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CIRCUBATT

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D2.2 Cost Optimisation Analysis Report

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List of acronyms

Direct – Direct recycling

DOD – Depth of discharge

EOL – End-of-life

FR – France

Hydro - Hydrometallurgical recycling

LCC – Life Cycle Cost

LFP – $LiFePO_4$

LIB – Lithium-ion battery

NMC811 – $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$

PL – Poland

Pyro – Pyrometallurgical recycling

SOH – State of health

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Executive Summary

The report describes life cycle cost of NMC811 and LFP chemistries recycling considering pyrometallurgical, hydrometallurgical and direct recycling technologies in Poland and France, at both cell and pack levels, with 1'000 and 10'000 tonnes of feedstock per year.

In general, due to higher recycling costs (direct labour, electricity, natural gas, etc.) in France, recycling is less profitable compared to Poland. The most profitable method of recycling is usually direct recycling, followed by hydrometallurgy and lastly pyrometallurgy. Recycling of NMC811 is more profitable than recycling of LFP, due to the higher value of the recovered materials which is in line with other literature findings. From an economic point of view, high feedstock input recycling (10kt) is better than low feedstock recycling (1kt) due to lower labour and plant overheads, as well as lower annualised capital costs – so called economy of scale effects.

The profits of lithium-ion battery recycling are significantly influenced by raw materials cost. Profit sensitivity to raw material prices fluctuations is high which puts recycling as a relative high risk, low return business model in Europe. Higher market material prices result in higher profit (or lower loss for some methods). The analysis shows clearly that not only common findings like NCM being more profitable than LFP and large scale more profitable but also shed a light on how different labour cost, electricity costs and recycling method choice in the two European countries France and Poland can influence business profitability.

1.Introduction

1.1. Overview and scope

A life cycle cost (LCC) analysis was performed using the EverBatt model, which was developed by Argonne National Laboratory, IL. 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. For the purpose of the project, the battery recycling module was implemented to evaluate 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 documentation[1] and is displayed as a flow sheet below in Figure 1.

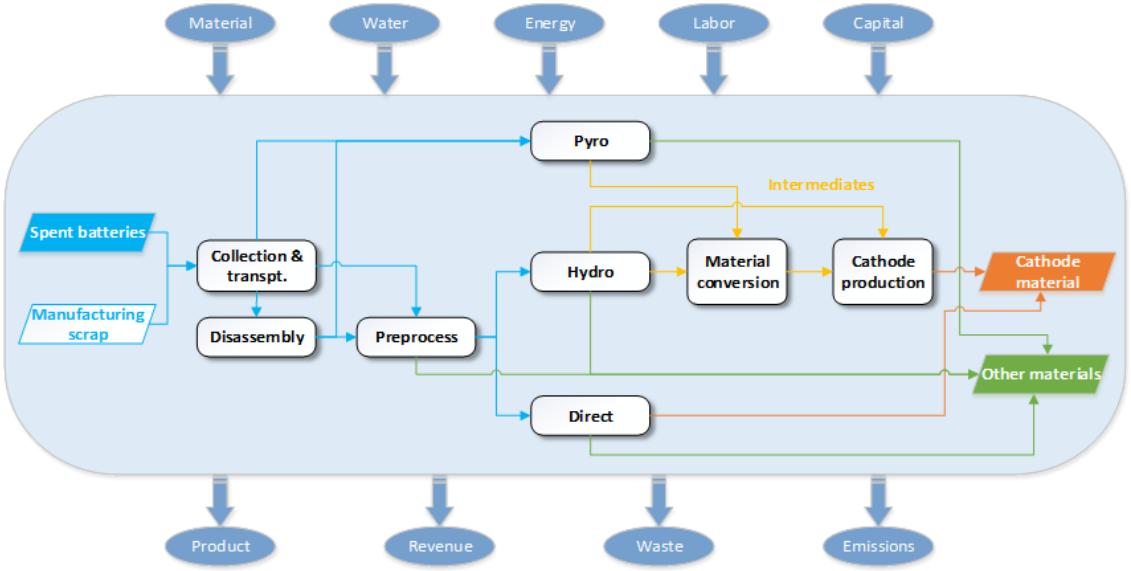


Figure 1. Schematic of the EverBatt recycle module.

Tables 1-3: Recovered materials using pyrometallurgy (Table 1), hydrometallurgy (Table 2), and direct recycling (Table 3).

Pyrometallurgy	
NMC811	LFP
Copper metal	Copper metal
Co^{2+} in product	
Ni^{2+} in product	

Direct recycling	
NMC811	LFP
NMC811	LFP
Graphite	Graphite
Cu+Al metal	Cu+Al metal
Steel*	Steel*

Hydrometallurgy	
NMC811	LFP
Li_2CO_3 (crude)	Li_2CO_3 (crude)
Co^{2+} in product	Graphite
Ni^{2+} in product	Copper metal
Mn^{2+} in product	Aluminium metal
Graphite	Steel*
Copper metal	
Aluminium metal	
Steel*	

*For pack level recycling only.

The tables 1-3 list the recovered materials, which are produced using various recycling technologies for different chemistries by recycling method.

1.2. Aim and objectives

The aim of the analysis was to study the LCC of recycling spent batteries. The investigation was conducted for two countries, Poland and France (see Table 4) because of their difference in both labor cost but also energy mix on CO2 intensity relevant for other D2.4 later and show the spread in Europe for recycling cost overall. For each country, two different feedstock input levels for recycling were considered: 1'000 and 10'000 tonnes per year, in order to simulate the conditions of both a start-up/SME and a well-developed recycling plant. Various battery chemistries were also studied, including NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$) and LFP ($LiFePO_4$), at both the pack and cell levels. Additionally, a sensitivity analysis was performed considering current, five-year lowest (5Y MIN) and highest (5Y MAX) material prices (Table 5).

Simulation is set that the cost of LFP feedstock for recycling is zero. However, the cost of NMC811 feedstock varies according to material market prices. For pack level recycling, the payment for NMC811 feedstock is set at 0.870, 0.750 and 2.213 USD/kg for the current, 5Y MIN and 5Y MAX scenarios which comes from the residual value of spend NCM batteries as also assumed in Everbatt [1], respectively. For cell level recycling, the payment for NMC811 feedstock is 1.429, 1.231 and 3.634 USD/kg for the current, 5Y MIN and 5Y MAX scenarios, accordingly.

Table 4. Cost information by geographical location [2-8].

	Poland	France
Direct labour (USD/hr)	13	30
Electricity cost (USD/kWh)	0.166	0.18
Natural gas cost (USD/MMBTU)	30	35
Water cost (USD/gal)	0.014	0.02
Wastewater discharge cost (USD/gal)	0.01	0.01
Landfill cost (tip fee USD/ton)	77	83

Table 5. Prices of materials.

USD/kg	Current	5Y MIN	5Y MAX
Co	46.7	23.89	91.47
Ni	17.15	16.82	47.03
Mn	1.9	1.47	7.07
Al	2.9	2.45	3.8
Cu	11.66	8.16	12.02
Li_2CO_3	10.31	5.82	79.18
NMC811	21.05	19.48	68.13
LFP	4.84	4.47	22.27

1.3. Report structure

The structure of the report is as follows:

- Section 2 presents the LCC of recycling results for Poland.
- Section 3 presents the LCC of recycling results for France.
- Section 4 presents the LCC comparison of recycling in Poland and France.
- Section 5 presents spent battery reuse in Poland and France.

2. LCC of recycling in Poland

The parameters of section 1 were fed into Everbatt [1] for which data for current labor cost, utility cost, raw material prices and price fluctuation have been set. Figure 2 and Table 6 show the economic evaluations of NMC811 chemistry recycling using pyrometallurgical, hydrometallurgical and direct recycling processes in Poland.
With a feedstock input of 10'000 tonnes per year, direct recycling is the most cost-effective method at both the pack and cell levels (with profits of 2.834 and 4.355 USD per tonne of feedstock, respectively), followed by hydrometallurgy and pyrometallurgy (see Table 7).
However, in a scenario where the feedstock input is 1'000 tonnes per year, all three recycling methods would be unprofitable. Even if the recycling revenues were the same as for 10'000 tonnes of input, the recycling costs would exceed the revenues, resulting in a loss.

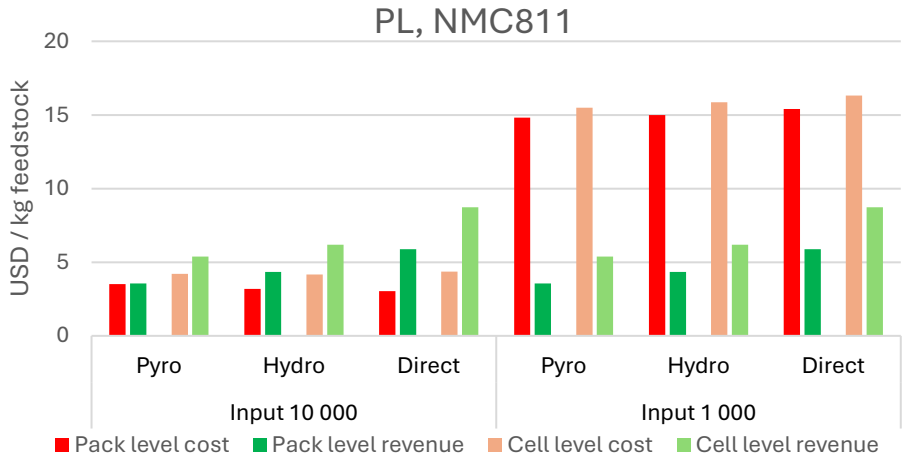


Figure 2. LCC of recycling in Poland for NMC811.

The higher costs of recycling per kilogram of feedstock in the lower input scenario are mainly due to higher labour and plant overheads, as well as annualized capital costs, compared to the high feedstock scenario (see Figure 3 for direct recycling comparison). A detailed breakdown of the costs and revenues for NMC811 in Poland can be found in Appendix 1.

Table 6. Cost and revenue of recycling in Poland for NMC811

USD/kg feedstock	Input: 10'000 t/y				Input: 1'000 t/y		
	Pyro	Hydro	Direct		Pyro	Hydro	Direct
Pack level cost	3.507	3.186	3.040		14.824	14.995	15.404
Pack level revenue	3.554	4.338	5.878		3.554	4.338	5.878
Cell level cost	4.212	4.164	4.367		15.486	15.871	16.310
Cell level revenue	5.390	6.194	8.722		5.390	6.194	8.722

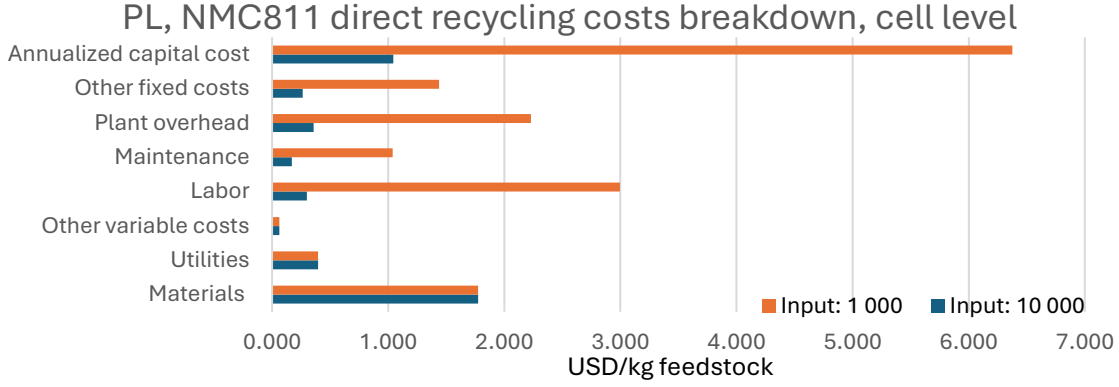


Figure 3. NMC811 direct recycling costs breakdown for low and high input in Poland

The cost of recycling per kilogram of feedstock is higher at cell level than at pack level, mainly due to materials cost (see Figure 4). A detailed breakdown of the costs and revenues for NMC811 in Poland can be found in Appendix 1.

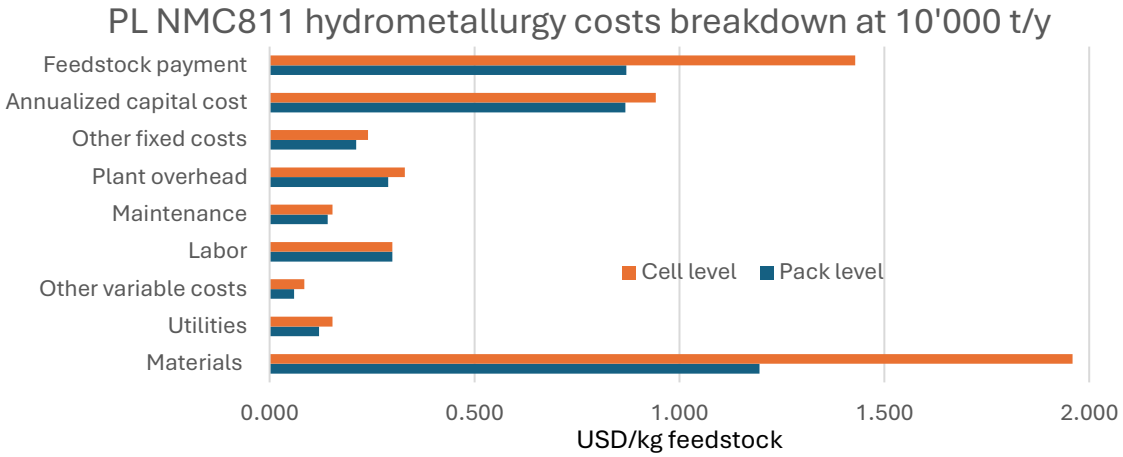


Figure 4. NMC811 hydrometallurgy costs breakdown for cell and pack level in Poland.

Table 7. Profit of recycling in Poland for NMC811.

Profit [USD/kg feedstock]	Input: 10'000 t/y				Input: 1'000 t/y		
	Pyro	Hydro	Direct		Pyro	Hydro	Direct
Pack level	0.047	1.152	2.838		-11.270	-10.658	-9.526
Cell level	1.178	2.030	4.355		-10.096	-9.678	-7.588

Figure 5 and Table 8 show the economic evaluations of LFP chemistry recycling using pyrometallurgical, hydrometallurgical and direct processes in Poland.

The costs of all three recycling methods are lower for LFP recycling compared to NMC811 recycling. However, with a feedstock input of 10'000 tonnes per year, direct recycling is the only cost-effective method at both the pack and cell levels (with profits of 0.077 and 0.434 USD per tonne of feedstock, respectively, see Table 9).

When the feedstock input is reduced to 1 000 tonnes per year, all three methods become unprofitable (see Table 9).

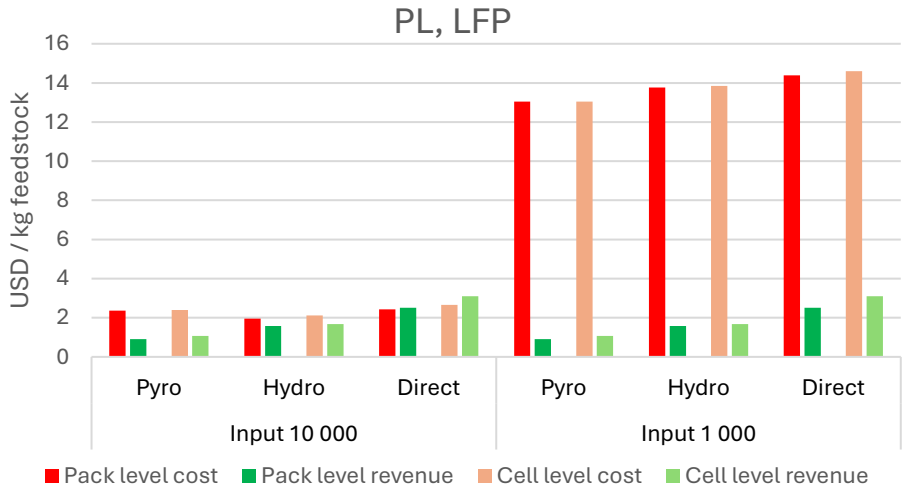


Figure 5. LCC of recycling in Poland for LFP.

Table 8. Cost and revenue of recycling in Poland for LFP

USD/kg feedstock	Input: 10'000 t/y				Input: 1'000 t/y		
	Pyro	Hydro	Direct		Pyro	Hydro	Direct
Pack level cost	2.357	1.957	2.432		13.043	13.767	14.383
Pack level revenue	0.914	1.580	2.509		0.914	1.580	2.509
Cell level cost	2.399	2.111	2.659		13.051	13.840	14.592
Cell level revenue	1.067	1.672	3.093		1.067	1.672	3.093

Similar to NMC811, costs of recycling per kilogram of feedstock in the lower input scenario are higher than in the higher input scenario, resulting in a loss for all three recycling technologies (see Figure 6 for hydrometallurgy comparison). A detailed breakdown of the costs and revenues for LFP in Poland can be found in Appendix 1.

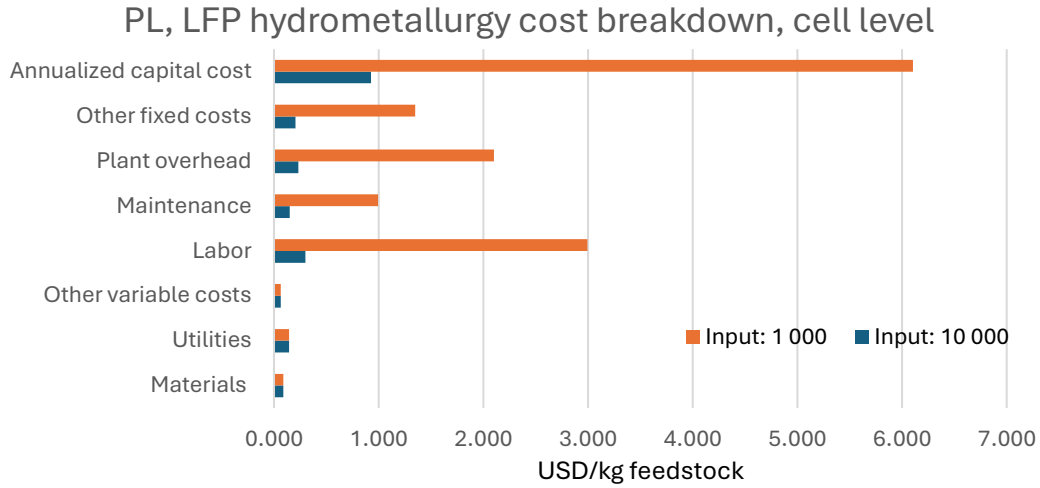


Figure 6. LFP hydrometallurgy costs breakdown for low and high input in Poland.

As there is no feedstock payment for LFP chemistry, the difference in cost between cell and pack level LFP recycling is much smaller compared to NMC811 chemistry. (see Figure 7 for pyrometallurgy comparison). A detailed breakdown of LFP costs and revenues in Poland can be found in Appendix 1.

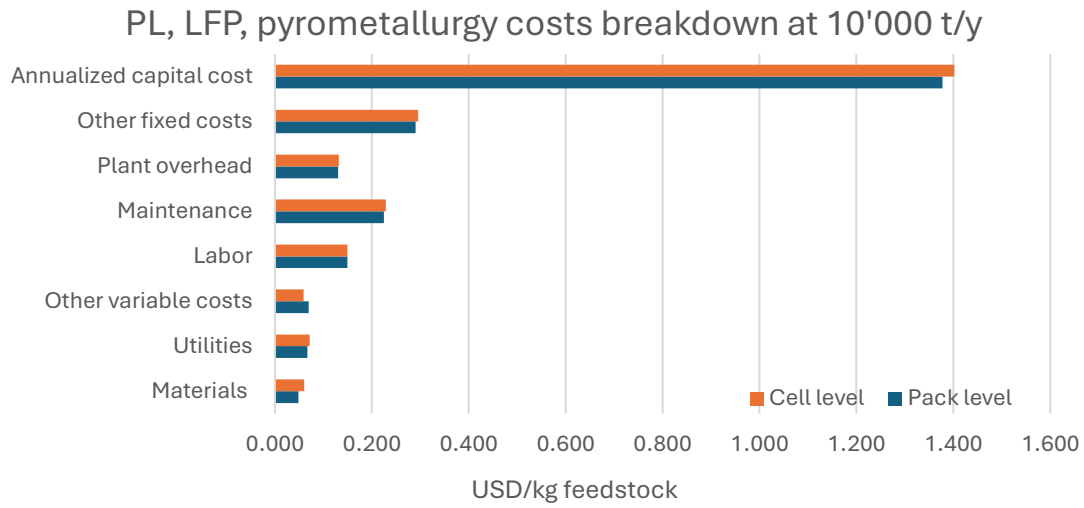


Figure 7. LFP pyrometallurgy costs breakdown for cell and pack level in Poland.

Table 9. Profit of recycling in Poland for LFP.

Profit [USD/kg feedstock]	Input: 10 000				Input: 1 000		
	Pyro	Hydro	Direct		Pyro	Hydro	Direct
Pack level	-1.443	-0.377	0.077		-12.130	-12.187	-11.875
Cell level	-1.332	-0.440	0.434		-11.984	-12.168	-11.499

Sensitivity analysis

Sensitivity analysis was conducted to determine the influence of material prices on the LCC analysis (Table 10). The analysis considered current material prices, as well as the five-year lowest (5Y MIN) and highest (5Y MAX) material market prices (see Table 5 for price references).

Higher material market prices result in higher profit/lower loss (see Figure 8).

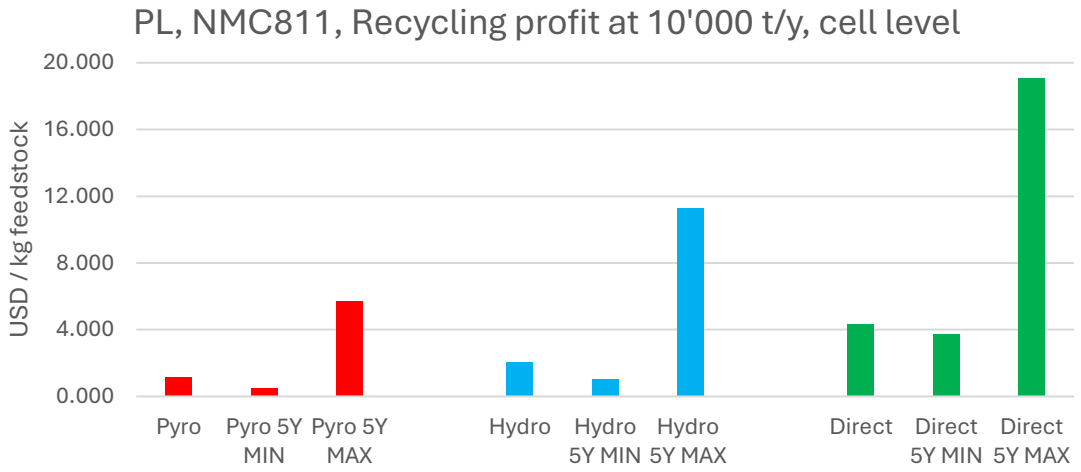


Figure 8. NMC811 recycling profit comparison for current, 5Y MIN and 5Y MAX material market prices for high feedstock input in Poland at cell level.

Table 10. Recycling profit for current (10/25), 5Y MIN and 5Y MAX material prices in Poland.

Profit [USD/kg feedstock]	Pyro 10/25	Pyro 5Ymin	Pyro 5Ymax		Hydro	Hydro 5Ymin	Hydro 5Ymax		Direct	Direct 5Ymin	Direct 5Ymax
NMC811, Pack level											
Input: 10 kt/y	0.047	-0.438	2.83		1.15	0.448	6.86		2.84	2.35	11.89
Input: 1 kt/y	-11.27	-11.76	-8.48		-10.66	-11.37	-4.95		-9.53	-10.01	-0.476
NMC811, Cell level											
Input: 10 kt/y	1.18	0.514	5.74		2.030	1.06	11.27		4.36	3.74	19.08
Input: 1 kt/y	-10.1	-10.76	-5.54		-9.68	-10.66	-0.437		-7.588	-8.20	7.14
LFP, Pack level											
Input: 10 kt/y	-1.44	-1.72	-1.42		-0.377	-0.815	1.77		0.077	-0.32	4.60
Input: 1 kt/y	-12.13	-12.40	-12.10		-12.19	-12.63	-10.04		-11.88	-12.27	-7.35
LFP, Cell level											
Input: 10 kt/y	-1.33	-1.65	-1.3		-0.44	-0.965	2.73		0.434	-0.033	7.25
Input: 1 kt/y	-11.98	-12.30	-11.95		-12.17	-12.69	-9.00		-11.50	-11.97	-4.69

3. LCC of recycling in France

Figure 9 and Table 11 show the economic evaluations of NMC811 chemistry recycling using pyrometallurgical, hydrometallurgical and direct processes in France.

With a feedstock input of 10 000 tonnes per year, direct recycling is the most cost-effective method at both the pack and cell levels (with profits of 1.885 and 3.282 USD per tonne of feedstock, respectively), followed by hydrometallurgy (see Table 12). The pyrometallurgical method is profitable at the cell level, in contrast to the pack level where it is unprofitable (-0.808 USD per tonne of feedstock).

In a scenario where the feedstock input is 1 000 tonnes per year, all three recycling methods are unprofitable.

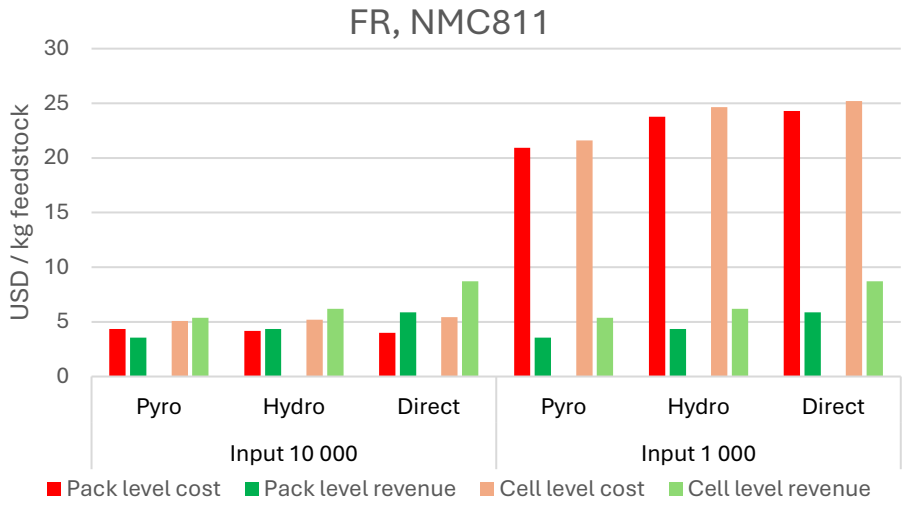


Figure 9. LCC of recycling in France for NMC811.

Table 11. Cost and revenue of recycling in France for NMC811

USD/kg feedstock	Input: 10 000				Input: 1 000		
	Pyro	Hydro	Direct		Pyro	Hydro	Direct
Pack level cost	4.362	4.175	3.993		20.929	23.777	24.288
Pack level revenue	3.554	4.338	5.878		3.554	4.338	5.878
Cell level cost	5.076	5.185	5.440		21.589	24.660	25.209
Cell level revenue	5.390	6.194	8.722		5.390	6.194	8.722

Similar to Poland, the higher costs of recycling per kilogram of feedstock in the lower input scenario are primarily the result of increased labour and plant overheads, as well as annualized capital costs, compared to the high feedstock scenario (see Figure 10 for direct recycling comparison). A detailed breakdown of the costs and revenues for NMC811 in France can be found in Appendix 2.

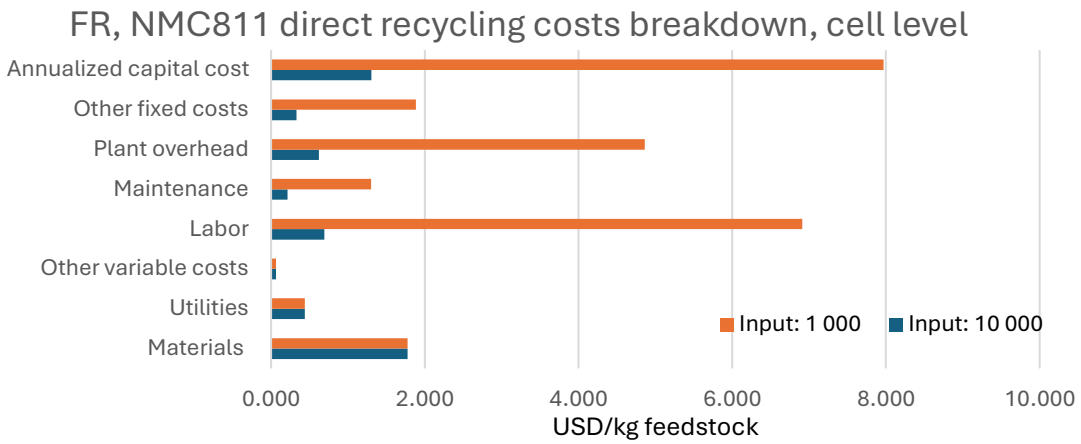


Figure 10. NMC811 direct recycling costs breakdown for low and high input in France.

The cost of recycling per kilogram of feedstock is higher at cell level than at pack level, mainly due to materials cost (see Figure 11). A detailed breakdown of the costs and revenues for NMC811 in France can be found in Appendix 2.

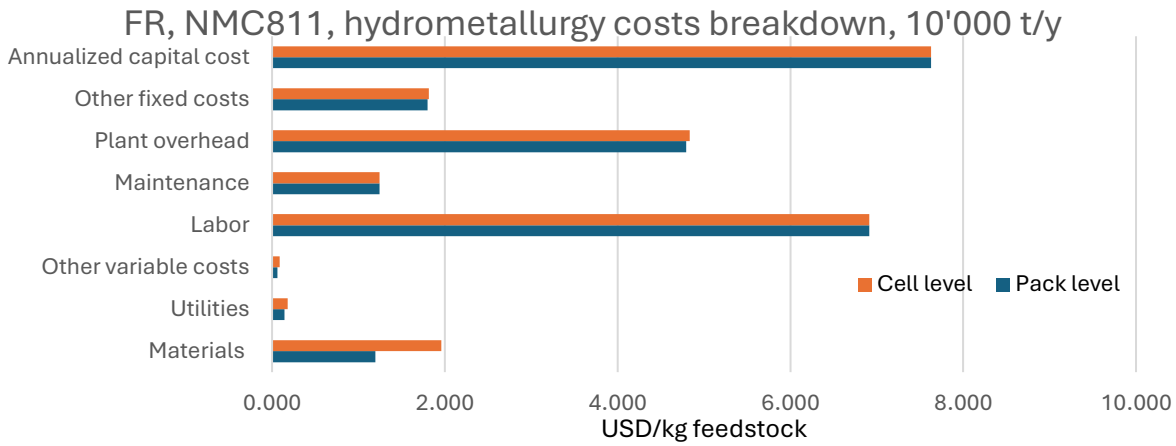


Figure 11. NMC811 hydrometallurgy costs breakdown for cell and pack level in France.

Table 12. Profit of recycling in France for NMC811.

Profit [USD/kg feedstock]	Input: 10 000			Input: 1 000		
	Pyro	Hydro	Direct	Pyro	Hydro	Direct
Pack level	-0.808	0.163	1.885	-17.374	-19.439	-18.410
Cell level	0.313	1.009	3.282	-16.200	-18.466	-16.487

Figure 12 and Table 13 present the economic evaluations of LFP chemistry recycling using pyrometallurgical, hydrometallurgical and direct processes in France.

The costs of all three recycling methods are lower for LFP recycling compared to NMC811 recycling. However, all three recycling methods are unprofitable for an input of either 1 000 or 10 000 tonnes per year, for both pack and cell level recycling (see Table 14).

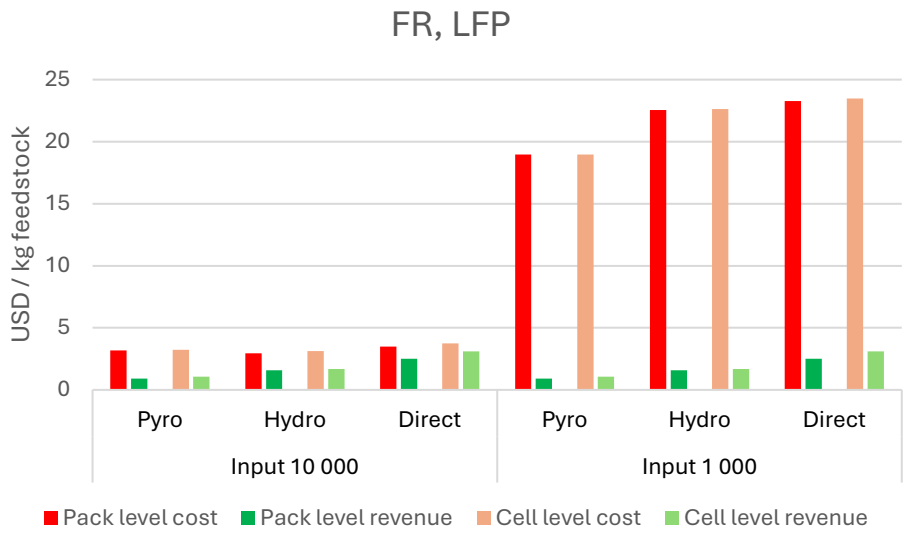


Figure 12. LCC of recycling in France for LFP.

Table 13. Cost and revenue of recycling in France for LFP

USD/kg feedstock	Input: 10 000				Input: 1 000		
	Pyro	Hydro	Direct		Pyro	Hydro	Direct
Pack level cost	3.181	2.947	3.49		18.96	22.55	23.27
Pack level revenue	0.914	1.580	2.51		0.914	1.580	2.509
Cell level cost	3.230	3.127	3.736		18.97	22.63	23.49
Cell level revenue	1.067	1.672	3.093		1.067	1.672	3.093

Similar to NMC811, costs of recycling per kilogram of feedstock are higher in the lower input scenario compared to higher input scenario, resulting in a loss for all three recycling technologies (see Figure 13 for hydrometallurgy comparison). A detailed breakdown of the costs and revenues for LFP in France can be found in Appendix 2.

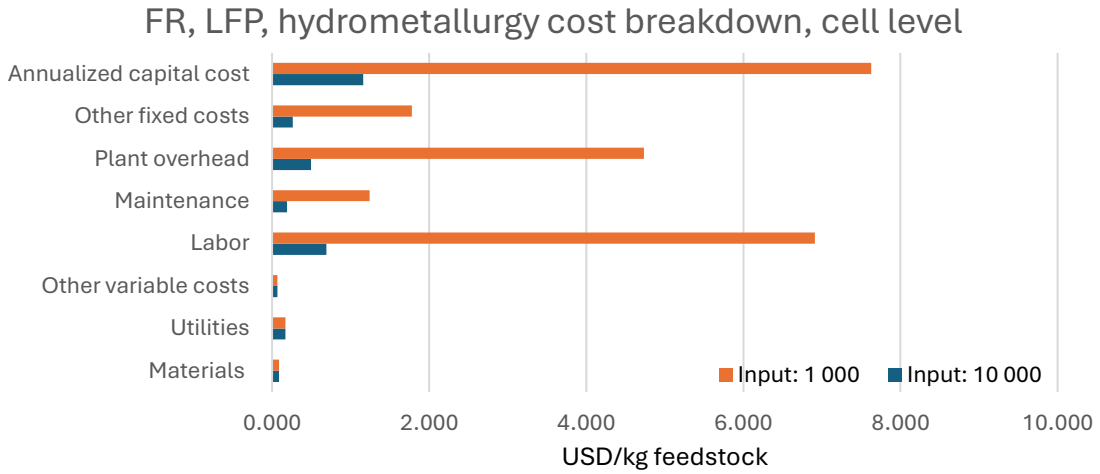


Figure 13. LFP hydrometallurgy costs breakdown for low and high input in France.

As in Poland, where there is no feedstock payment for LFP chemistry, the difference in cost between cell and pack level LFP recycling is much smaller compared to NMC811 chemistry (see Figure 14 for pyrometallurgy comparison). A detailed breakdown of the costs and revenues for LFP in France can be found in Appendix 2.

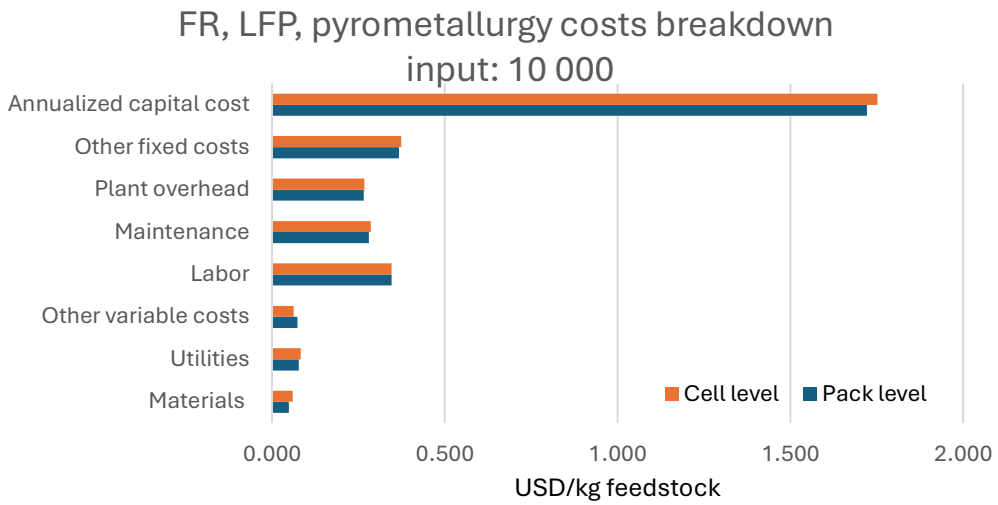


Figure 14. LFP pyrometallurgy costs breakdown for cell and pack level in France.

Table 14. Profit of recycling in France for LFP.

Profit [USD/kg feedstock]	Input: 10 000			Input: 1 000		
	Pyro	Hydro	Direct	Pyro	Hydro	Direct
Pack level	-2.267	-1.367	-0.98	-18.05	-20.97	-20.76
Cell level	-2.164	-1.456	-0.64	-17.90	-20.96	-20.40

Sensitivity analysis

Sensitivity analysis was conducted to determine the influence of material prices on the LCC analysis (Table 15). Sensitivity analysis was performed considering current, five-year lowest (5Y MIN) and highest (5Y MAX) material market prices (see Table 5 for price references).

The higher material price the higher profit/less loss (see Figure 15).

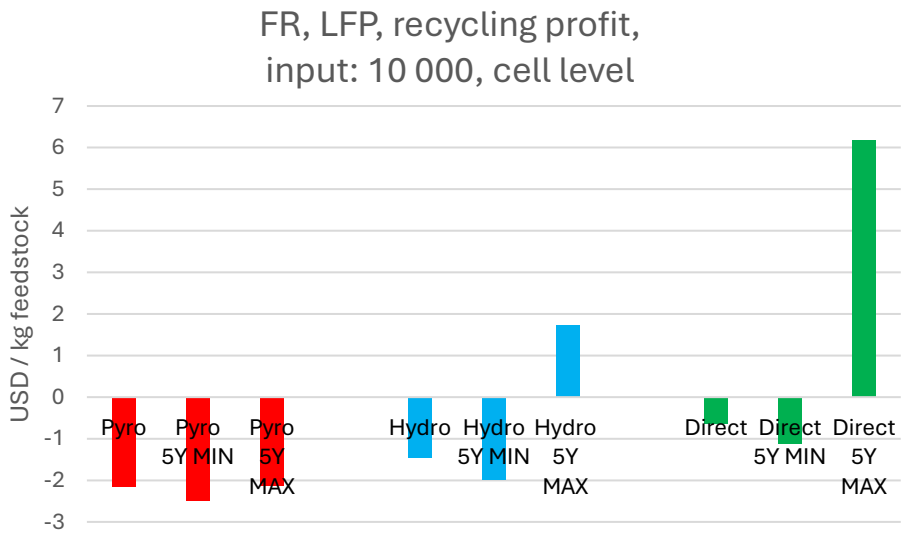


Figure 15. LFP recycling profit comparison for current, 5Y MIN and 5Y MAX material market prices for high input in France at cell level.

Table 15. Recycling profit for current, 5Y MIN and 5Y MAX material prices in France.

Profit [USD/kg feedstock]	Pyro	Pyro 5Ymin	Pyro 5Ymax	Hydro	Hydro 5Ymin	Hydro 5Ymax	Direct	Direct 5Ymin	Direct 5Ymax
NMC811, Pack level									
Input: 10 kt/y	-0.808	-1.293	1.98	0.163	-0.541	5.87	1.885	1.40	10.94
Input: 1 kt/y	-17.37	-17.86	-14.59	-19.44	-20.14	-13.73	-18.41	-18.90	-9.36
NMC811, Cell level									
Input: 10 kt/y	0.313	-0.351	4.87	1.009	0.037	10.25	3.28	2.67	18.01
Input: 1 kt/y	-16.20	-16.86	-11.64	-18.47	-19.44	-9.23	-16.49	-17.10	-1.76
LFP, Pack level									
Input: 10 kt/y	-2.267	-2.539	-2.24	-1.37	-1.805	0.778	-0.982	-1.38	3.54
Input: 1 kt/y	-18.05	-18.32	-18.02	-20.97	-21.41	-18.83	-20.76	-21.16	-16.24
LFP, Cell level									
Input: 10 kt/y	-2.16	-2.481	-2.13	-1.46	-1.98	1.72	-0.643	-1.11	6.17
Input: 1 kt/y	-17.9	-18.22	-17.87	-20.96	-21.48	-17.79	-20.40	-20.87	-13.59

4. LCC comparison of recycling in Poland and France

Figure 16 and Table 16 show a comparison of the profitability of NMC811 recycling for a high input in Poland and France. In Poland, all three recycling technologies are profitable at cell and pack level. However, due to higher recycling costs in France (direct labour, electricity, natural gas, etc.; see Table 4), profits are lower in France than in Poland. Pyrometallurgy is even unprofitable at pack level (-0.808 USD per kg of feedstock).

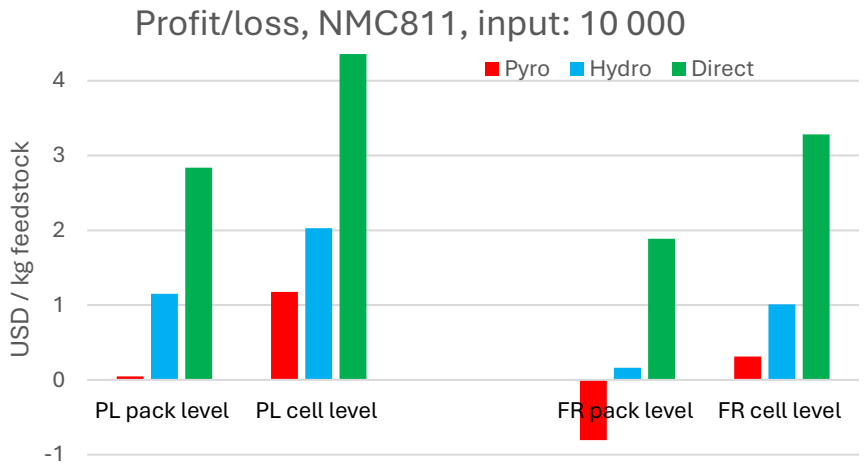


Figure 16. NMC811 recycling profit comparison for high input in Poland and France.

Table 16. NMC811 recycling profit comparison for high input in Poland and France.

NMC811, Input: 10 000 tonnes per year			
Profit [USD/kg feedstock]	Pyro	Hydro	Direct
PL pack level	0.047	1.152	2.838
PL cell level	1.178	2.030	4.355
FR pack level	-0.808	0.163	1.885
FR cell level	0.313	1.009	3.282
Δpack level*	-1805%	-86%	-34%
Δcell level*	-73%	-50%	-25%

*Δ=[FR profit-PL profit]/|PL profit|

Figure 17 and Table 17 show a comparison of the profitability of NMC811 recycling with a low input in Poland and France. All three recycling methods are unprofitable at pack and cell level in both countries, with greater losses occurring in France.

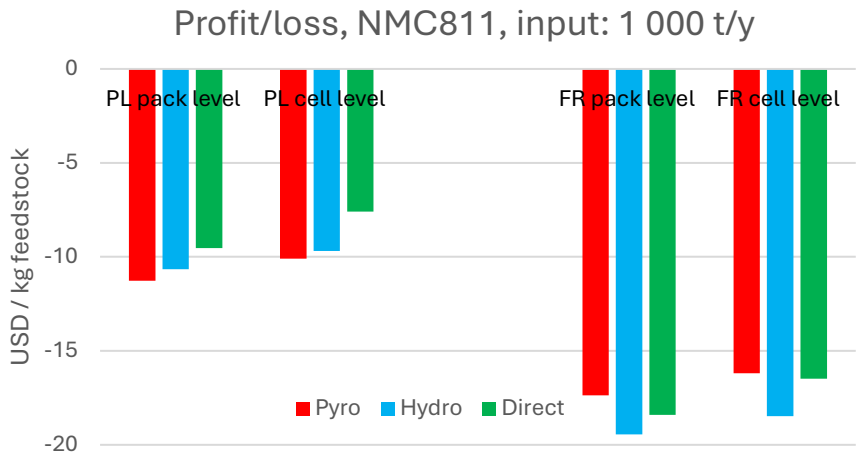


Figure 17. NMC811 recycling profit comparison for low input in Poland and France.

Table 17. NMC811 recycling profit comparison for low input in Poland and France.

NMC811, Input: 1 000 tonnes per year			
Profit [USD/kg feedstock]	Pyro	Hydro	Direct
PL pack level	-11.270	-10.658	-9.526
PL cell level	-10.096	-9.678	-7.588
FR pack level	-17.374	-19.439	-18.410
FR cell level	-16.200	-18.466	-16.487
Δpack level*	-54%	-82%	-93%
Δcell level*	-60%	-91%	-117%

*Δ=[FR profit-PL profit]/|PL profit|

Figure 18 and Table 18 show a comparison of the profitability of LFP recycling with a high input in Poland and France. In case of Poland, only the direct recycling method is profitable. In France, none of the three methods are profitable.

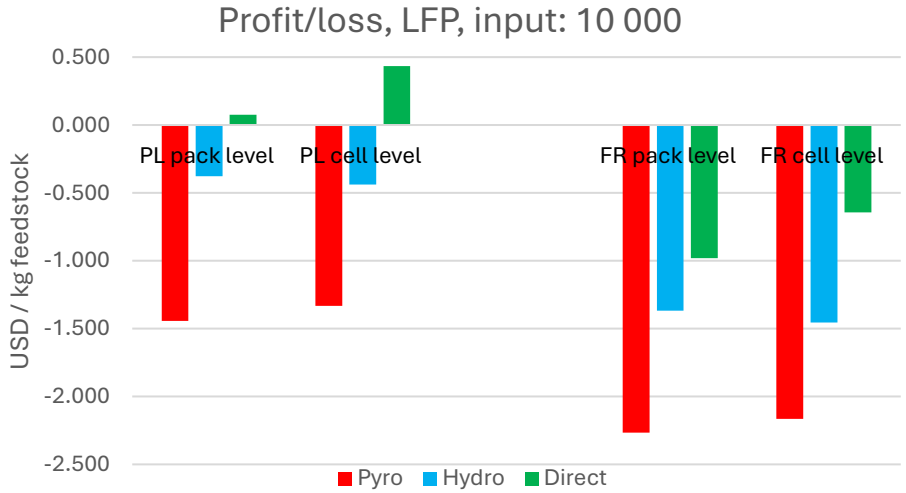


Figure 18. LFP recycling profit comparison for high input in Poland and France.

Table 18. LFP recycling profit comparison for high input in Poland and France.

LFP, Input: 10 000 tonnes per year			
Profit [USD/kg feedstock]	Pyro	Hydro	Direct
PL pack level	-1.443	-0.377	0.077
PL cell level	-1.332	-0.440	0.434
FR pack level	-2.267	-1.367	-0.982
FR cell level	-2.164	-1.456	-0.643
Δpack level*	-57%	-262%	-1382%
Δcell level*	-62%	-231%	-248%

*Δ=[FR profit-PL profit]/|PL profit|

Figure 19 and Table 19 show a comparison of the profitability of LFP recycling with a low input in Poland and France. All three recycling methods are unprofitable at pack and cell level in both countries, with France experiencing higher losses.

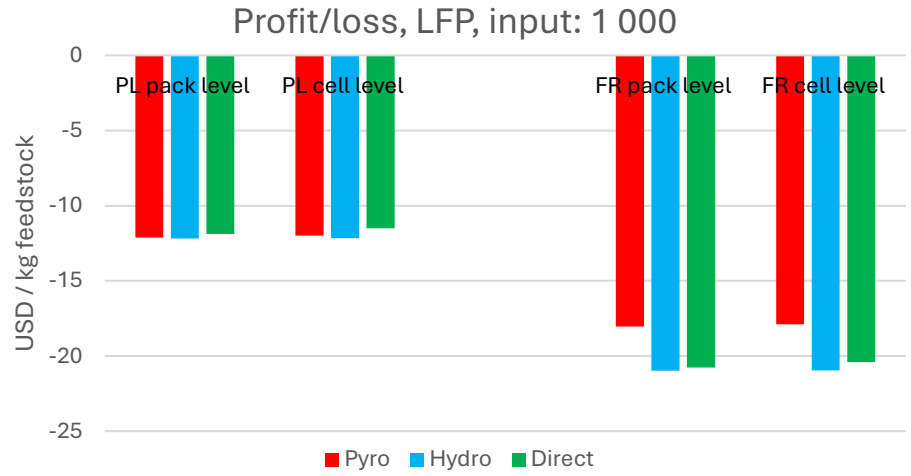


Figure 19. LFP recycling profit comparison for low input in Poland and France.

Table 19. LFP recycling profit comparison for low input in Poland and France.

LFP, Input: 1 000 tonnes per year			
Profit [USD/kg feedstock]	Pyro	Hydro	Direct
PL pack level	-12.130	-12.187	-11.875
PL cell level	-11.984	-12.168	-11.499
FR pack level	-18.045	-20.970	-20.761
FR cell level	-17.899	-20.957	-20.399
Δpack level*	-49%	-72%	-75%
Δcell level*	-49%	-72%	-77%

*Δ=[FR profit-PL profit]/|PL profit|

As mentioned in section 1.2 the cost of LFP feedstock for recycling is zero. On the other hand, the cost of NMC811 feedstock varies according to material market prices.

An additional scenario assumes, for LFP chemistry, battery fees to recyclers equal -2.00 USD/kg of feedstock. This negative value indicates that recyclers are paid to take the batteries. Consequently, the LFP recycling cost per kg of feedstock decreases, increasing

the profit margin (see Table 20). Most methods become profitable when fees are included (with the exception of pyrometallurgical recycling in France).

Table 20. Comparison of profit with and without recycling fee for LFP, input: 10 000 tonnes per year.

	LFP, Input: 10 000 tonnes per year					
Profit [USD/kg feedstock]	Pyro		Hydro		Direct	
	No fee	With fee	No fee	With fee	No fee	With fee
PL pack level	-1.443	0.557	-0.377	1.623	0.077	2.077
PL cell level	-1.332	0.668	-0.440	1.560	0.434	2.434
FR pack level	-2.267	-0.267	-1.367	0.633	-0.982	1.018
FR cell level	-2.164	-0.164	-1.456	0.544	-0.643	1.357

The next scenario assumes that, for NMC811 chemistry, there is no feedstock payment related to the material market price (the cost of NMC811 feedstock for recycling is zero). Consequently, the NMC811 recycling profit margin is increasing (see Table 21). All methods become profitable when feedstock payments are excluded.

Table 21. Comparison of profit with and without feedstock payment for NMC811, input: 10 000 tonnes per year.

	NMC811, Input: 10 000 tonnes per year					
Profit [USD/kg feedstock]	Pyro		Hydro		Direct	
	No feedstock payment	With feedstock payment	No feedstock payment	With feedstock payment	No feedstock payment	With feedstock payment
PL pack level	0.917	0.047	2.022	1.152	3.708	2.838
PL cell level	2.607	1.178	3.459	2.030	5.785	4.355
FR pack level	0.062	-0.808	1.033	0.163	2.725	1.885
FR cell level	1.742	0.313	2.438	1.009	4.711	3.282

5. Reuse comparison

This section evaluates the economic viability of repurposing end-of-life (EOL) NMC and LFP batteries as Battery Energy Storage Systems (BESS) to exploit daily fluctuations in electricity prices in France and Poland. The fundamental operating principle exploits intraday electricity price variations by purchasing electricity during low-cost off-peak hours and selling stored electricity during high-price peak hours, completing either one or two full charge-discharge cycles daily depending on market conditions and grid constraints.

The economic model calculates cumulative daily profit margins based on the price differential between the minimum and maximum hourly electricity prices, determined over a 3-hour window representing the time required for battery charging and discharging as we assume that only at average C/3 will be charged and discharged to increase battery life at low rate operation. For each configuration analysed—defined by geography, battery chemistry type, physical form (cell versus integrated pack), daily cycle frequency, and initial battery state of health (SOH)—the analysis tracks profit accumulation over batteries operational period, normalized per kilogram of battery feedstock. All results are presented in USD/kg feedstock.

The model simulates battery operations from initial SOH: 100% (new), 90%, 80%, 70% (refurbished) down to an ending Soc of 40% being defined as EOL, using 90% depth of discharge (DOD) per cycle. Battery degradation follows empirical aging curves for NCM and LFP measured from real battery aging data. Due to limited data for LFP aging curves to capacity aging from 100% to only 56% remaining capacity, its curve from 56% to 40% SOH was extrapolated using a linear regression which is a simplified assumption as no further aging data was available and to allow modelling Reuse case to 40% EoL capacity as for NCM cells and allow comparison.

The model computes the total profit by first determining the net revenue for each charge–discharge cycle and then summing these values over the battery's operational lifetime. The profit for an individual cycle is defined as follows:

Equation 1. Profit per cycle calculation

$$Profit = Cope - (Cinv + Cmai + Cepc + Ccont)$$

Where:

- C_{ope}: Daily revenue from charging (buying electricity) at low-price hours and discharging (selling) at high-price hours.

  Equation 2. Operational cost formula

  $$Cope = C_0 \cdot SOH \cdot DOD \cdot (price_{max} - price_{min})$$

  - C_0 is initial battery cell/package capacity (values provided in the Table 22Table 22), SOH is battery state of health, DOD is Depth of Discharge set at 90%, and maximum and minimum prices derived from averaged hourly electricity price data.

Table 22. Initial battery capacity values.

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

- C_{inv}: Initial investment cost, including the purchase of refurbished or new batteries, with refurbished units typically costing significantly less, as provided in Table 23.

Table 23. Investment costs

C_{inv} [USD/kg feedstock]	New		Refurbished	
	NCM	LFP	NCM	LFP
Pack level	20.79	8.8	0.87	0
Cell level	27.79	8.92	1.429	0

- C_{mai}: Battery maintenance cost – in presented calculations we used 0.02 $ / kWh for both chemistries and both types of batteries.
- C_{epc}: Container installation cost ($15/kWh for NMC and LFP).
- C_{cont}: Container cost (NMC: $106k, LFP: $120k per 5 MWh).

Figure 20 and Figure 21 presents averaged prices per hour for annual hourly data from 2024 for France and Poland. The French electricity market demonstrates moderate intraday price volatility, in contrast, the Polish electricity market exhibits substantially higher price volatility with absolute pricing levels approximately 70% larger than in France.

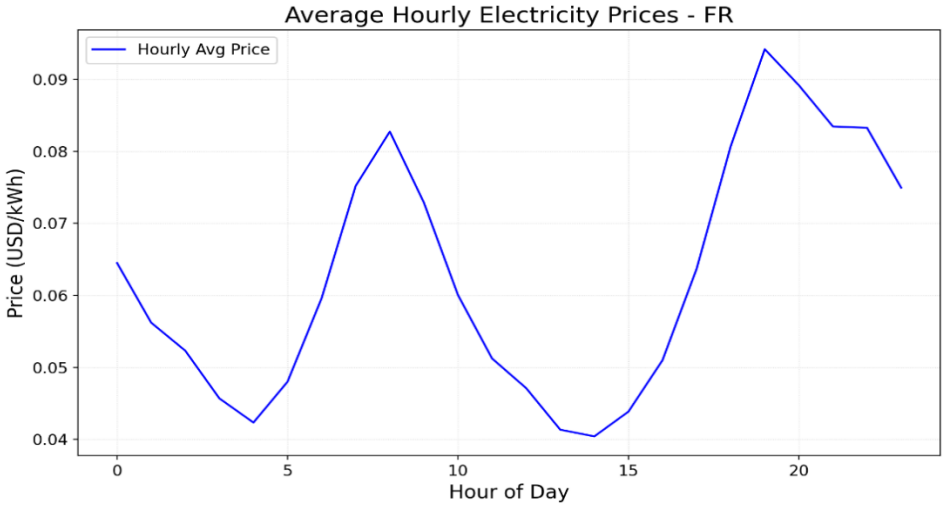


Figure 20. Average 24-Hour Electricity Price Profile for France in 2024

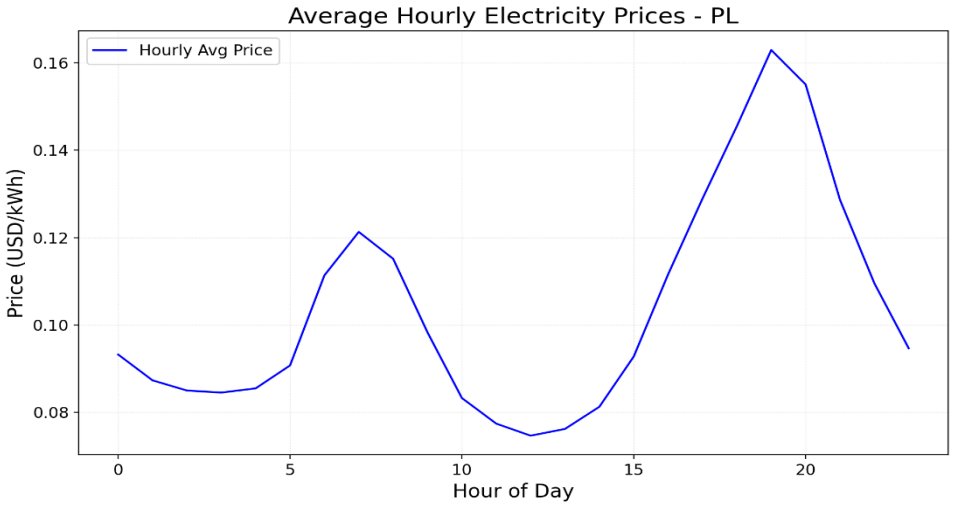


Figure 21. Average 24-Hour Electricity Price Profile for Poland in 2024

5.1 Single Cycle Per Day Operation

Beginning with the battery cell under single cycle per day operation, the economic performance differs substantially between French and Polish market. For cell-level systems using NMC811 chemistry – Figure 22 and Figure 23, batteries starting at 100% initial SOH begin with an initial investment equivalent to approximately $40 per kilogram due to high investment costs. Over the operational lifetime typical for NMC811 under daily cycling, these batteries accumulate revenue but fail to reach profitability, ending with a cumulative loss of approximately $29/kg (France) and $16/kg (Poland). Although refurbished batteries with 70–90% SOH have significantly lower initial costs, around $13/kg compared to the new NMC batteries, they still fail to reach a positive profit over their operational lifetime. The only exception is the Polish scenario, where 90%-SOH batteries reach a modest profit of approximately $3/kg.

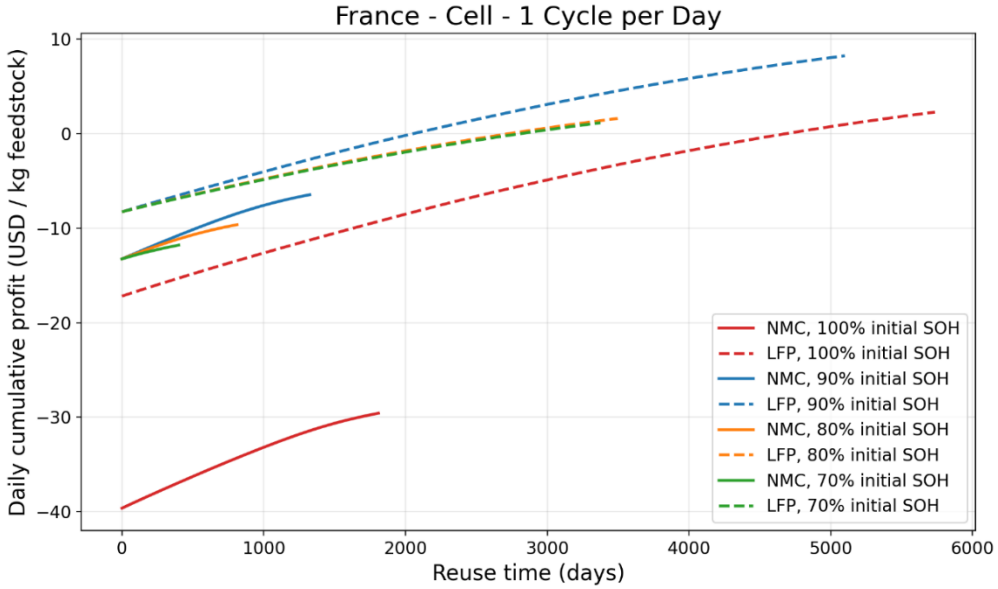


Figure 22. Profitability of New vs. Refurbished NMC and LFP Battery Cells for Daily Energy Price-Difference Operation in France - 1 cycle

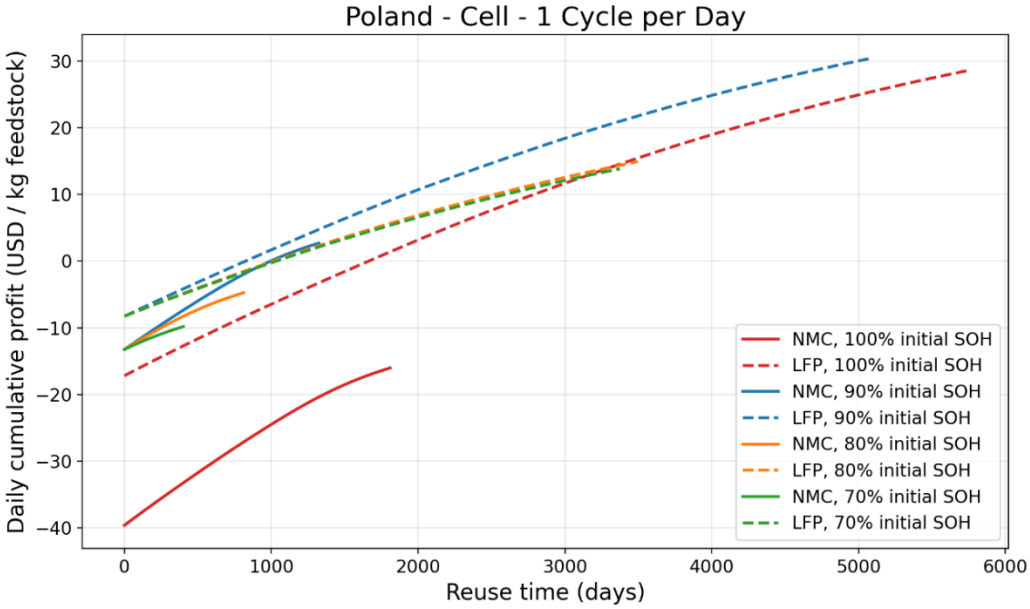


Figure 23. Profitability of New vs. Refurbished NMC and LFP Battery Cells for Daily Energy Price-Difference Operation in Poland - 1 cycle

LFP chemistry at the cell level demonstrates markedly superior performance compared to NMC in both France and Poland. Batteries with an initial SOH of 100% require an investment of approximately $17/kg. Their extended lifetime of around 5735 cycles enables them to generate cumulative profits slightly above $2/kg in France and nearly $29/kg in Poland. LFP batteries with an initial SOH of 70–90% require an investment of approximately $8/kg. In the French market, they yield positive cumulative profits of around $8/kg at 90% SOH and approximately $1.5/kg at 70–80% SOH. In the Polish market, profitability is significantly higher, reaching roughly $30/kg at 90% SOH and around $14/kg at 70–80% SOH.

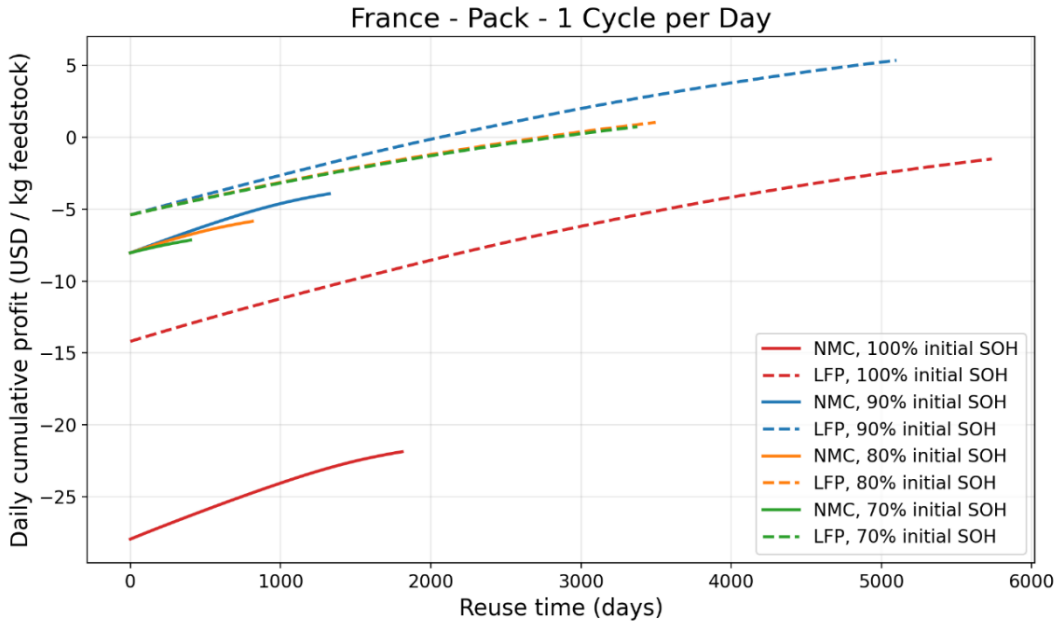


Figure 24. Profitability of New vs. Refurbished NMC and LFP Battery Packs for Daily Energy Price-Difference Operation in France - 1 cycle

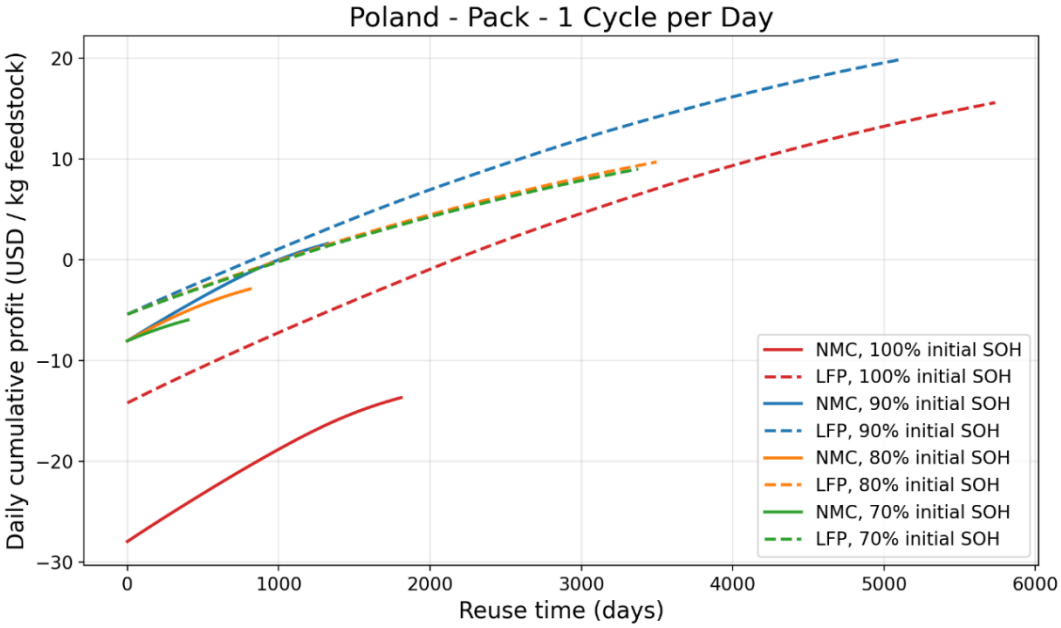


Figure 25. Profitability of New vs. Refurbished NMC and LFP Battery Packs for Daily Energy Price-Difference Operation in Poland - 1 cycle

Pack-level systems show somewhat improved economics compared to cell-level configurations due to reduced investment costs, Figure 24 and Figure 25. For NMC811 packs at 100% SOH, the starting investment is approximately $28/kg, lower than the cell-level equivalent. The cumulative loss reduces to approximately $22/kg in case of France and ~14$/kg for Poland, representing an improvement over cell-level systems, but still failing to achieve profitability. Situation with refurbished battery packs is similar as with battery cells, where only profitable case is 90% SOH reaching positive profit only near the battery end of life. LFP packs demonstrate their economic advantage more clearly, although cumulative profit in both France and Poland is lower compared to cell-level equivalent. In case of France new battery pack is not reaching positive profit, while 70-90% SOH systems achieving similar results like in case of battery cells with SOH 90% being slightly lower ~5$/kg. Pack-level systems in Poland show the strongest overall economics across all scenarios examined. LFP packs at SOH 90% achieve approximately $20/kg cumulative profit at ~5100 cycles/days, with break-even occurring around 800 cycles/days, while SOH 70-80% achieve approximately $9/kg cumulative profit. The combination of pack-level integration benefits and the high-margin Polish market creates optimal conditions for second-life battery deployment.

5.2 Two Cycles Per Day Operation

The implementation of two charge-discharge cycles per day represents a distinctly different operational strategy with distinct economic implications. The initial investment costs for acquiring and installing the second-life battery system remain identical to the single-cycle scenario, as the physical system requirements are the same. However, the operational dynamics change significantly through the exploitation of two separate price arbitrage opportunities within each 24-hour period rather than targeting only the single most profitable opportunity.

As on the figures Figure 20 and Figure 21, under the two-cycle regime, the first cycle charges the battery during the early morning off-peak period (~3:00-5:00 (France) and ~2:00-4:00 (Poland)) when prices reach their 2nd minimum, then discharges during the morning demand increase (~7:00-9:00 (France) and ~6:00-8:00 (Poland)). The second cycle charges again during the midday when prices reach their daily minimum (~13:00-15:00 (France) and ~11:00-13:00 (Poland)) and discharges during the evening when prices reach their daily maximum (~18:00-20:00 (France and Poland)). The critical economic constraint is that the second cycle of these cycles captures the maximum daily price differential and exploits the same maximum price point that would be targeted in single-cycle operation. However, the first cycle must discharge during a secondary peak period where prices are lower than the evening maximum, resulting in a smaller price difference and consequently lower profitability per cycle. In France, the price structure reveals this limitation clearly. The second cycle achieves the same differential available to single-cycle operation, approximately $0.054 per kWh, by charging at the midday minimum around $0.041 per kWh and discharging at the evening peak around $0.095 per kWh. The first cycle, however, must settle for the morning peak price of approximately $0.083 per kWh, yielding a differential of only $0.043 per kWh. When averaged across both daily cycles, the effective price differential drops to approximately $0.048 per kWh, representing an 11% reduction compared to the optimal single-cycle approach. This reduced average profitability per cycle must then be evaluated against the doubled cycle frequency and the two times shortened operational lifetime.

The operational lifetime under two-cycle conditions experiences dramatic compression. The fundamental degradation mechanisms in Li-ion batteries are driven by cycle count and calendar time within normal temperature ranges. By doubling the daily cycle count, the battery reaches its EOL cycle threshold in approximately half the calendar time.

Comparing cell-level systems under two-cycle operation between France and Poland (Figure 26 and Figure 27) reveals the dramatic impact of market conditions on economic viability. French cell-level operations demonstrate severely constrained economics, with NMC811 batteries at all SOH levels remaining deeply unprofitable, accumulating losses ranging from $6/kg at 90% SOH to $28/kg at 100% SOH over their compressed operational lifetimes of ~900 days. LFP cells in France perform better, but still show marginal results, with the most favourable scenario of 90% SOH achieving only $11/kg profit over ~2867 days, while even 80% and 70% SOH batteries reach modest profits of ~$3/kg.

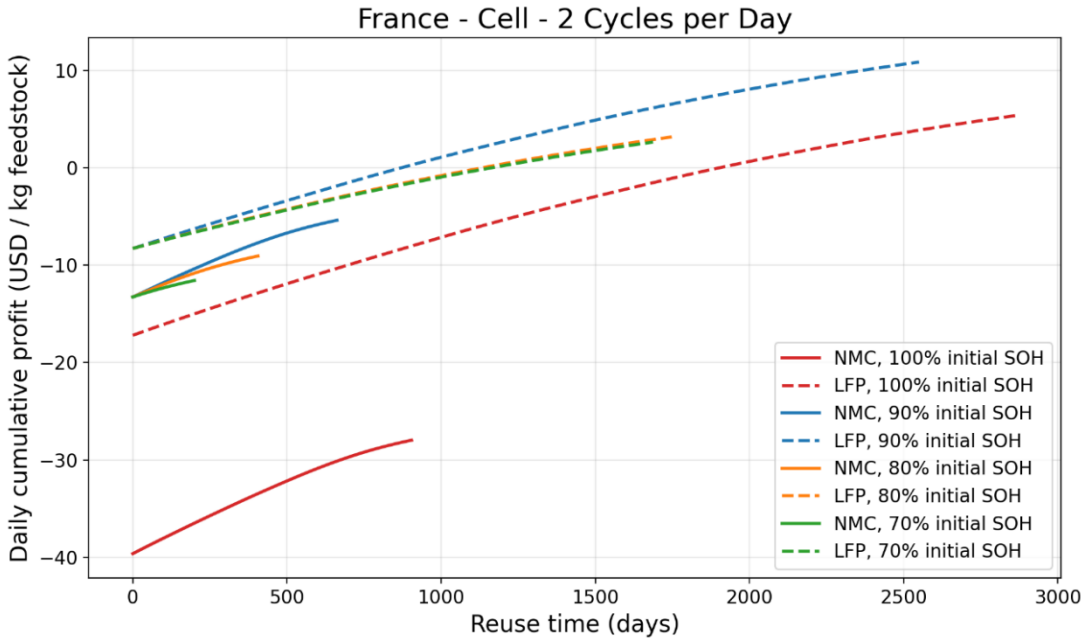


Figure 26. Profitability of New vs. Refurbished NMC and LFP Battery Cells for Daily Energy Price-Difference Operation in France - 2 cycle

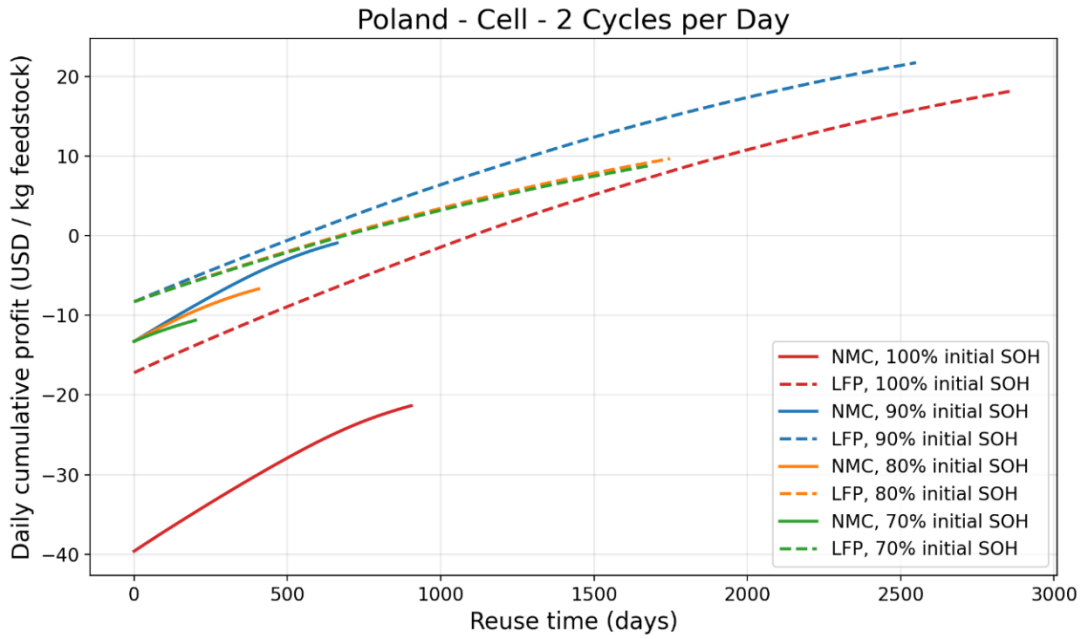


Figure 27. Profitability of New vs. Refurbished NMC and LFP Battery Cells for Daily Energy Price-Difference Operation in Poland - 2 cycle

In contrast, Polish cell-level systems operating under the same two-cycle regime demonstrate fundamentally transformed economics due to the market's ~70% higher price differentials. Polish LFP cells at 90% SOH achieve remarkable profitability of $22/kg over almost 2867 days, representing more than double the French equivalent, while 80% and 70% SOH scenarios reach $10/kg and $9/kg respectively. However, in the Polish market, NMC811 battery cells starting at 90% SOH still result in a loss of approximately $2/kg, and those at 100% SOH incur losses of about $21/kg. This outcome demonstrates that even under favourable price conditions, the combination of high acquisition cost and accelerated degradation prevents high-SOH NMC batteries from achieving economic viability under higher cycling intensity.

Pack-level systems under two-cycle operation exhibit similar geographic disparities, but consistently lower absolute profitability than cell-level systems. French pack-level NMC811 systems remain unprofitable across all SOH levels, Figure 28, with 90% SOH batteries still accumulating approximately $3/kg loss over ~660 days despite the pack-level efficiency advantages.

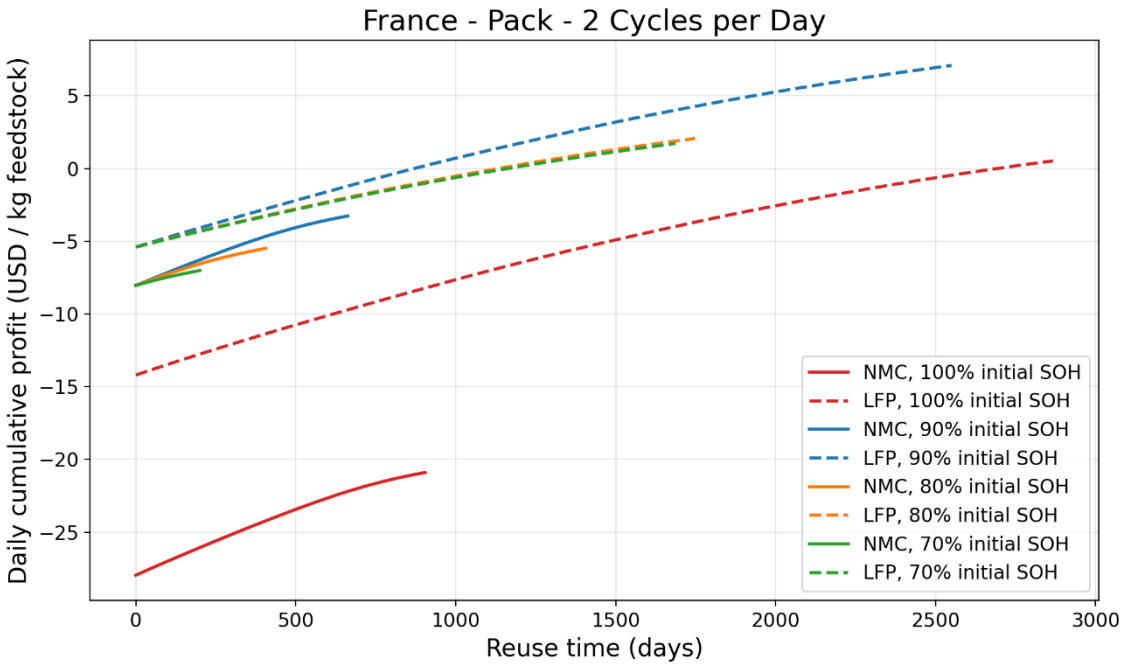


Figure 28. Profitability of New vs. Refurbished NMC and LFP Battery Packs for Daily Energy Price-Difference Operation in France - 2 cycle

French LFP packs achieve modest gains, with 90% SOH systems reaching approximately $7/kg profit over almost 2867 days and 70-80% SOH achieving ~$2/kg profit. Polish pack-level systems demonstrate the strongest overall economics under two-cycle operation, with LFP packs at 90% SOH achieving $13/kg profit, representing both higher returns and faster profit accumulation rates than any French configuration. As illustrated in Figure 29, Polish NMC811 packs at 90% SOH reach $1/kg loss over ~660 days, while 100% SOH NMC packs still end with approximately $17/kg loss. The pack-level comparison shows that, although Poland consistently outperforms France by a factor of 2–3 in cumulative profit, packs are less profitable than cell-level systems in both markets. This indicates that system-level integration benefits do not outweigh the performance advantage of individual cells, and that market fundamentals remain the dominant factor determining overall economic viability.

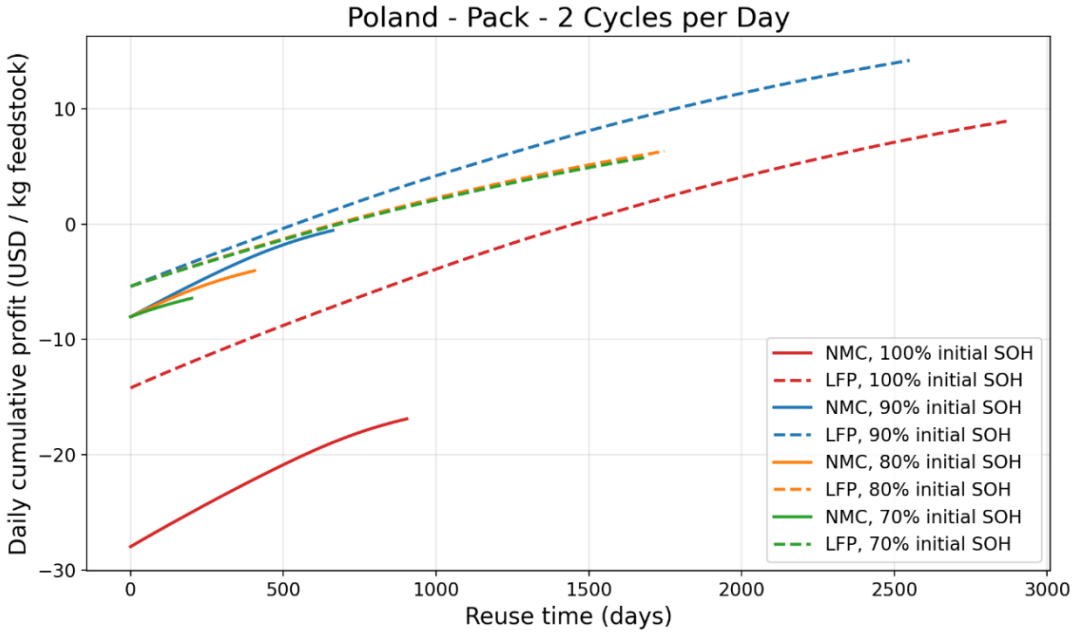


Figure 29. Profitability of New vs. Refurbished NMC and LFP Battery Packs for Daily Energy Price-Difference Operation in Poland - 2 cycle

6. Conclusions

The study examined the economic benefits of NMC811 and LFP chemistries reuse and recycling considering pyrometallurgical, hydrometallurgical and direct recycling technologies in Poland and France, at both cell and pack levels, with 1'000 and 10'000 tonnes of feedstock per year.

In general, due to higher recycling costs in France (direct labour, electricity, natural gas, etc.), recycling is less profitable in France compared to Poland. The most profitable method of recycling is direct recycling, followed by hydrometallurgy and pyrometallurgy.

Recycling of NMC811 is more profitable compared to LFP, due to higher value of the recovered materials, especially with a high feedstock input (lower labour and plant overheads, as well as annualized capital costs, compared to the low feedstock scenario). In the case of high input scenario, the recycling of NMC811 is only unprofitable for the pyrometallurgical method in France. Low input of NMC811 recycling generates losses for both Poland and France.

Recycling of LFP is only profitable for direct recycling in Poland for the high feedstock scenario. For all other scenarios, costs exceed revenue, resulting in losses.

The economics of LIB recycling are significantly influenced by materials cost. Higher material prices result in higher profit (lower loss).

Reuse of NMC811 and LFP battery cells and packs shows higher profitability in Poland, driven by greater electricity price volatility. NMC811 reuse is unprofitable in almost all scenarios, with the only exception being operation at one cycle per day for both cells and packs at 90% SOH in Poland. In contrast, LFP reuse is profitable in nearly all scenarios, except for battery packs at 100% SOH operated at one cycle per day.

Appendix 1. Detailed cost & revenue breakdown for Poland

Feedstock input: 10 000 tonnes/year
Chemistry: NMC811
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.010	0.885	2.393	1.196	1.071	2.579	1.084	0.960	2.467
Utilities	0.067	0.067	0.067	0.120	0.120	0.120	0.267	0.267	0.267
Other variable costs	0.077	0.075	0.104	0.060	0.057	0.087	0.046	0.043	0.073
Labour	0.150	0.150	0.150	0.300	0.300	0.300	0.300	0.300	0.300
Maintenance	0.240	0.240	0.240	0.142	0.142	0.142	0.120	0.120	0.120
Plant overhead	0.168	0.160	0.226	0.289	0.277	0.407	0.303	0.293	0.455
Other fixed costs	0.326	0.323	0.350	0.211	0.209	0.236	0.185	0.183	0.210
Annualized capital cost	1.470	1.470	1.470	0.868	0.868	0.868	0.735	0.735	0.735
Feedstock payment	0.870	0.750	2.213	0.870	0.750	2.213	0.870	0.750	2.213

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.798	0.558	0.822
Co^{2+} in product	0.702	0.359	1.375
Ni^{2+} in product	2.054	2.015	5.634

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.434	0.245	3.335
Co^{2+} in product	0.688	0.352	1.348
Ni^{2+} in product	2.013	1.975	5.521
Mn^{2+} in product	0.026	0.020	0.097
Graphite	0.030	0.030	0.030
Copper metal	0.756	0.529	0.779
Aluminium metal	0.316	0.267	0.413
Steel	0.074	0.074	0.074

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
NMC811	4.702	4.351	15.218
Graphite	0.030	0.030	0.030
Copper metal	0.756	0.529	0.779
Aluminium metal	0.316	0.267	0.413
Steel	0.074	0.074	0.074

Feedstock input: 10 000 tonnes/year
Chemistry: NMC811
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.639	1.434	3.910	1.959	1.755	4.230	1.776	1.572	4.047
Utilities	0.072	0.072	0.072	0.153	0.153	0.153	0.395	0.395	0.395
Other variable costs	0.070	0.066	0.114	0.085	0.081	0.129	0.062	0.058	0.107
Labour	0.150	0.150	0.150	0.300	0.300	0.300	0.300	0.300	0.300
Maintenance	0.245	0.245	0.245	0.154	0.154	0.154	0.170	0.170	0.170
Plant overhead	0.193	0.182	0.288	0.330	0.311	0.522	0.357	0.342	0.606
Other fixed costs	0.343	0.339	0.382	0.240	0.237	0.281	0.263	0.259	0.305
Annualized capital cost	1.501	1.501	1.501	0.942	0.942	0.942	1.044	1.044	1.044
Feedstock payment	1.429	1.231	3.634	1.429	1.231	3.634	1.429	1.231	3.634

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.864	0.604	0.890
Co^{2+} in product	1.153	0.590	2.258
Ni^{2+} in product	3.373	3.308	9.250

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.713	0.402	5.475
Co^{2+} in product	1.130	0.578	2.213
Ni^{2+} in product	3.306	3.242	9.065
Mn^{2+} in product	0.043	0.033	0.159
Graphite	0.050	0.050	0.050
Copper metal	0.818	0.573	0.843
Aluminium metal	0.134	0.114	0.176

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
NMC811	7.720	7.144	24.987
Graphite	0.050	0.050	0.050
Copper metal	0.818	0.573	0.843
Aluminium metal	0.134	0.114	0.176

Feedstock input: 1 000 tonnes/year
Chemistry: NMC811
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.010	0.885	2.393	1.196	1.071	2.579	1.084	0.960	2.467
Utilities	0.067	0.067	0.067	0.120	0.120	0.120	0.267	0.267	0.267
Other variable costs	0.077	0.075	0.104	0.060	0.057	0.087	0.046	0.043	0.073
Labour	1.498	1.498	1.498	2.995	2.995	2.995	2.995	2.995	2.995
Maintenance	1.305	1.305	1.305	0.995	0.995	0.995	1.038	1.038	1.038
Plant overhead	1.157	1.150	1.215	2.160	2.147	2.277	2.179	2.169	2.331
Other fixed costs	1.706	1.704	1.730	1.367	1.364	1.392	1.423	1.420	1.448
Annualized capital cost	8.005	8.005	8.005	6.103	6.103	6.103	6.371	6.371	6.371
Feedstock payment	0.870	0.750	2.213	0.870	0.750	2.213	0.870	0.750	2.213

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.798	0.558	0.822
Co^{2+} in product	0.702	0.359	1.375
Ni^{2+} in product	2.054	2.015	5.634

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.434	0.245	3.335
Co^{2+} in product	0.688	0.352	1.348
Ni^{2+} in product	2.013	1.975	5.521
Mn^{2+} in product	0.026	0.016	0.097
Graphite	0.030	0.030	0.030
Copper metal	0.756	0.529	0.779
Aluminium metal	0.316	0.267	0.413
Steel	0.074	0.074	0.074

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
NMC811	4.702	4.351	15.218
Graphite	0.030	0.030	0.030
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Steel	0.074	0.074	0.074

Feedstock input: 1 000 tonnes/year
Chemistry: NMC811
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.639	1.434	3.910	1.959	1.755	4.230	1.776	1.572	4.047
Utilities	0.072	0.072	0.072	0.153	0.153	0.153	0.395	0.395	0.395
Other variable costs	0.070	0.066	0.114	0.085	0.081	0.129	0.062	0.058	0.107
Labour	1.498	1.498	1.498	2.995	2.995	2.995	2.995	2.995	2.995
Maintenance	1.305	1.305	1.305	0.995	0.995	0.995	1.039	1.039	1.039
Plant overhead	1.182	1.171	1.277	2.199	2.180	2.391	2.229	2.214	2.477
Other fixed costs	1.717	1.713	1.756	1.381	1.377	1.422	1.438	1.434	1.480
Annualized capital cost	8.005	8.005	8.005	6.103	6.103	6.103	6.376	6.376	6.376
Feedstock payment	1.429	1.231	3.634	1.429	1.231	3.634	1.429	1.231	3.634

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.864	0.604	0.890
Co^{2+} in product	1.153	0.590	2.258
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Ni^{2+} in product	3.306	3.242	9.065
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Graphite	0.050	0.050	0.050
Copper metal	0.818	0.573	0.843
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Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
NMC811	7.720	7.144	24.987
Graphite	0.050	0.050	0.050
Copper metal	0.818	0.573	0.843
Aluminium metal	0.134	0.114	0.176

Feedstock input: 10 000 tonnes/year
Chemistry: LFP
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.049	0.049	0.049	0.060	0.060	0.060	0.136	0.136	0.136
Utilities	0.067	0.067	0.067	0.118	0.118	0.118	0.293	0.293	0.293
Other variable costs	0.069	0.069	0.069	0.048	0.048	0.048	0.028	0.028	0.028
Labour	0.150	0.150	0.150	0.300	0.300	0.300	0.300	0.300	0.300
Maintenance	0.225	0.225	0.225	0.142	0.142	0.142	0.169	0.169	0.169
Plant overhead	0.130	0.127	0.130	0.230	0.226	0.252	0.244	0.240	0.290
Other fixed costs	0.290	0.290	0.290	0.192	0.191	0.192	0.230	0.230	0.231
Annualized capital cost	1.378	1.378	1.378	0.868	0.868	0.868	1.034	1.034	1.034
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.914	0.639	0.942

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.306	0.173	2.346
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
LFP	1.234	1.140	5.681
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Feedstock input: 10 000 tonnes/year
Chemistry: LFP
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.060	0.060	0.060	0.088	0.088	0.088	0.204	0.204	0.204
Utilities	0.072	0.072	0.072	0.144	0.144	0.144	0.412	0.412	0.412
Other variable costs	0.059	0.059	0.059	0.064	0.064	0.064	0.032	0.032	0.032
Labour	0.150	0.150	0.150	0.300	0.300	0.300	0.300	0.300	0.300
Maintenance	0.229	0.229	0.229	0.151	0.151	0.151	0.171	0.171	0.171
Plant overhead	0.132	0.129	0.132	0.233	0.227	0.265	0.252	0.247	0.322
Other fixed costs	0.296	0.295	0.296	0.205	0.205	0.205	0.237	0.237	0.238
Annualized capital cost	1.402	1.402	1.402	0.927	0.927	0.927	1.051	1.051	1.051
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	1.067	0.747	1.100

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.468	0.264	3.590
Graphite	0.039	0.039	0.039
Copper metal	1.011	0.707	1.042
Aluminium metal	0.155	0.131	0.203

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
LFP	1.889	1.745	8.694
Graphite	0.039	0.039	0.039
Copper metal	1.011	0.707	1.042
Aluminium metal	0.155	0.131	0.203

Feedstock input: 1 000 tonnes/year
Chemistry: LFP
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.049	0.049	0.049	0.060	0.060	0.060	0.136	0.136	0.136
Utilities	0.067	0.067	0.067	0.118	0.118	0.118	0.293	0.293	0.293
Other variable costs	0.069	0.069	0.069	0.048	0.048	0.048	0.028	0.028	0.028
Labour	1.498	1.498	1.498	2.995	2.995	2.995	2.995	2.995	2.995
Maintenance	1.215	1.215	1.215	0.995	0.995	0.995	1.038	1.038	1.038
Plant overhead	1.113	1.110	1.113	2.100	2.096	2.122	2.116	2.112	2.162
Other fixed costs	1.577	1.577	1.577	1.347	1.347	1.347	1.406	1.406	1.407
Annualized capital cost	7.455	7.455	7.455	6.103	6.103	6.103	6.371	6.371	6.371
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.914	0.639	0.942

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.306	0.173	2.348
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
LFP	1.234	1.140	5.681
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Feedstock input: 1 000 tonnes/year
Chemistry: LFP
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.060	0.060	0.060	0.088	0.088	0.088	0.204	0.204	0.204
Utilities	0.072	0.072	0.072	0.144	0.144	0.144	0.412	0.412	0.412
Other variable costs	0.059	0.059	0.059	0.064	0.064	0.064	0.032	0.032	0.032
Labour	1.498	1.498	1.498	2.995	2.995	2.995	2.995	2.995	2.995
Maintenance	1.215	1.215	1.215	0.995	0.995	0.995	1.039	1.039	1.039
Plant overhead	1.115	1.111	1.115	2.102	2.097	2.134	2.124	2.119	2.193
Other fixed costs	1.577	1.577	1.577	1.348	1.348	1.349	1.410	1.410	1.412
Annualized capital cost	7.455	7.455	7.455	6.103	6.103	6.103	6.375	6.375	6.375
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	1.067	0.747	1.100

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.468	0.264	3.593
Graphite	0.039	0.039	0.039
Copper metal	1.011	0.707	1.042
Aluminium metal	0.155	0.131	0.203

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
LFP	1.889	1.745	8.694
Graphite	0.039	0.039	0.039
Copper metal	1.011	0.707	1.042
Aluminium metal	0.155	0.131	0.203

Appendix 2. Detailed cost & revenue breakdown for France

Feedstock input: 10 000 tonnes/year
Chemistry: NMC811
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.010	0.885	2.393	1.196	1.071	2.579	1.084	0.960	2.467
Utilities	0.078	0.078	0.078	0.142	0.142	0.142	0.298	0.298	0.298
Other variable costs	0.081	0.078	0.108	0.062	0.059	0.088	0.047	0.045	0.074
Labour	0.346	0.346	0.346	0.691	0.691	0.691	0.691	0.691	0.691
Maintenance	0.299	0.299	0.299	0.177	0.177	0.177	0.150	0.150	0.150
Plant overhead	0.304	0.296	0.361	0.554	0.541	0.672	0.567	0.557	0.719
Other fixed costs	0.407	0.405	0.431	0.268	0.266	0.293	0.235	0.233	0.261
Annualized capital cost	1.837	1.837	1.837	1.085	1.085	1.085	0.919	0.919	0.919
Feedstock payment	0.870	0.750	2.213	0.870	0.750	2.213	0.870	0.750	2.213

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.798	0.558	0.822
Co^{2+} in product	0.702	0.359	1.375
Ni^{2+} in product	2.054	2.015	5.634

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.434	0.245	3.335
Co^{2+} in product	0.688	0.352	1.348
Ni^{2+} in product	2.013	1.975	5.521
Mn^{2+} in product	0.026	0.020	0.097
Graphite	0.030	0.030	0.030
Copper metal	0.756	0.529	0.779
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Steel	0.074	0.074	0.074

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Steel	0.074	0.074	0.074

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Chemistry: NMC811
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.639	1.434	3.910	1.959	1.755	4.230	1.776	1.572	4.047
Utilities	0.083	0.083	0.083	0.181	0.181	0.181	0.439	0.439	0.439
Other variable costs	0.072	0.068	0.116	0.087	0.083	0.131	0.064	0.060	0.108
Labour	0.346	0.346	0.346	0.691	0.691	0.691	0.691	0.691	0.691
Maintenance	0.306	0.306	0.306	0.192	0.192	0.192	0.213	0.213	0.213
Plant overhead	0.329	0.318	0.424	0.595	0.576	0.787	0.623	0.608	0.871
Other fixed costs	0.426	0.422	0.465	0.301	0.298	0.342	0.329	0.326	0.371
Annualized capital cost	1.876	1.876	1.876	1.178	1.178	1.178	1.305	1.305	1.305
Feedstock payment	1.429	1.231	3.634	1.429	1.231	3.634	1.429	1.231	3.634

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.864	0.604	0.890
Co^{2+} in product	1.153	0.590	2.258
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Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.010	0.885	2.393	1.196	1.071	2.579	1.084	0.960	2.467
Utilities	0.078	0.078	0.078	0.142	0.142	0.142	0.298	0.298	0.298
Other variable costs	0.081	0.078	0.108	0.062	0.059	0.088	0.047	0.045	0.074
Labour	3.456	3.456	3.456	6.912	6.912	6.912	6.912	6.912	6.912
Maintenance	1.631	1.631	1.631	1.243	1.243	1.243	1.298	1.298	1.298
Plant overhead	2.491	2.484	2.549	4.793	4.781	4.911	4.814	4.803	4.966
Other fixed costs	2.177	2.174	2.200	1.800	1.798	1.825	1.870	1.867	1.895
Annualized capital cost	10.006	10.006	10.006	7.629	7.629	7.629	7.964	7.964	7.964
Feedstock payment	0.870	0.750	2.213	0.870	0.750	2.213	0.870	0.750	2.213

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.798	0.558	0.822
Co^{2+} in product	0.702	0.359	1.375
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Mn^{2+} in product	0.026	0.020	0.097
Graphite	0.030	0.030	0.030
Copper metal	0.756	0.529	0.779
Aluminium metal	0.316	0.267	0.413
Steel	0.074	0.074	0.074

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
NMC811	4.702	4.351	15.218
Graphite	0.030	0.030	0.030
Copper metal	0.756	0.529	0.779
Aluminium metal	0.316	0.267	0.413
Steel	0.074	0.074	0.074

Feedstock input: 1 000 tonnes/year
Chemistry: NMC811
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	1.639	1.434	3.910	1.959	1.755	4.230	1.776	1.572	4.047
Utilities	0.083	0.083	0.083	0.181	0.181	0.181	0.439	0.439	0.439
Other variable costs	0.072	0.068	0.116	0.087	0.083	0.131	0.064	0.060	0.108
Labour	3.456	3.456	3.456	6.912	6.912	6.912	6.912	6.912	6.912
Maintenance	1.631	1.631	1.631	1.243	1.243	1.243	1.299	1.299	1.299
Plant overhead	2.516	2.505	2.611	4.833	4.814	5.025	4.864	4.849	5.112
Other fixed costs	2.187	2.183	2.226	1.814	1.811	1.855	1.886	1.882	1.928
Annualized capital cost	10.006	10.006	10.006	7.629	7.629	7.629	7.970	7.970	7.970
Feedstock payment	1.429	1.231	3.634	1.429	1.231	3.634	1.429	1.231	3.634

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.864	0.604	0.890
Co^{2+} in product	1.153	0.590	2.258
Ni^{2+} in product	3.373	3.308	9.250

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.713	0.402	5.475
Co^{2+} in product	1.130	0.578	2.213
Ni^{2+} in product	3.306	3.242	9.065
Mn^{2+} in product	0.043	0.033	0.159
Graphite	0.050	0.050	0.050
Copper metal	0.818	0.573	0.843
Aluminium metal	0.134	0.114	0.176

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
NMC811	7.720	7.144	24.987
Graphite	0.050	0.050	0.050
Copper metal	0.818	0.573	0.843
Aluminium metal	0.134	0.114	0.176

Feedstock input: 10 000 tonnes/year
Chemistry: LFP
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.049	0.049	0.049	0.060	0.060	0.060	0.136	0.136	0.136
Utilities	0.077	0.077	0.077	0.139	0.139	0.139	0.327	0.327	0.327
Other variable costs	0.074	0.074	0.074	0.051	0.051	0.051	0.029	0.029	0.029
Labour	0.346	0.346	0.346	0.691	0.691	0.691	0.691	0.691	0.691
Maintenance	0.281	0.281	0.281	0.177	0.177	0.177	0.211	0.211	0.211
Plant overhead	0.266	0.263	0.266	0.495	0.490	0.516	0.509	0.505	0.555
Other fixed costs	0.367	0.367	0.367	0.248	0.248	0.249	0.295	0.295	0.296
Annualized capital cost	1.722	1.722	1.722	1.085	1.085	1.085	1.292	1.292	1.292
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.914	0.639	0.942

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.306	0.173	2.348
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
LFP	1.234	1.140	5.681
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Feedstock input: 10 000 tonnes/year
Chemistry: LFP
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.060	0.060	0.060	0.088	0.088	0.088	0.204	0.204	0.204
Utilities	0.083	0.083	0.083	0.170	0.170	0.170	0.458	0.458	0.458
Other variable costs	0.062	0.062	0.062	0.067	0.067	0.067	0.034	0.034	0.034
Labour	0.346	0.346	0.346	0.691	0.691	0.691	0.691	0.691	0.691
Maintenance	0.286	0.286	0.286	0.189	0.189	0.189	0.214	0.214	0.214
Plant overhead	0.268	0.264	0.268	0.497	0.492	0.530	0.518	0.513	0.587
Other fixed costs	0.374	0.374	0.374	0.265	0.265	0.265	0.303	0.303	0.305
Annualized capital cost	1.753	1.753	1.753	1.159	1.159	1.159	1.314	1.314	1.314
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	1.067	0.747	1.100

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.468	0.264	3.593
Graphite	0.039	0.039	0.039
Copper metal	1.011	0.707	1.042
Aluminium metal	0.155	0.131	0.203

Revenue [USD/kg feedstock]	Direct	Direct 5Y MIN	Direct 5Y MAX
LFP	1.889	1.745	8.694
Graphite	0.039	0.039	0.039
Copper metal	1.011	0.707	1.042
Aluminium metal	0.155	0.131	0.203

Feedstock input: 1 000 tonnes/year
Chemistry: LFP
Level: Pack

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.049	0.049	0.049	0.060	0.060	0.060	0.136	0.136	0.136
Utilities	0.077	0.077	0.077	0.139	0.139	0.139	0.327	0.327	0.327
Other variable costs	0.074	0.074	0.074	0.051	0.051	0.051	0.029	0.029	0.029
Labour	3.456	3.456	3.456	6.912	6.912	6.912	6.912	6.912	6.912
Maintenance	1.519	1.519	1.519	1.243	1.243	1.243	1.298	1.298	1.298
Plant overhead	2.445	2.442	2.445	4.734	4.730	4.756	4.751	4.747	4.797
Other fixed costs	2.020	2.020	2.020	1.780	1.780	1.781	1.853	1.853	1.854
Annualized capital cost	9.319	9.319	9.319	7.629	7.629	7.629	7.964	7.964	7.964
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	0.914	0.639	0.942

Revenue [USD/kg feedstock]	Hydro	Hydro 5Y MIN	Hydro 5Y MAX
Li_2CO_3 (crude)	0.306	0.173	2.348
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
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Steel	0.067	0.067	0.067

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LFP	1.234	1.140	5.681
Graphite	0.025	0.025	0.025
Copper metal	0.866	0.606	0.892
Aluminium metal	0.317	0.268	0.415
Steel	0.067	0.067	0.067

Feedstock input: 1 000 tonnes/year
Chemistry: LFP
Level: Cell

Cost [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX	Hydro	Hydro 5Y MIN	Hydro 5Y MAX	Direct	Direct 5Y MIN	Direct 5Y MAX
Materials	0.060	0.060	0.060	0.088	0.088	0.088	0.204	0.204	0.204
Utilities	0.083	0.083	0.083	0.170	0.170	0.170	0.458	0.458	0.458
Other variable costs	0.062	0.062	0.062	0.067	0.067	0.067	0.034	0.034	0.034
Labour	3.456	3.456	3.456	6.912	6.912	6.912	6.912	6.912	6.912
Maintenance	1.519	1.519	1.519	1.243	1.243	1.243	1.299	1.299	1.299
Plant overhead	2.447	2.443	2.447	4.736	4.730	4.768	4.759	4.754	4.828
Other fixed costs	2.020	2.020	2.020	1.782	1.782	1.782	1.858	1.858	1.859
Annualized capital cost	9.319	9.319	9.319	7.629	7.629	7.629	7.969	7.969	7.969
Feedstock payment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Revenue [USD/kg feedstock]	Pyro	Pyro 5Y MIN	Pyro 5Y MAX
Copper metal	1.067	0.747	1.100

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