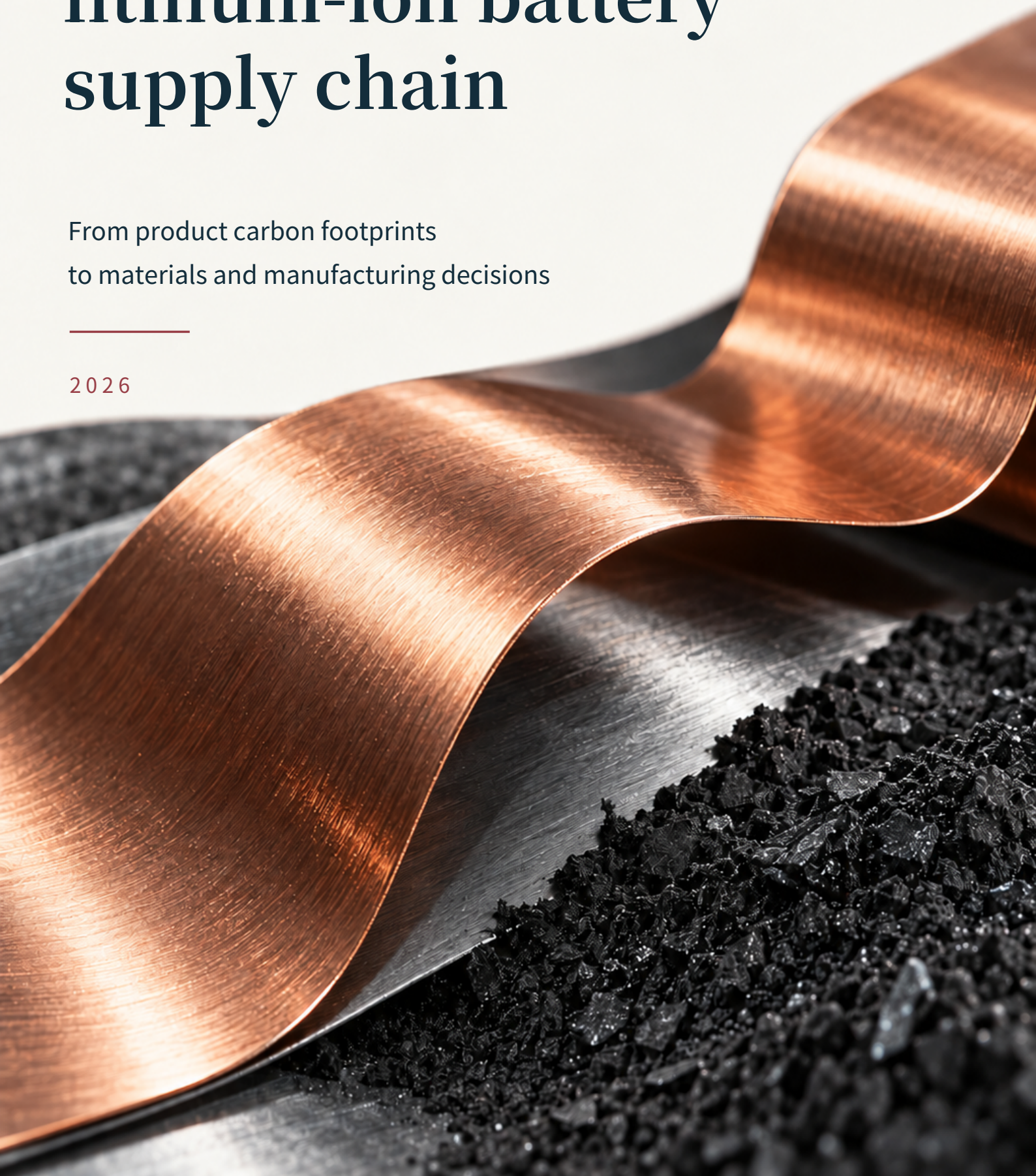


Decarbonizing the lithium-ion battery supply chain

From product carbon footprints
to materials and manufacturing decisions

2026



Decarbonization starts with what can be changed

Chemistry, supply routes and factory conditions shape where reductions are possible. A product footprint becomes useful when it is traced to variables a business can choose or control.

01 Material sourcing shapes procurement opportunities

For products dominated by material emissions, trace mineral processing and active-material routes. Compare specific products, locations and production conditions, rather than ranking suppliers on headline numbers alone.

02 Factory efficiency needs qualified output as context

Analyze process energy, utilities, operating load and yield together. Lower total energy use does not always mean better unit performance: production volume and product mix also affect the result.

03 Circular benefits depend on actual displacement

The next use of recovered material, the virgin input it displaces and the added treatment burden determine the net benefit. Recovered tonnage alone does not establish carbon value.

Connect accounting to procurement, production and material recovery to make better choices.

Sources: IEA, 2024; Machala et al, 2025

Connect the carbon question to the action

From product boundaries to materials, manufacturing and circularity, then back to feasible choices.

01	Where differences create opportunities	02
02	Bring material differences into procurement	06
03	Connect energy use to qualified output	10
04	Make circular materials displace virgin inputs	15
05	Turn opportunities into a workable portfolio	19
06	Start with one product and keep improving	22
07	Methods and sources	26
	References	28

Turn one footprint into three decisions

The business value of a product footprint lies in explaining how different choices change the same product.

One product, three sets of choices

Procurement

Source • Route • Substitution

Build a set of eligible material options

Procurement compares materials that meet performance and supply requirements. Production identifies where energy use and losses occur. R&D assesses whether changes to formulation, design or processing affect life and quality. These questions can share data, but a total footprint cannot answer them all.

Production

Energy • Load • Yield

Identify measurable process improvements

Start with a product that has a clear business need. Connect its bill of materials, production line and supply routes so that analysis leads to specific sourcing options, measurement tasks and trials.

R&D

Formulation • Design • Service

Test connected effects across the product

Define the choice to be changed before defining the data to collect.

The boundary determines whether a comparison holds

A cell, a battery pack and a lifetime of service involve different inputs and deliver different functions.

Choose the boundary to match the decision



Materials and manufacturing → factory gate; changes to performance and life → equivalent service.

Material and manufacturing improvements can first be compared from raw-material extraction to qualified cells at the factory gate. If an option also changes pack design, use-phase efficiency or service life, include those changes in the relevant modules.

Rated capacity, usable capacity and lifetime energy delivered are different denominators. Procurement options for the same specification can be compared at the factory gate. Products delivering the same service require performance, operating conditions and replacement needs to be assessed together. Set the boundary and functional unit before ranking options.

Begin the comparison with equivalent delivery requirements.

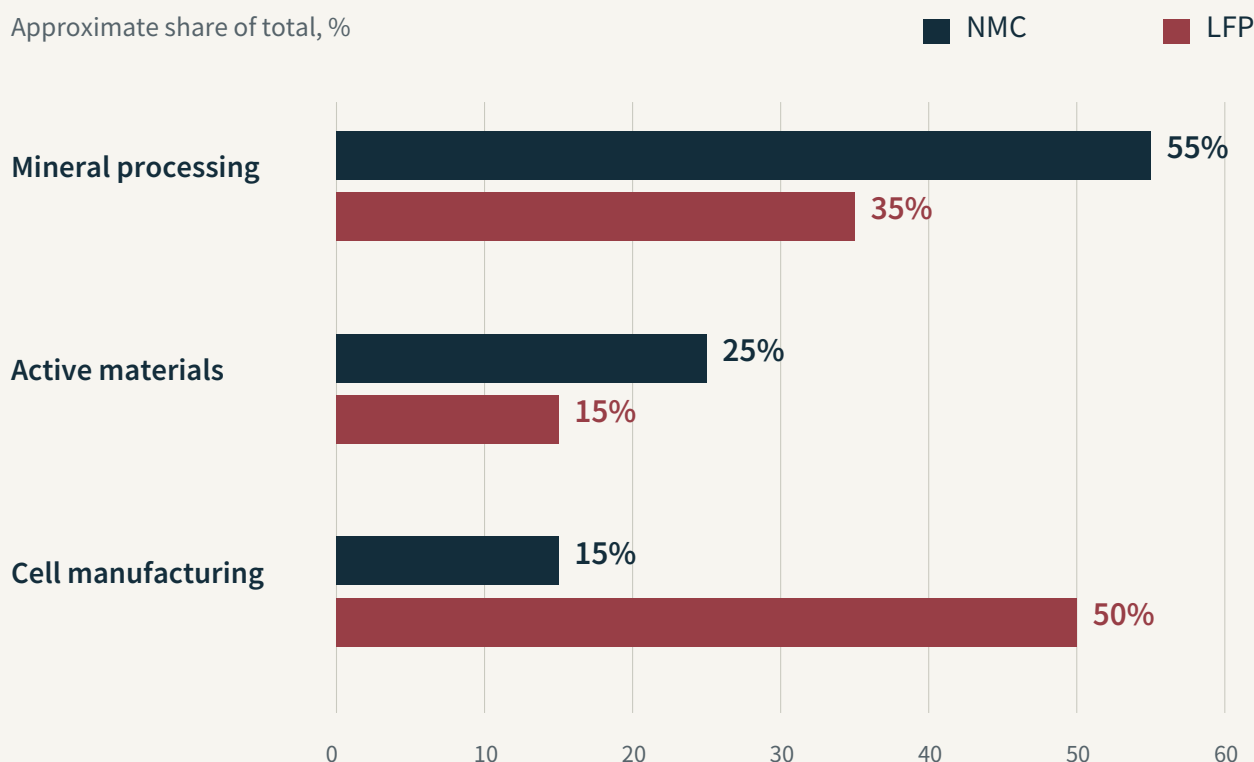
Sources: WRI / WBCSD, 2011

Battery chemistry changes where to look first

NMC emissions are more concentrated in upstream materials; manufacturing contributes a larger share for LFP. Priorities depend on the process and energy conditions of each system.

Contributions to battery production emissions

Approximate share of total, %



Sources: IEA, 2024 . Shares are approximate. A further 5% for NMC is not shown.

Procurement: compare equivalent materials

Assess mineral sources, refining routes and supplier energy conditions. Establish a set of options with equivalent performance and supply conditions before estimating substitution benefits.

Manufacturing: connect energy to output

Analyze process energy, utility loads and yield together. Use qualified output to interpret energy intensity, then assess efficiency improvements and lower-carbon electricity in combination.

Make supplier differences comparable

Equivalent performance and reliable supply are prerequisites. Carbon data should explain the differences between eligible materials and whether those differences can benefit the product.

Dimension	Difference to explain	Evidence for the decision
Material and route	Mineral sources, refining and precursor processes	Process data for the specific product and location
Energy and time	Electricity, heat and production period	Energy quantities, factors and applicable year
Accounting basis	Boundary, allocation and background data version	Methods and reproducible inputs
Substitution conditions	Performance, qualification, supply and losses	Eligible materials and achievable replacement share

Explain the source of a difference before calculating an achievable benefit.

Compare options that can enter the product

Use quality, supply and qualification conditions to define the candidate set.

Keep carbon evidence current

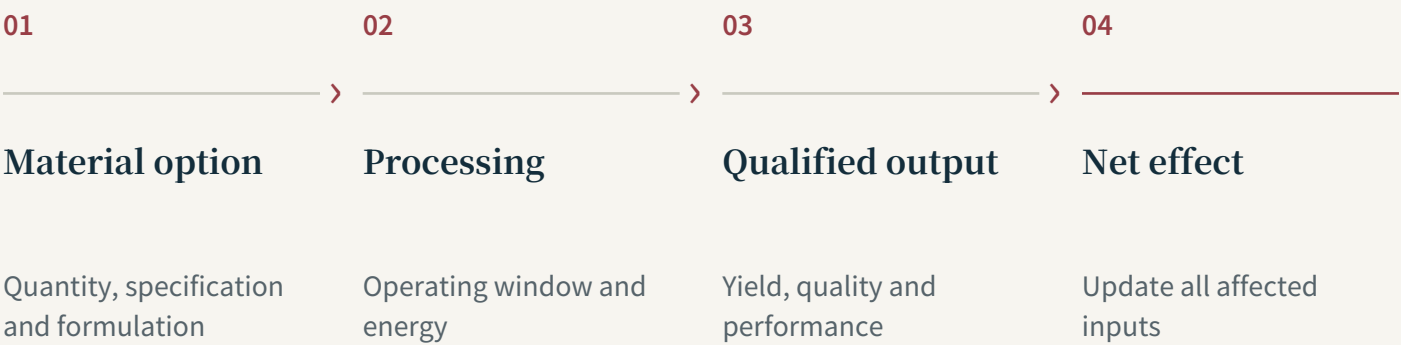
Update evidence when feedstocks, energy or processes change.

Sources: WRI / WBCSD, 2011

Look beyond the cathode to connected effects

The benefits of material reduction or substitution need to be tested across the complete cell.

Trace a material change to the qualified product



Record materials, energy and quality in the same trial so that connected changes enter the model.

Include copper and aluminum foils, graphite, electrolyte, separators and auxiliary materials alongside the cathode. Preserve the relationship between purchased quantities, process inputs, qualified output and scrap destinations to identify losses and omissions.

Thinner foil or a different formulation may change the processing window, yield and in-use performance. Update the affected manufacturing parameters when assessing an option. Counting only the reduction in one material can miss extra energy or losses; cross-functional trials establish whether those effects change the net benefit.

Test a local material improvement against the complete product.

Local process data makes differences traceable

Background data describes upstream processes. Company records establish the actual route taken by a product.

Process-level detail connects supply routes

75

Raw-material acquisition and pretreatment

52

Principal product production

87

End-of-life treatment and recycling

214 processes / 3,197 flows / 53 sources

The China-specific lithium-ion battery dataset compiles 214 processes and 3,197 flows from 53 sources. The associated paper groups the processes into raw-material acquisition and pretreatment, principal product production, and end-of-life treatment and recycling: 75, 52 and 87 processes respectively.

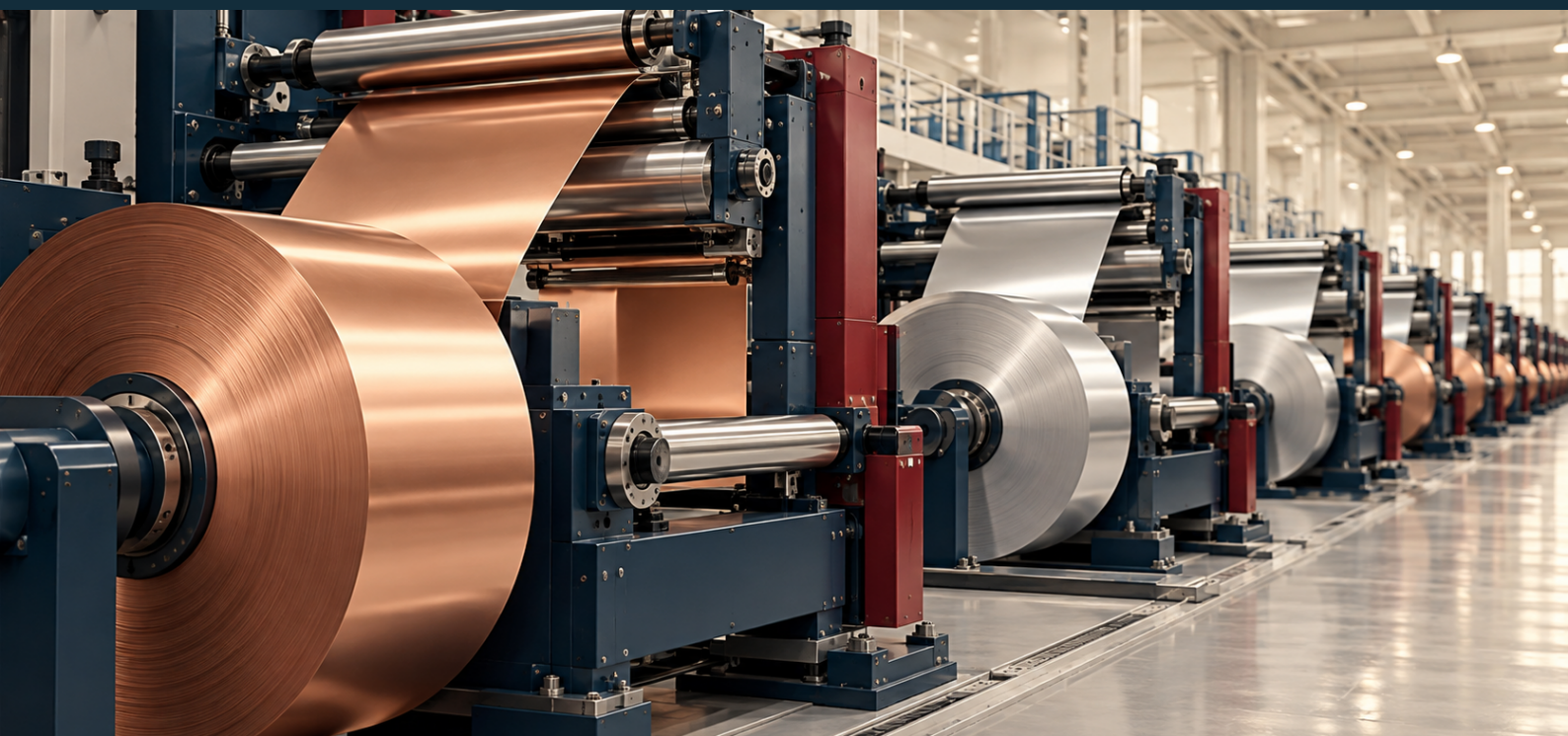
Bills of materials, supply sources and energy measurements should describe actual foreground processes. Match background processes by geography, technology, year and boundary. Existing data provides a traceable starting point for gaps; it does not remove the need for matching or for replacing critical assumptions with measurements.

Start with traceable background data; strengthen the model with critical measurements.

Sources: Tian et al, 2024; Xie et al, 2024; Gao et al., 2025

Manufacturing reductions start with every unit of energy

The same energy bill can reflect different volumes, product mixes and operating stages. Connect consumption to qualified output to identify improvements that can last.



01

Process energy

Meter coating, drying, formation and other operations to locate the actual hotspots.

02

Shared utilities

Connect dry-environment and auxiliary-system loads to the relevant lines and periods.

03

Qualified output

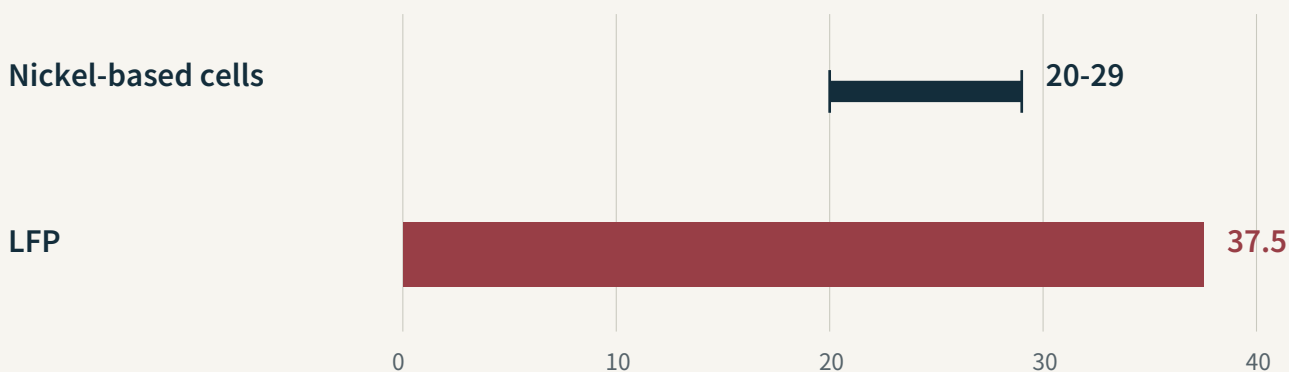
Record volume, yield and product mix alongside energy use to explain changes in intensity.

Sources: Degen et al, 2023; Knehr et al, 2024

Research gives scale. Metering guides investment.

Differences between manufacturing energy models need to be interpreted alongside process and operating conditions.

Modeled cell-manufacturing energy



kWh production energy / kWh cell capacity; excludes material extraction and refining.

In the manufacturing model by Degen et al., nickel-based cells require approximately 20-29 kWh of production energy per kWh of cell capacity, compared with 37.5 for LFP. The figures exclude material extraction and refining. They describe a particular model, not a universal factory target or a ranking of total battery footprints.

On site, separate electricity and heat, and identify coating and drying, formation, dry environments and auxiliary loads. Where submetering is absent, start with measurements that explain the main variations rather than expanding reporting fields indiscriminately.

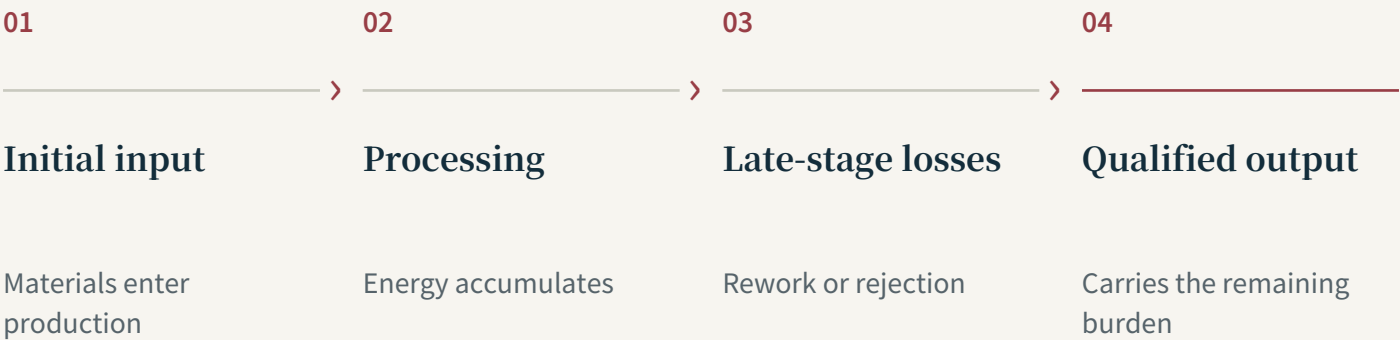
Measure where the data can explain a difference and support an action.

Sources: Degen et al, 2023; Knehr et al, 2024

Yield changes both material and energy burdens

Where a loss occurs determines how much burden qualified output must carry.

The loss point determines the burden already incurred



Track inputs, rework and rejects at critical stages, including scrap destinations.

The same quantity of scrap can have different implications before processing and after most manufacturing steps are complete. Record inputs, transfers, rework and rejects at critical stages rather than using a factory-wide yield to explain every loss.

Include avoided losses, rework energy and scrap treatment in the assessment. If higher yield requires longer processing or extra treatment, recalculate the net change per unit of qualified output. An improvement in one percentage alone does not establish the environmental benefit.

Locate the loss before calculating the net benefit of an improvement.

Separate base loads from production effects

Observe output, operating time and energy together. A single energy-intensity figure can conceal different operating causes.

Three quantities explain energy intensity

01

Base energy

Environment and auxiliary systems

02

Process energy

Inputs that vary with production

03

Qualified output

Same period and product mix

Energy intensity = (base energy + process energy) / qualified output

Separate energy needed to maintain the environment and auxiliary systems from energy that varies with processing, then relate both to qualified output. Neither category is perfectly fixed or linear in practice: the distinction helps identify relationships that need measurement and testing.

If qualified output grows faster than base energy demand, the burden per unit can fall without an improvement in equipment efficiency. Align product mix, operating hours, environmental requirements and yield to distinguish volume effects from process changes.

Explain the roles of efficiency, output and quality in any fall in energy intensity.

Sources: Degen et al, 2023; Knehr et al, 2024

Efficiency and cleaner power act on the same burden

Record energy quantities and emission factors separately, then recalculate the combined result from the underlying inputs.

Recalculate the combination from its inputs

$$Q_0 \times f_0$$

Baseline electricity emissions

$$Q_1 \times f_1$$

Electricity emissions after changes

Q: electricity quantity; f: applicable factor. Net reduction = $Q_0 f_0 - Q_1 f_1$.

Reducing electricity use and lowering its applicable emission factor both affect electricity-related emissions. Adding benefits calculated separately against the original baseline double-counts part of the reduction. Multiply the updated quantity by the updated factor to obtain the combined burden.

Keep physical supply, contractual evidence, applicable periods and accounting rules connected. Corporate purchased-electricity reporting and product footprints can follow different requirements. Buying an electricity instrument does not automatically determine its treatment in every product declaration.

Update the quantity and the factor, then calculate the combined result once.

Sources: GHG Protocol, 2015

Circular value is realized in the next material choice

Recovery becomes connected to product decarbonization when output from a recycler becomes usable input for a manufacturer.



01

Identify feedstock

Distinguish production scrap from end-of-life batteries, including composition and collection conditions.

02

Confirm quality

Match recovered output specifications to the requirements of the next production process.

03

Verify displacement

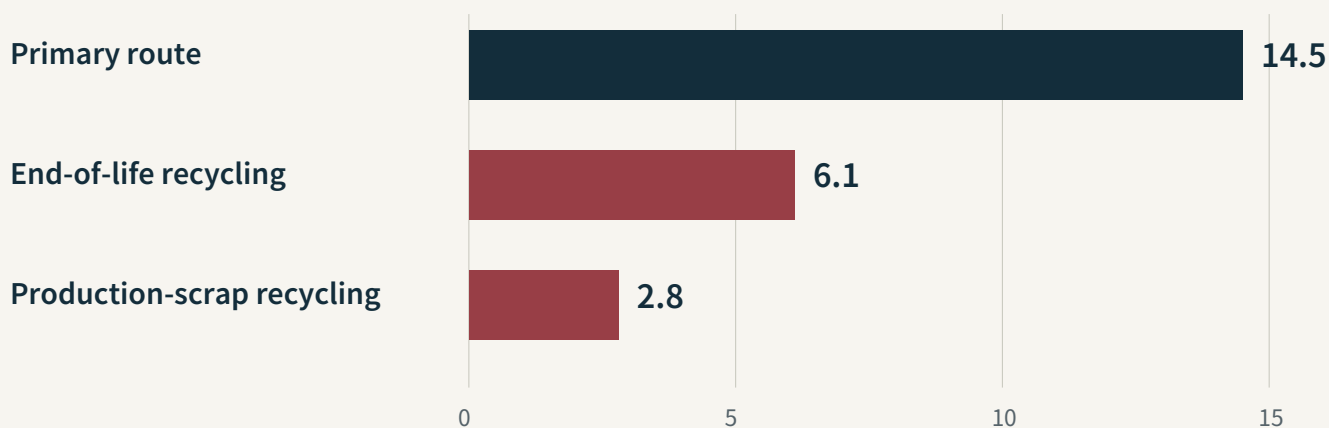
Calculate net change using the actual next use and feasible substitution share.

Sources: Machala et al, 2025; WRI / WBCSD, 2011

Recycling benefits depend on the route and its outputs

Environmental performance needs to be traced to feedstock, products and energy conditions.

Gate-to-gate refining GHG emissions



kg CO2e / kg NCA-equivalent; mainly 2021 data, with different output forms.

Machala et al. compare industrial recycling and primary-material supply chains. Their gate-to-gate refining results are 14.5, 6.1 and 2.8 kg CO2e per kg NCA-equivalent for the primary route, end-of-life battery recycling and production-scrap recycling respectively. Data is mainly from 2021. Outputs are equivalent in elemental content, but differ in product form.

The findings support separate assessment of feedstock and processing conditions. Production scrap and end-of-life batteries are not interchangeable inputs. Match collection, pretreatment and refining steps to the proposed route, then assess whether its actual conditions support a comparable direction of benefit.

Research identifies a possibility; matching the route determines whether it transfers.

Sources: Machala et al, 2025

Beyond recovery rates: what is displaced?

Recovered material enters a substitution analysis only to the extent that it changes subsequent production inputs.

Compare added burdens and actual displacement

Added burdens

Collection • Transport • Treatment

Conditions for producing and using recovered output

For substitution analysis: net change = added minus avoided burdens; specify allocation separately.

Define the quality, destination and feasible substitution share of each recovered material. Battery-grade use and other applications imply different comparison objects. Recovered output is not automatically equal to avoided virgin input.

Avoided burdens

The virgin route actually displaced

Match quality, application and substitution share

Net effects depend on added collection, treatment and transport, together with the burden of the route actually displaced. Align boundaries, time periods and product functions. For multiple recovered products, explain allocation so that the same benefit is not claimed repeatedly by different parties.

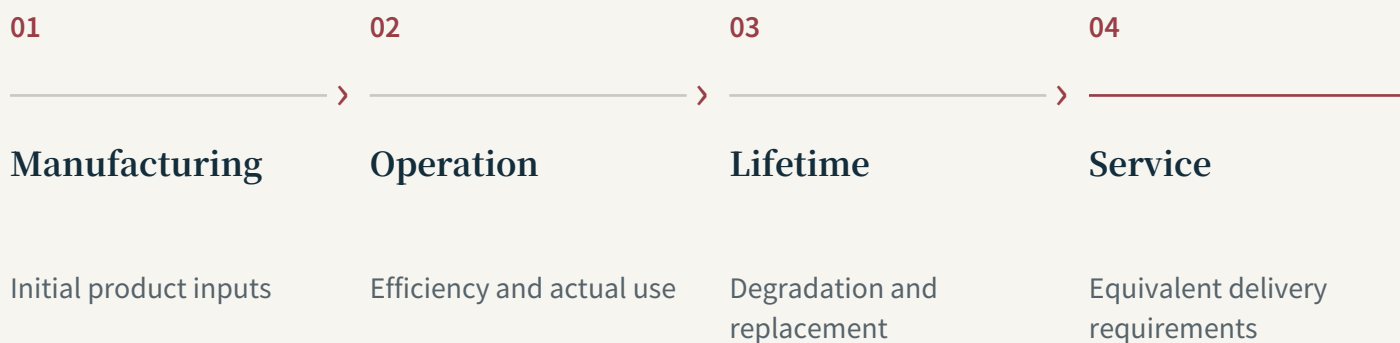
Compare a circular option with the production route it actually changes.

Sources: WRI / WBCSD, 2011

From cells to service, lifetime changes the comparison

A lower manufacturing footprint does not necessarily mean a lower impact for equivalent service.

Extend the comparison from product to service



The functional unit should reflect the decision, not merely the most convenient denominator.

When a material or product option affects lifetime, efficiency or replacement frequency, extend the comparison to the same service. Stationary storage requires actual cycling, degradation and operating conditions; traction batteries need to match the vehicle service being considered.

Manufacturing and use can share basic data while retaining distinct boundaries and assumptions. Avoid applying a single per-kWh ranking across applications. The useful result states the uses and operating conditions under which an advantage persists.

Carry the manufacturing advantage through equivalent service to complete the comparison.

Sources: WRI / WBCSD, 2011

Map the connections before combining the benefits

Materials, processes and energy choices can change the same underlying activity.

Map measures to shared process variables

Material substitution	Yield improvement	Operating changes
Supply factor ↔ Processing conditions	Material input ↔ Energy per unit	Utilization ↔ Base-load allocation

Use one updated set of inputs for the combined option; count each physical change once.

Lower-carbon materials may alter processing conditions. Higher yield may reduce material demand. Changes in line operation may affect energy allocated per unit. Update connected parameters rather than changing only the most favorable input for each measure.

Combination analysis reveals reinforcing effects, double counting and added burdens. Record what changed, why it changed and which inputs were held constant so that the model can be matched to a real trial.

Include connected changes to make combined benefits relevant to implementation.

Close the gaps that could change the choice

The sensitivity of a decision should determine the priority of data collection.

Let uncertainty guide the next step

Stable ranking	Stronger evidence	Proceed to feasibility and trial validation
Stable ranking	Evidence gaps	Confirm critical boundaries and applicability
Reversible ranking	Stronger evidence	Make the choice conditional on scenarios
Reversible ranking	Evidence gaps	Measure the inputs that may change the conclusion

Vary supply factors, energy use, yield and substitution shares within plausible ranges and observe whether the ranking changes. A parameter that reverses the conclusion after a small change deserves early verification. Ranges must reflect feasible conditions, not an arbitrary combination of favorable assumptions.

If the ranking remains stable across plausible conditions, proceed to feasibility testing. If it reverses readily, obtain stronger evidence first. This sequence directs data effort toward action rather than assigning equal priority to every gap.

The next piece of data should help resolve the next decision.

Bring carbon, cost and quality into one decision

A lower-carbon option must also meet product and business requirements.

Organize the comparison around decision gates

Product and supply	Performance, quality, qualification, availability	Define feasible options
Net environmental effect	Aligned boundary, interactions, sensitivity	Identify conditional advantages
Business and delivery	Investment, operating cost, timing, ownership	Plan trials and investment

For the same product and production baseline, identify additional investment, energy and material savings, maintenance, qualification and operating changes. Cost and environmental scenarios should share physical inputs while retaining their own price, lifetime and accounting assumptions.

Screen technical feasibility, performance and supply conditions before comparing net reductions and incremental costs. Near-term operating improvements and long-term capital projects need not compete in one ranking. Organize actions by readiness and timescale to connect them to investment and production plans.

Meet product requirements first, then sequence lower-carbon actions by readiness.

Start with one product. Build a repeatable path.

Connect scope, evidence, options and validation so that each step produces something the next can use.

Stage outputs

01 Define one decision

Select the product, factory and application, and the procurement or production choice to be supported.

Scope and decision
objective

02 Build a common baseline

Connect materials, energy, output and sources. Close the gaps most likely to change the conclusion.

Reproducible
baseline and hotspots

03 Compare feasible options

Include performance, supply and cost constraints. Test interactions and sensitive inputs.

Candidate options
and trial conditions

04 Validate and update

Recalculate actual changes consistently, then extend effective practices to product families and supply networks.

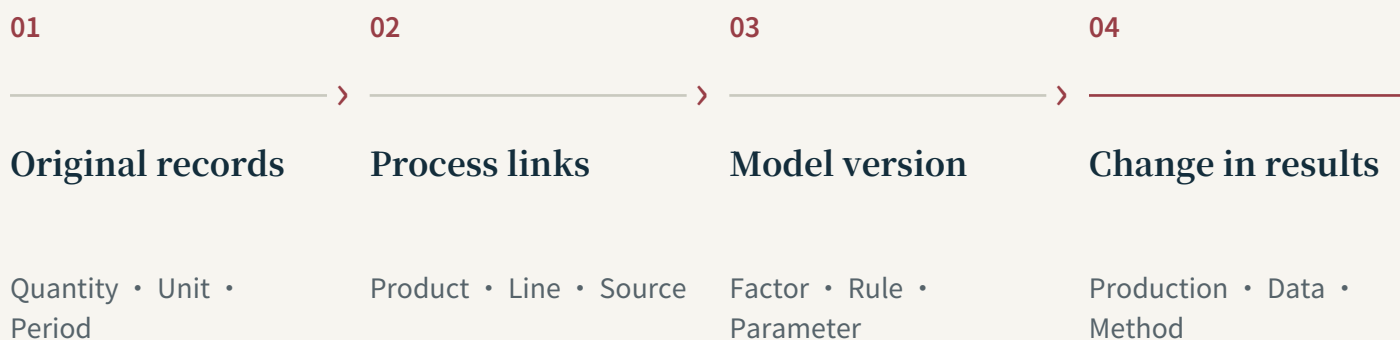
Verified results and
update process

The next product update should build on the data and methods already established.

Make the first analysis useful for the next one

A maintainable data package explains why results change.

From original records to explainable updates



Every update should be traceable to inputs, calculations and reasons for change.

Retain original quantities, units, sources, periods, applicable products and owners. Manage calculation relationships and background factors separately, with results tied to input versions. Updates can then distinguish production improvements, data replacement and methodological changes.

Define update triggers for supply sources, production processes and background factors. After a supplier change, a shift in output mix or a data revision, rerun the model consistently and attribute the difference to specific causes. The same data package can then support the next sourcing decision, product iteration or factory improvement.

Preserve the ability to update the analysis, not only its results.

Build quality checks into the work

Verification starts with inputs and continues through the model to the conclusion.

Place checks at three points

Inputs	Model	Claims
Do material and energy records reconcile? Cross-check purchases, inventories, production and scrap. Use purchasing, inventory, output and waste records to reconcile major material flows, and energy and production records to explain loads. Investigate anomalies before comparing options so that missing data or changing definitions are not mistaken for improvements.	Are relationships and units consistent? Check duplicate processes, allocation, conversions and linked inputs. Model checks cover units, duplicated processes, allocation and parameter relationships. External claims need their boundaries, evidence and intended use checked. Confirm the validation requirements for customer communication, comparative claims and regulatory submissions separately.	Does the conclusion fit the intended use? Check boundaries, sources, applicability and validation needs.

Make each conclusion traceable to the relevant process and evidence.

Sources: WRI / WBCSD, 2011

Bring research and data into the next decision

Material selection, factory improvement and circular routes can each begin with a specific question.

Three concrete starting questions

Materials	Manufacturing	Circularity
What explains supplier differences?	Where does the energy change occur?	What does recovery actually displace?
Connect routes, methods and feasible substitution.	Connect metering, load, yield and qualified output.	Connect recovered quality, actual use and displaced routes.
Start with the product, the current choice and the available data. Are supplier differences difficult to explain? Is manufacturing energy hard to locate? Is the net benefit of a circular route unclear? Define the decision before selecting the processes and evidence to connect.	China-specific unit-process data and product-footprint research provide a published methodological foundation. Connecting that foundation to actual company records can support a baseline, contribution analysis, conditional options and a validation path. Explore the public research and team at Tiangong Discover.	

Build a shared analytical foundation around one clearly defined question.

Sources: Tian et al, 2024; Gao et al., 2025

Keep the comparison on a consistent basis

Use every quantitative result with its boundary, functional unit and data period.

Retain four coordinates for every comparison

Object and function	Same product or equivalent service	Specify denominator and performance
Scope and time	Processes, factory and production period	Explain inclusions and exclusions
Data and method	Technology, geography, allocation, data version	Retain reproducible inputs
Results and interpretation	Totals, contributions, scenarios, limits	Do not rank totals using stage shares

Production comparisons center on qualified cells at the factory gate. Add separate modules for changes to packs, use or end-of-life treatment. For options with different performance or life, establish equivalent service requirements. Match background processes by technology, geography, time and boundary, retaining replacement records.

Cite literature results with their original boundaries and data periods; recalculate company options using actual product and process data. Retain scenario inputs, equations and conditions, distinguishing production changes from data updates. Stage shares describe contribution patterns, not the ranking of total product footprints.

A consistent basis makes changes interpretable.

Sources: WRI / WBCSD, 2011

Reuse the inputs. Check each reporting purpose.

Internal improvement, customer communication and regulatory submissions can share inputs while following their applicable rules.

One data foundation, different requirements

Internal improvement	Actual processes and controllable variables	Support sourcing and production choices
Customer communication	Agreed basis and required evidence	Make results explainable and checkable
Regulatory submission	Product category, timing and applicable rules	Verify methods and validation for each obligation

Battery passport: manage applicability and effective dates field by field.

The start of the EU battery passport and the obligations for different information fields have distinct applicability dates. Check product categories, carbon footprints, recycled content and other fields separately instead of assigning one date to every obligation.

Manage each field through its source, owner, update frequency and access permissions. Once the reporting purpose is defined, verify the applicable calculation method, validation procedure and legal text, and maintain version links to the internal improvement model.

Use a common data foundation while meeting the requirements of each purpose.

Sources: European Commission, 2026; European Commission, 2026-08-21; European Union, 2026-08-13

Research and data

Research figures retain the boundaries and conditions of their original sources.

01 China-specific unit process dataset for lithium-ion batteries

Tian et al, 2024

[doi.org](#)

02 China-specific Lithium-ion Battery Unit Process Dataset, v1

Xie et al, 2024

[data.mendeley.com](#)

03 Localized product carbon footprint accounting in China: The lithium-ion battery industry

Gao et al., 2025

[www.engineering.org.cn](#)

04 Global EV Outlook 2024: Outlook for emissions reductions

IEA, 2024

[www.iea.org](#)

Sources checked: 27 October 2026

Manufacturing and accounting methods

Research figures retain the boundaries and conditions of their original sources.

05 Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells

Degen et al, 2023

www.nature.com

06 Energy consumption of lithium-ion pouch cell manufacturing plants

Knehr et al, 2024

doi.org

07 Life cycle comparison of industrial-scale lithium-ion battery recycling and mining supply chains

Machala et al, 2025

www.nature.com

08 Product Life Cycle Accounting and Reporting Standard: Chapters 6 and 9

WRI / WBCSD, 2011

ghgprotocol.org

Sources checked: 27 October 2026

Market rules and data requirements

Research figures retain the boundaries and conditions of their original sources.

09 Scope 2 Guidance

GHG Protocol, 2015

ghgprotocol.org

10 EU Digital Product Passport FAQ for Batteries

European Commission, 2026

single-market-economy.ec.europa.eu

11 Guidance to support preparations for the Digital Batteries Passport

European Commission, 2026-08-21

single-market-economy.ec.europa.eu

12 Regulation (EU) 2023/1542, consolidated text

European Union, 2026-08-13

eur-lex.europa.eu

Sources checked: 27 October 2026

What evidence does the next decision need?

Bring the research back to a specific product and use testable conditions to choose the next step.

01	Consistent scope	Are the comparison objects, functional unit, factory and time period aligned?
02	Explainable differences	Does the change reflect production conditions, or different data and methods?
03	Feasible substitution	Are performance, supply, qualification and replacement shares achievable?
04	Credible net effect	Are added burdens, parameter interactions and uncertainty included?
05	Repeatable results	Who updates the inputs, when is the model rerun and how are changes verified?

Use evidence at every step to make decarbonization a repeatable product capability.

Give the next decision a clearer foundation.

Start with one product, one production line or one material.
Connect process data to actual conditions and identify
achievable pathways to lower emissions.

Research and team

discover.tiangong.earth

TIANGONGDISCOVER