher CO₂ emissions compared to France due to the coal-dominated electricity grid. Cell-level NMC811 systems at 100% SOH accumulate approximately 5365 grams of CO₂ emissions over their 1800-cycles operational lifetime. This represents roughly 14 times the emissions of the equivalent French operation, directly reflecting the grid carbon intensity ratio. As initial SOH decreases to 90%, 80%, and 70%, cumulative emissions reduce to approximately 3628 grams, 1936 grams, and 781 grams respectively.

LFP cell-level systems in Poland face particularly severe environmental impacts due to the combination of extended operational lifetime and high grid carbon intensity. Batteries at 100% SOH operating for 5735 cycles accumulate approximately 12348 grams of CO₂. This means that each kilogram of LFP battery material, when used for energy storage in Poland over its complete second-life, generates emissions equivalent to more than 12 times its own mass in CO₂. The 90% initial SOH scenario, which showed optimal economics in the previous analysis, generates approximately 10466 grams of CO₂ over 5100 cycles. Lower initial SOH values of 80% and 70% produce cumulative emissions of approximately 6263 and 5972 grams respectively. But remember, these CO₂ emissions come from the electric losses inside the batteries which are here assumed to be 2x 30mV out of 3.2V LFP battery. Any improvement in overpotential can reduce the emissions due to losses and increase profitability of the business case additionally as this electricity is not “lost” in heat dissipation.

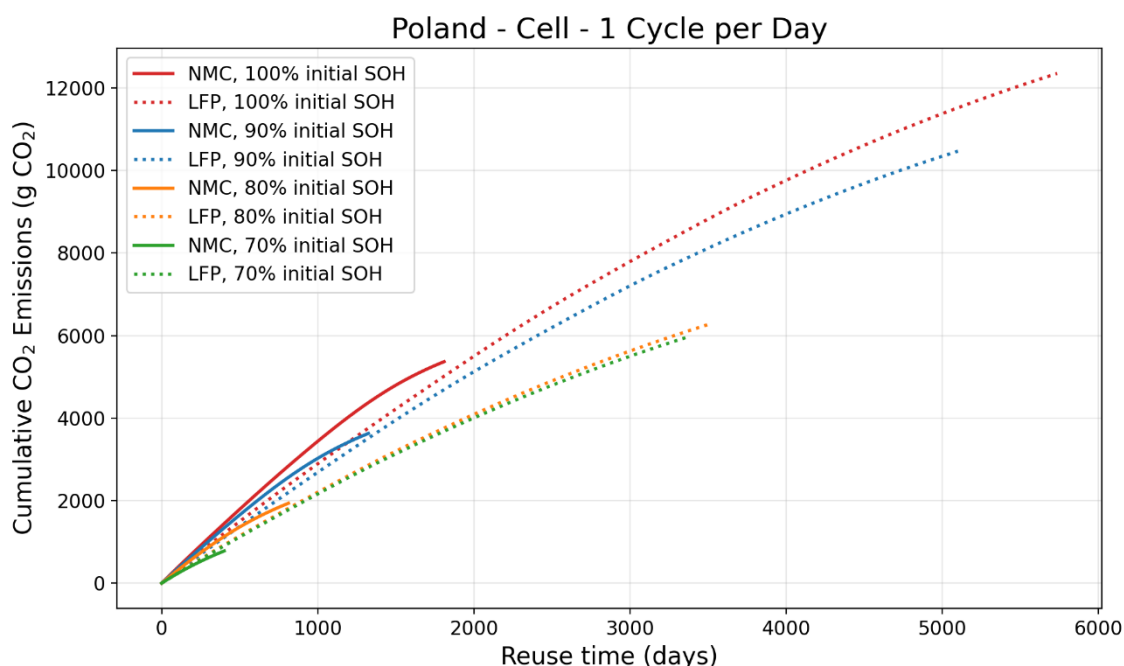


Figure 6. Cumulative CO₂ emissions of NMC and LFP battery cells under single-cycle-per-day reuse in Poland.

3.1.2 CO₂ Footprint of Pack-Level Battery Reuse

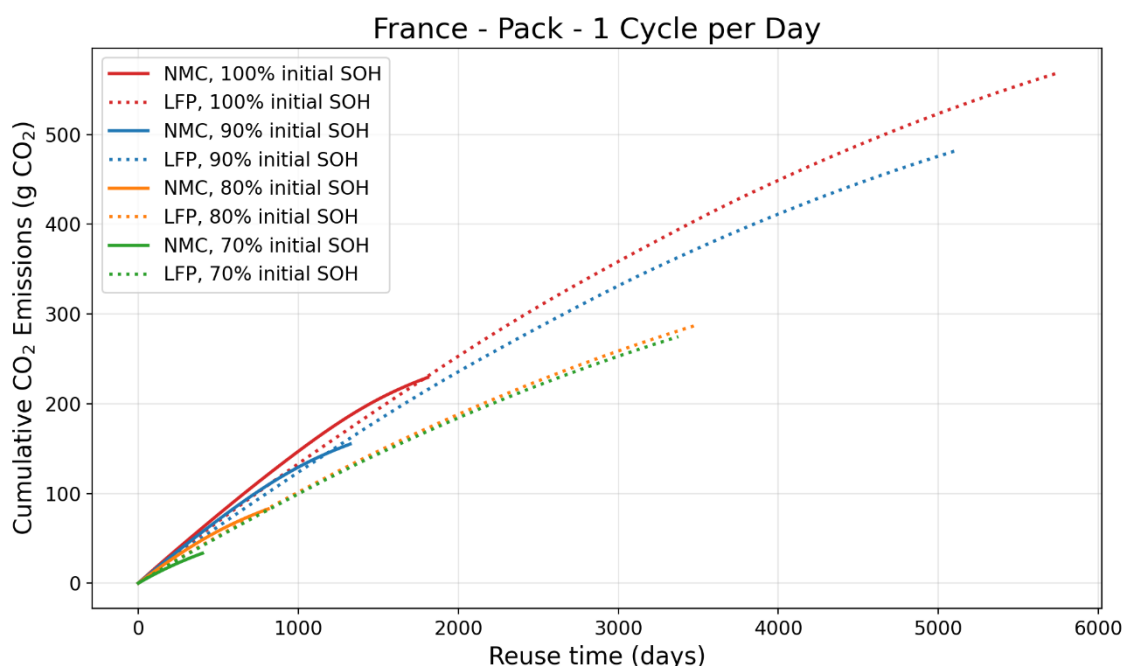


Figure 7. Comparison of cumulative CO₂ emissions for NMC and LFP battery packs under single-cycle-per-day reuse in France.

As shown in Figure 7, pack-level systems in France show emission patterns similar to cell-level configurations with marginal differences attributable to the slightly improved thermal management and system-level efficiency optimization inherent in integrated pack designs. NMC811 packs at 100% initial SOH generate approximately 230 grams of CO₂ over 1800 days, while 90-70% SOH systems produce approximately 155, 83 and 34 grams, respectively. LFP packs demonstrate the same extended lifetime advantage, with 100% initial SOH systems accumulating approximately 570 grams of CO₂ over 5735 days and 90%

SOH systems generating roughly 480 grams, while SOH 80 and 70% accumulate 288 and 274 grams, respectively. Compared with cell-level batteries, pack-level systems exhibit roughly 10–15% lower CO₂ emissions, likely due to the improvements in system efficiency.

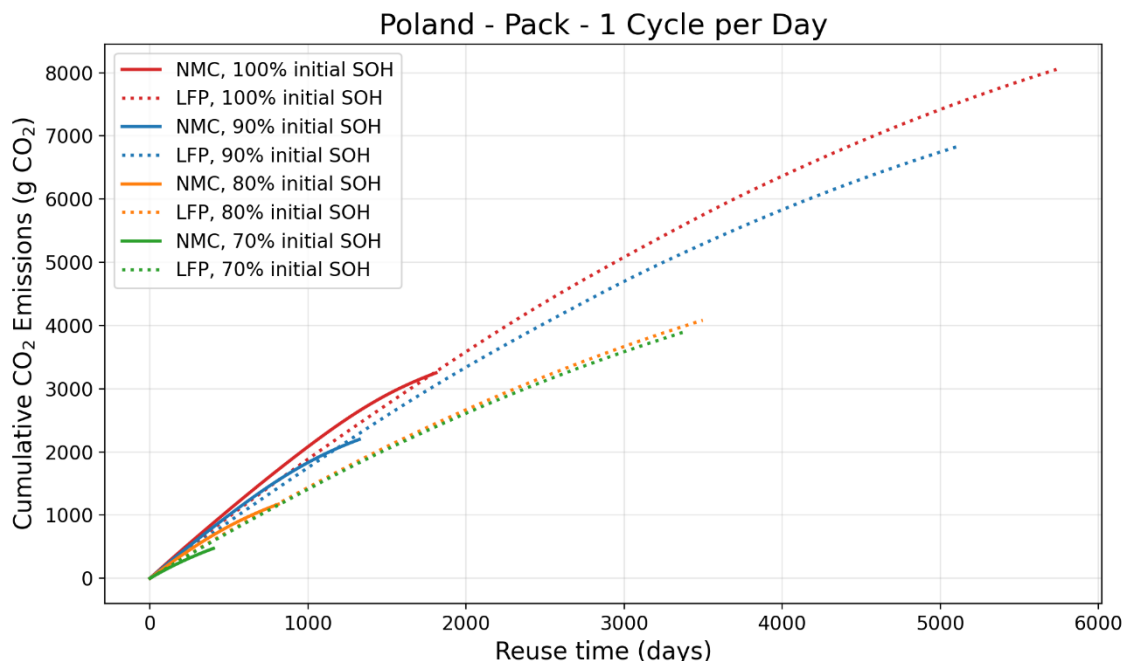


Figure 8. Comparison of cumulative CO₂ emissions for NMC and LFP battery packs under single-cycle-per-day reuse in Poland.

Figure 8 illustrates that pack-level systems in Poland show proportionally high emissions tracking the cell-level patterns. NMC811 packs at 100% initial SOH generate approximately 3250 grams of CO₂ over 1800 days, while 90-70% SOH systems produce approximately 2195, 1173 and 473 grams, respectively. LFP packs at 100% initial SOH accumulate approximately 8052 grams of CO₂ over 5735 days, with 90% SOH systems generating roughly 6825 grams, while SOH 80 and 70% accumulate almost 4085 and 3895 grams, respectively. The pack-level integration provides the same 10-15% emissions reduction compared to cell-level systems, but the absolute emissions remain an order of magnitude higher than French operations.

3.2 Two Cycles Per Day Operation

Operating batteries through two complete charge-discharge cycles per day fundamentally alters the emissions trajectory by doubling the daily electricity consumption while simultaneously reducing the operational lifetime due to accelerated degradation.

3.2.1 CO₂ Footprint of Cell-Level Battery Reuse

In France under two-cycle operation, cell-level NMC811 systems at 100% initial SOH accumulate approximately 379 grams of CO₂ over their reduced 900-day lifetime. This represents nearly the same cumulative emissions as single-cycle operation despite half the operational duration, demonstrating that doubled daily electricity consumption almost exactly compensates for the shortened lifetime. The 90-70% initial SOH scenarios generates approximately 256, 137 and 55 grams of CO₂ over 660, 406 and 200 days,

respectively. LFP cells show similar patterns, with 100% initial SOH systems accumulating approximately 900 grams of CO₂ over 2867 days under two-cycle operation, essentially matching the total emissions from single-cycle operation. The 90% initial SOH LFP cells generate approximately 730 grams over 2550 days. These similar emissions resulted from similar used overpotential as we assume C/2 charge and discharge in both cases of single-usage per day, and a double cycle.

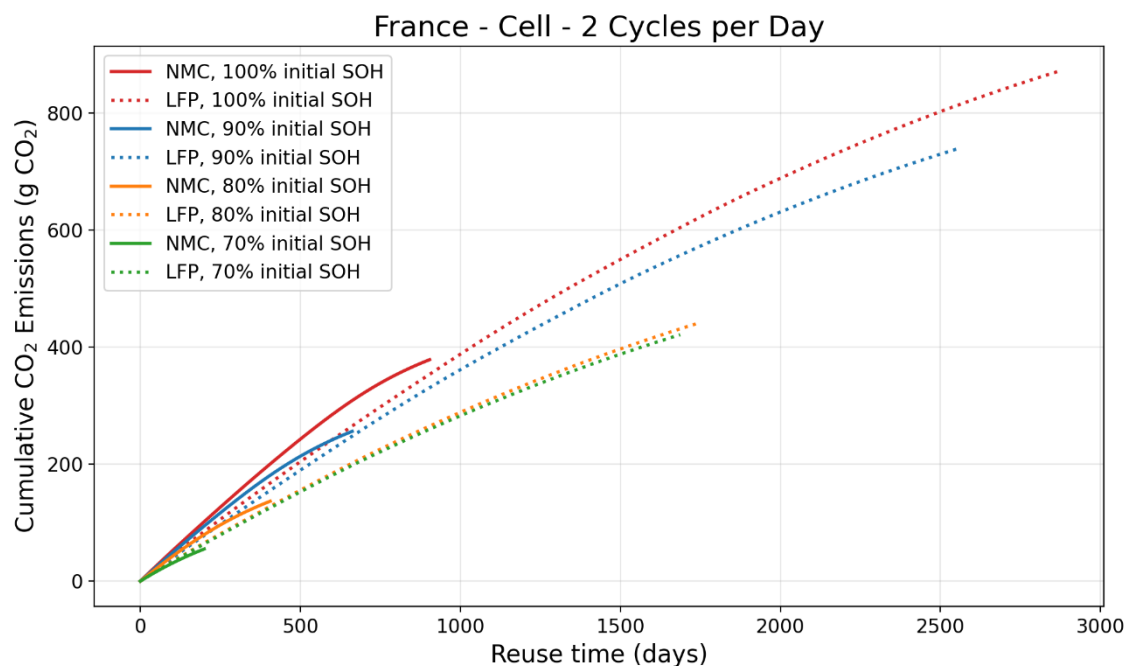


Figure 9. Cumulative CO₂ emissions of NMC and LFP battery cells under two cycles-per-day reuse in France.

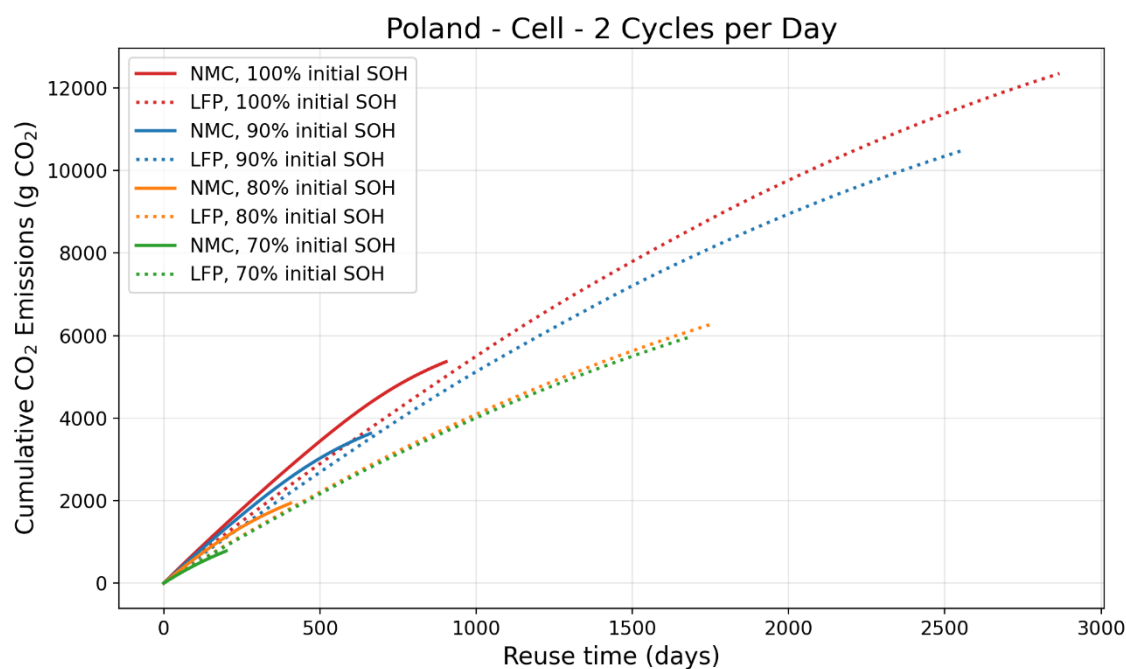


Figure 10. Cumulative CO₂ emissions of NMC and LFP battery cells under two cycles-per-day reuse in Poland.

Poland under two-cycle operation demonstrates proportionally high emissions scaling with the grid carbon intensity. Cell-level NMC811 systems at 100% initial SOH generate

approximately 5366 grams of CO₂ over 900 days, nearly matching the single-cycle cumulative emissions despite half the operational period. The 90-70% initial SOH scenario produces approximately 3630, 1937 and 780 grams over 660, 406 and 200 days, respectively. LFP cells at 100% initial SOH accumulate approximately 12348 grams of CO₂ over 2867 days, essentially the same total as single-cycle operation over twice the duration. The 90-70% initial SOH configuration generates approximately 10467, 6242 and 5971 grams, respectively.

3.2.2 CO₂ Footprint of Pack-Level Battery Reuse

French pack-level systems under two-cycle operation show marginally lower emissions than cell-level equivalents. NMC811 packs at 100% initial SOH produce approximately 229 grams of CO₂ over 900 days, while 90-70% SOH systems generate approximately 155, 83 and 33 grams over 660, 406 and 200 days, respectively. LFP packs at 100% initial SOH accumulate approximately 568 grams of CO₂ over 2867 days, with 90-70% SOH systems producing roughly 481, 288 and 274 grams, respectively.

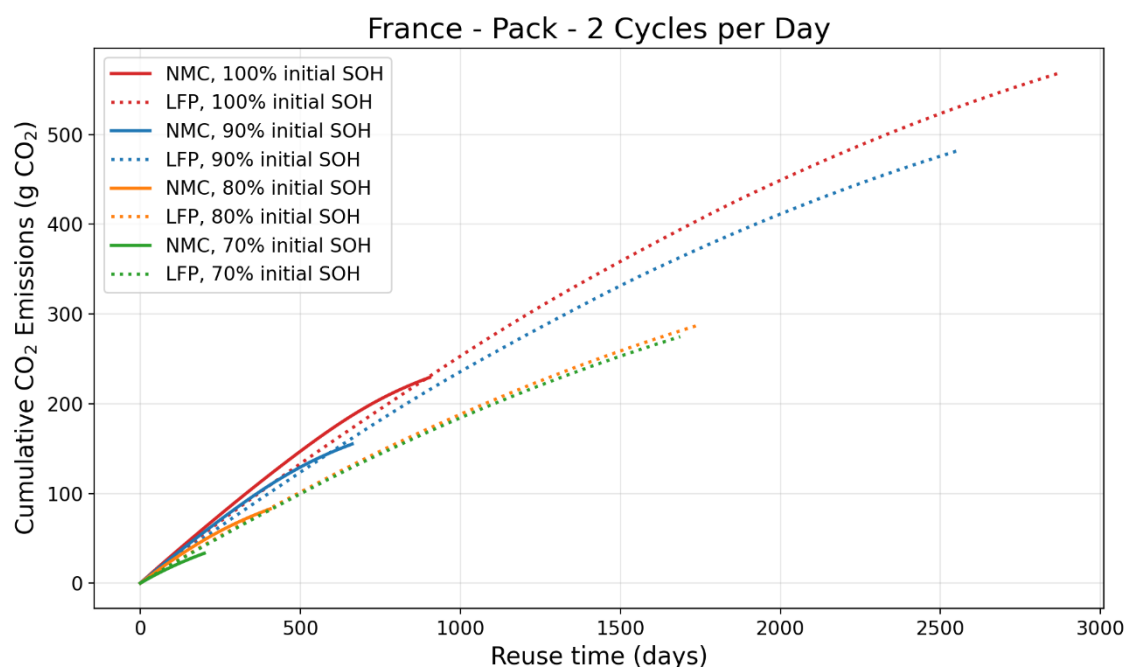


Figure 11. Comparison of cumulative CO₂ emissions for NMC and LFP battery packs under two cycles-per-day reuse in France.

In Figure 12 are presented Polish pack-level systems mirroring patterns with 10-15% lower emissions than cell-level configurations. NMC811 packs at 100% initial SOH produce approximately 3250 grams of CO₂ over 900 days, while 90-70% SOH systems generate approximately 2198, 1173 and 472 grams of CO₂, respectively. LFP packs at 100% initial SOH accumulate approximately 8051 grams of CO₂ over 2867 days, with 90-70% SOH systems producing roughly 6825, 4084 and 3894 grams, respectively.

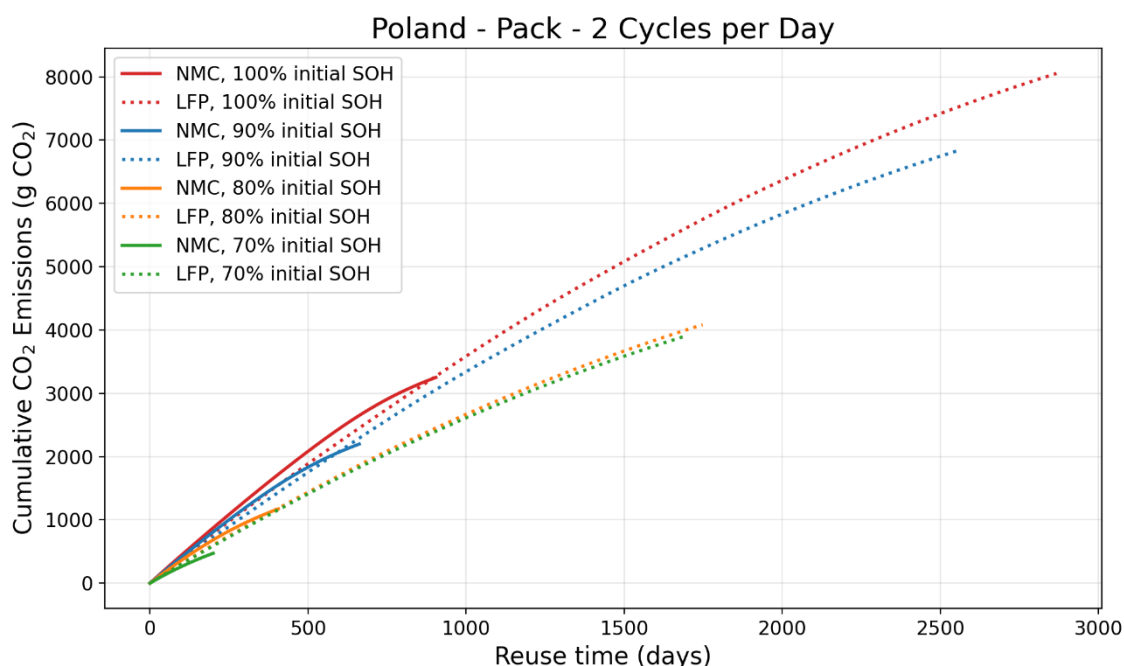


Figure 12. Comparison of cumulative CO₂ emissions for NMC and LFP battery packs under two cycles-per-day reuse in Poland.

The initial reuse study only analysis the losses incurred by operating the battery which “burns” electricity during usage. In the follow up study of D2.3, also the energy savings compared to no use of ESS will be calculated. Here, the battery operation would produce more the longer it operates which is true as it produces losses from the overpotentials. However, one also needs to compare the opportunity losses from “not using” the electricity in access in the grid during peak sun and wind which is a more complex simulation then the initial direct battery operation considered here.

4. Conclusions

The study examined energy and water consumption as well as greenhouse gas emissions for recycling and reusing in Poland and France.

The NMC811 recycling process uses more energy and water compared to LFP recycling. In case of NMC811 recycling, hydrometallurgical method is the technology that consumes the most energy and water per kg of feedstock, followed by direct recycling and pyrometallurgy. In case of LFP recycling, direct recycling is the technology that consumes the most energy per kg of feedstock, followed by hydrometallurgy and pyrometallurgy.

The primary energy demand in France is lower than in Poland for all three analysed methods, at both pack and cell level, due to cleaner and more efficient energy generation. However, France's water usage is higher than Poland's because their electricity systems use and withdraw water very differently per unit of electricity produced.

The greenhouse gas emissions per kg of feedstock is higher in Poland than in France, both at pack and cell level. Cell level recycling emits more GHGs per kg of feedstock compared to pack level. Moreover, NMC811 recycling results in higher GHGs emissions per kg of feedstock than LFP recycling.

The CO₂ emissions analysis of second-life battery systems reveals that grid carbon intensity dominates environmental impact, creating a ~14-fold difference in cumulative emissions between low-carbon France and coal-dependent Poland. French operations generate modest emissions of 0.05-0.9 kilograms of CO₂ per kilogram of battery material over 5700-day lifetimes, representing minimal environmental burden and likely providing net climate benefits through grid flexibility services. Polish operations generate 0.5-12.5 kilograms of CO₂ per kilogram of battery material over equivalent periods, representing emissions comparable to primary material production and calling into question the environmental justification for battery reuse in high-carbon grids.

LFP batteries generate 2.5 times higher cumulative emissions than NMC811 due to extended operational lifetimes which is largely due to the accumulation of more losses over the much longer lifetime of LFP cells, though emissions per cycle are equivalent. Two-cycle daily operation provides no environmental benefit compared to single-cycle operation while sacrificing economic returns. Pack-level integration reduces emissions by 10-15% compared to cell-level systems through improved efficiency.

Environmental sustainability depends critically on the carbon intensity of electricity grids where batteries are reused. In low-carbon markets, reuse provides clear environmental benefits and should be encouraged as the losses in battery operation also are less CO₂ intensive. However, the full analysis how much CO₂ could be saved from battery operation in both Poland and France is out of scope in this preliminary deliverable.



Appendix 1. Detailed LCA breakdown for Poland

	NMC811 Pack			NMC811 Cell		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	4.393	21.247	20.613	4.928	32.599	31.578
Fossil fuels [MJ/kg feedstock]	3.800	19.441	18.153	4.292	29.710	27.614
Coal [MJ/kg feedstock]	2.030	7.177	12.467	2.251	9.871	18.564
Natural gas [MJ/kg feedstock]	0.782	13.444	6.043	0.967	20.158	8.017
Petroleum [MJ/kg feedstock]	0.989	4.020	4.844	1.074	4.881	6.234
Water use [gallon]	1.342	2.653	1.938	1.408	4.261	3.097
Total Emissions [g/kg feedstock]						
VOC	0.067	0.246	0.241	0.075	0.364	0.357
CO	0.276	1.039	0.972	0.308	1.539	1.430
NOx	0.729	1.942	2.248	0.808	2.823	3.326
PM10	0.066	0.174	0.266	0.076	0.266	0.417
PM2.5	0.046	0.125	0.176	0.054	0.187	0.271
SOx	0.979	1.960	1.474	1.340	3.172	2.375
BC	0.015	0.027	0.032	0.016	0.036	0.044
OC	0.010	0.033	0.037	0.012	0.049	0.056
CH ₄	0.526	3.202	2.718	0.599	4.895	4.102
N ₂ O	0.008	0.031	0.034	0.008	0.047	0.051
CO ₂	1263.227	1499.119	1634.644	1849.226	2274.509	2498.369
CO ₂ (w/ C in VOC & CO)	1263.868	1501.518	1636.924	1849.945	2278.062	2501.727
GHGs	1281.625	1605.432	1727.168	1870.068	2436.700	2638.027

	LFP Pack			LFP Cell		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	4.268	6.447	20.583	4.721	7.977	29.627
Fossil fuels [MJ/kg feedstock]	3.657	6.114	17.939	4.052	7.530	25.644
Coal [MJ/kg feedstock]	2.148	4.226	12.540	2.438	4.888	17.617
Natural gas [MJ/kg feedstock]	0.599	3.945	5.993	0.668	4.454	7.598
Petroleum [MJ/kg feedstock]	0.910	3.143	4.607	0.946	3.389	5.629
Water use [gallon]	1.339	1.135	1.915	1.397	1.658	2.861



Total Emissions [g/kg feedstock]						
VOC	0.062	0.104	0.229	0.068	0.127	0.318
CO	0.265	0.455	0.944	0.289	0.558	1.308
NO _x	0.661	0.923	2.158	0.697	1.110	3.001
PM ₁₀	0.063	0.075	0.254	0.071	0.098	0.373
PM _{2.5}	0.043	0.058	0.164	0.048	0.074	0.236
SO _x	0.519	0.370	1.413	0.590	0.529	2.125
BC	0.014	0.021	0.030	0.015	0.024	0.039
OC	0.008	0.013	0.033	0.009	0.016	0.047
CH ₄	0.503	0.965	2.704	0.560	1.177	3.841
N ₂ O	0.007	0.011	0.035	0.008	0.013	0.050
CO ₂	1119.223	634.124	1642.515	1532.409	814.437	2358.841
CO ₂ (w/ C in VOC & CO)	1119.834	635.165	1644.714	1533.074	815.710	2361.889
GHGs	1136.859	666.876	1734.884	1551.988	854.340	2490.075

Appendix 2. Detailed LCA breakdown for France

	NMC811 Pack			NMC811 Cell		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	2.917	20.394	14.832	3.390	31.397	22.279
Fossil fuels [MJ/kg feedstock]	1.692	18.223	9.895	2.096	27.993	14.330
Coal [MJ/kg feedstock]	0.270	6.160	5.576	0.418	8.438	7.480
Natural gas [MJ/kg feedstock]	0.550	13.310	5.135	0.725	19.970	6.556
Petroleum [MJ/kg feedstock]	0.871	3.952	4.384	0.952	4.785	5.495
Water use [gallon]	1.461	2.698	2.382	1.532	4.335	3.826
Total Emissions [g/kg feedstock]						
VOC	0.049	0.236	0.173	0.057	0.350	0.246
CO	0.201	0.996	0.679	0.230	1.478	0.958
NO _x	0.557	1.842	1.572	0.629	2.682	2.239
PM ₁₀	0.036	0.157	0.147	0.044	0.241	0.226
PM _{2.5}	0.031	0.116	0.117	0.038	0.175	0.177
SO _x	0.782	1.846	0.703	1.135	3.012	1.136
BC	0.014	0.027	0.029	0.015	0.036	0.039
OC	0.008	0.032	0.030	0.010	0.048	0.045
CH ₄	0.209	3.020	1.478	0.269	4.637	2.108
N ₂ O	0.003	0.028	0.015	0.003	0.043	0.021
CO ₂	1074.098	1389.826	893.853	1652.169	2120.460	1306.734
CO ₂ (w/ C in VOC & CO)	1074.567	1392.126	895.457	1652.708	2123.872	1309.006
GHGs	1081.576	1489.829	943.604	1661.632	2273.756	1377.589



	LFP Pack			LFP Cell		
	Pyro	Hydo	Direct	Pyro	Hydo	Direct
Total energy [MJ/kg feedstock]	2.683	5.584	14.061	2.992	6.819	19.806
Fossil fuels [MJ/kg feedstock]	1.393	4.881	8.624	1.582	5.877	11.615
Coal [MJ/kg feedstock]	0.259	3.197	4.768	0.377	3.508	5.911
Natural gas [MJ/kg feedstock]	0.350	3.809	4.969	0.396	4.272	6.055
Petroleum [MJ/kg feedstock]	0.784	3.074	4.088	0.808	3.297	4.849
Water use [gallon]	1.467	1.181	2.420	1.537	1.728	3.633
Total Emissions [g/kg feedstock]						
VOC	0.043	0.094	0.152	0.047	0.113	0.202
CO	0.185	0.411	0.613	0.201	0.499	0.809
NOx	0.476	0.822	1.395	0.495	0.974	1.852
PM10	0.031	0.057	0.120	0.035	0.074	0.171
PM2.5	0.027	0.049	0.098	0.031	0.063	0.136
SOx	0.308	0.255	0.544	0.360	0.374	0.817
BC	0.013	0.020	0.027	0.014	0.024	0.034
OC	0.006	0.012	0.025	0.007	0.014	0.035
CH ₄	0.163	0.780	1.305	0.190	0.929	1.734
N ₂ O	0.002	0.008	0.014	0.002	0.009	0.018
CO ₂	916.105	523.486	806.888	1310.818	666.117	1100.381
CO ₂ (w/ C in VOC & CO)	916.531	524.426	808.325	1311.281	667.254	1102.281
GHGs	922.013	549.850	851.008	1317.603	697.455	1158.953

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