Australia-Focused Copper Evidence Review

Topic 01 Copper

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Status: Internal draft
Audience: Internal research group
Primary goals: (a) research prioritisation, (b) industry partnership landscape positioning (Australia-first)
Scope note: Digital process control / sensing is out of scope for this report (deferred).

Abstract

This report provides an Australia-first copper evidence review, oriented to future copper use and end-to-end value capture across mining and concentration, smelting/refining (midstream), alloys and semi-fabrication, manufacturing/end use, and circularity. A scoping review was

conducted over a bounded corpus of public baselines, operator disclosures, and peer-reviewed technical literature (Appendix B). Retained quantitative claims used in the narrative are page-anchored and traceable through Appendix A. The evidence supports a two-mission analytical framing: (Mission A) low-carbon, impurity-tolerant processing and refining competitiveness; and (Mission B) circular copper and alloy loops from complex scrap and e-waste with explicit contamination and co-product-aware route design. Data centres are used as a near-term demand-side anchor for partner pull, supported by projected Australian data-centre electricity demand growth (AEMO and Oxford Economics, 2025, 4). The report closes by identifying evidence gaps and baseline work that would strengthen Australia-specific capacity, flow, and cost understanding.

Executive Summary

Purpose and scope (summary)

The purpose of this report is to summarise the most defensible evidence and logic for an Australia-first copper analysis. The framing is end-to-end value capture: what Australia can not only mine, but also **process, refine, specify, and circularly upgrade**. The scope spans the full copper chain and uses **copper plus co-products** as a boundary condition where co-products materially affect route viability and environmental performance (Z. Dong et al., 2020, 1, 5).

Two observations drive the research logic. First, multiple outlooks indicate tightening copper supply-demand conditions under electrification. Second, Australia's value capture is shaped by a small number of domestic midstream nodes and by the difficulty of upgrading complex secondary feeds into specification-compliant products. These observations map naturally to two research missions: midstream competitiveness and circular copper/alloys.

Key facts and findings (with page anchors for quantitative claims)

- **Global demand outlooks are materially higher than current levels.** S&P Global projects copper demand rising from **28 Mt (2025)** to **42 Mt (2040)** (S&P Global, 2026, 9). Wood Mackenzie projects **42.7 Mtpa by 2035** in its base case (Wood Mackenzie, 2025, 3).
- **Australian data-centre electricity demand is projected to rise substantially**, which strengthens the case for strategy framing that emphasises reliable processing capacity, quality, and circular feed availability. AEMO/Oxford estimates **3.9 TWh (FY25)** rising to **12.0 TWh (FY30)** and **34.5 TWh (FY50)** (AEMO and Oxford Economics, 2025, 4).

- **Public Australian baseline signals show copper export value growth**, rising from **A\$12.565b (2024-25)** to **A\$17.648b (2026-27f)** nominal (Department of Industry, Science and Resources, 2025, 60). However, export value alone does not resolve how value is captured across processing and circular flows.
- **Impurity and penalty element management is central to concentrate economics and operability** and influences concentrate value and negotiated terms (D. J. Lane et al., 2016, 2).
- **Secondary-feed upgrading is technically and environmentally route-dependent.** Printed circuit boards (PCBs) can reach copper contents of **20-25%** (F. Yang et al., 2024, 4), but route choice drives tradeoffs in contamination, energy use, and emissions (J. Torrubia et al., 2024, 1, 7–8).
- **"Low-carbon" claims require explicit modelling and measurement.** Wu et al. report an **18% reduction** in global warming potential for their bioleaching pathway compared to pyrometallurgical production (X. Wu et al., 2025, 7), and show strong sensitivity to electricity-transition scenarios (X. Wu et al., 2025, 9).

Research missions (logic, not a topic list)

Mission A: Low-carbon, high-resilience midstream processing and refining. The central logic is that midstream nodes translate ore and secondary feeds into specification-compliant products, and their economics are sensitive to impurities, energy, reliability, and environmental constraints. A university contribution is to make these constraints measurable and predictable (impurity transfer functions, operating windows, abatement curves) using lab evidence and partner data.

Mission B: Circular copper and alloys from complex secondary feeds. The central logic is that circular value capture depends on feed quality and contamination control, plus route design that is co-product-aware and environmentally defensible. A university contribution is to build the enabling evidence base (scrap characterisation, pre-treatment protocols, alloy tolerance thresholds, comparative TEA/LCA and MRV protocols) that reduces integration risk for partners.

Topic Interface (T1-T6)

The thematic structure of this report is fixed to six topic IDs: - `T1`: Demand Pull + Australia Value-Chain Structure - `T2`: Processing Pathways Across Primary/Secondary Feeds and Co-products - `T3`: Science 101 Technology Primer - `T4`: Research and Collaboration Landscape - `T5`: Policy, Funding, and Programs - `T6`: Evidence Quality, Gaps, and Confidence

Boundary controls: - `T3` contains technology fundamentals only (no policy/program framing). - `T6` contains confidence, evidence quality, and gap status only (no new thematic arguments). - `T1` and `T2` are separated as structure/demand versus processing-route mechanics.

1. Introduction

1.1 Australia-first framing

Australia's copper position cannot be reduced to mining tonnage. Copper value is created and retained when material can be processed into consistent, specification-compliant products and when secondary copper can be upgraded without unacceptable contamination or emissions. This report therefore emphasises research themes that influence value capture across the chain, with particular attention to midstream resilience and circular feed upgrading.

1.2 Scope and exclusions

Scope covers: mining and concentration, smelting/refining, alloys/semi-fabrication, manufacturing/end use, and recycling/circularity.

Explicit exclusions for this report: - digital process control / sensing / ore sorting (deferred) - a complete owner/operator census for all Australian mines and downstream manufacturers (treated as baseline work)

1.3 Boundary condition: copper plus co-products

Economic realism requires a boundary of **copper plus co-products** where project viability depends on co-product value and/or environmental constraints (for example, refining residues/anode slime pathways with multi-metal interactions) (Z. Dong et al., 2020, 1, 5).

2. Methods

2.1 Review approach (scoping review)

This report is based on a scoping review over a bounded corpus of: - public baselines (Australia and global) - operator disclosures and public announcements relevant to Australian midstream nodes - peer-reviewed technical literature relevant to impurity management, circular routes, and decarbonisation pathways

The intent is not a full systematic review. It is a strategy-focused synthesis designed to keep core claims traceable while remaining useful for program design and partner engagement.

2.2 Evidence handling and traceability

Retained quantitative claims used in the narrative are page-anchored. Appendix A lists the claim-to-evidence mapping for retained quantitative claims used in the report.

2.3 Limitations

The main limitations are practical and affect interpretation: - Some datasets and market intelligence products are subscription-only (not in this corpus). - Several Australia-specific capacity, flow, and cost views are not harmonised into a single dataset; developing a harmonised baseline is part of the recommended near-term work.

Module Source Map

- Overview module: `subtopics/00_overview.qmd`
- T1 module: `subtopics/01_T1_demand-and-value-chain.qmd`
- T2 module: `subtopics/02_T2_processing-pathways.qmd`
- T3 module: `subtopics/03_T3_science-101.qmd`
- T4 module: `subtopics/04_T4_research-and-collaboration-landscape.qmd`
- T5 module: `subtopics/05_T5_policy-funding-programs.qmd`
- T6 module: `subtopics/06_T6_evidence-quality-gaps-confidence.qmd`
- Central references/appendices module: `subtopics/90_references-and-appendices.qmd`

T1. Demand Pull + Australia Value-Chain Structure

T1.1 Global demand trajectory (what the analysis must be robust to)

Multiple outlooks point to structurally tight copper supply relative to electrification-driven demand. For example, S&P Global projects demand rising from **28 Mt (2025)** to **42 Mt (2040)** (S&P Global, 2026, 9), while Wood Mackenzie projects **42.7 Mtpa by 2035** in its base case (Wood Mackenzie, 2025, 3). These figures are not used to produce a single forecast. They justify why Australia and partners will increasingly care about reliable processing, impurity tolerance and quality, and secondary feed availability.

T1.2 Data centres as a near-term anchor (without narrowing the analysis)

Data centres are used in this report as a high-urgency, partner-facing anchor because they intensify: - grid build and connection assets - high-reliability electrical equipment (transformers, switchgear, busbars, cabling) - short-cycle procurement and large project pipelines

In Australia, data-centre electricity demand is estimated at **3.9 TWh (FY25)** and projected to rise to **12.0 TWh (FY30)** and **34.5 TWh (FY50)** (AEMO and Oxford Economics, 2025, 4). The point is not that data centres are the only demand driver. The point is that "reliability and scale" procurement contexts tend to make issues of copper quality, processing capacity, and supply assurance more salient to partners across multiple sectors.

T1.3 Demand numbers used in this report (traceable)

Metric	Value(s)	Source
Global copper demand (illustrative outlook)	28 Mt (2025) -> 42 Mt (2040)	S&P Global (2026a, p. 9)
Global copper demand (base case)	42.7 Mtpa (2035)	Wood Mackenzie (2025, p. 3)
AU data-centre electricity demand	3.9 TWh (FY25); 12.0 TWh (FY30); 34.5 TWh (FY50)	AEMO and Oxford Economics (2025, p. 4)

T1.4 Australia Copper Value Chain: Baseline and Structural Nodes

T1.4.1 Why the Australia baseline matters

An Australia-focused research strategy becomes much stronger when it can point to a harmonised baseline describing: - where concentrates flow (domestic vs export) - midstream capacities and constraints (smelting/refining) - secondary copper availability and quality (scrap and e-waste) - downstream specifications that drive procurement and acceptance testing

This report provides a first-pass structural-node map and identifies the baseline tables required to quantify the hypotheses in T2.

T1.4.2 Public baseline signal (export value)

A public Australian baseline provides an outlook for copper export value (nominal) rising from **A\$12.565b (2024-25)** to **A\$17.648b (2026-27f)** (Department of Industry, Science and Resources, 2025, 60). This supports urgency, but it does not answer where value is captured (or lost) across processing, refining, and circular upgrading steps.

T1.4.3 Structural nodes (analysis-facing, non-exhaustive)

Node	Why it matters for the research strategy	Evidence
Midstream anchor (QLD): Mount Isa smelter and Townsville copper refinery	Partnership gravity well for impurity tolerance, feed flexibility, low-carbon process energy, and environmental performance	Glencore (2025)

Node	Why it matters for the research strategy	Evidence
Integrated chain (SA): Olympic Dam and SA processing/refining pathway	End-to-end pilot opportunities; signals and pathways for domestic processing/refining capability	BHP (2024)
Circular system (AU-wide): scrap and e-waste flows	Feed quality and contamination determine viable routes and specifications; opportunity for onshore value retention	Yang, Wu and Zhang (2024, p. 4)

T1.4.4 Benchmark architecture targets (EU example)

The EU CRMA provides a governance template by stating explicit capacity benchmarks (for strategic raw materials) including extraction capacity for at least **10%**, processing for at least **40%**, and recycling for at least **25%** of annual consumption (European Union, 2024, 3). These numbers should not be imported directly into Australia's context. Their value in this report is architectural: they highlight that extraction, processing, and recycling are distinct capacity topics that can be governed and resourced separately, which is consistent with the two-mission framing used here.

T2. Processing Pathways Across Primary/Secondary Feeds and Co-products

This section states hypotheses that structure the mission design and clarify what evidence is required to refine the program.

T2.1 Midstream resilience and competitiveness is a high-leverage bottleneck

Hypothesis: A large share of Australia's value-capture leverage sits in midstream competitiveness, defined as the ability to process varied feeds, manage impurities, deliver consistent product quality, and decarbonise without losing reliability.

Logic chain (why this follows from the facts): Midstream is where feed complexity becomes operational reality. Impurities and penalty elements are not abstract; they influence concentrate value, negotiated terms, and operability constraints (D. J. Lane et al., 2016, 2). When domestic midstream nodes are few and strategically important, research that improves predictability (impurity transfer functions, operating windows) and decarbonisation realism (abatement curves under reliability constraints) has high partner pull.

T2.2 Circular copper and alloy loops are a high-leverage capability wedge

Hypothesis: Additional value capture can be created by upgrading complex secondary copper domestically into specification-compliant feed and products, avoiding downcycling.

Logic chain (why this follows from the facts): Secondary feeds can be copper-rich (for example, PCBs reaching **20-25%** copper) (F. Yang et al., 2024, 4), but they are heterogeneous and contamination-sensitive. Route choices therefore dominate outcomes, including decarbonisation tradeoffs (J. Torrubia et al., 2024, 1, 7–8). Even when process routes appear "low carbon", comparative results and scenario studies show strong sensitivity to inventory boundaries and electricity transitions (X. Wu et al., 2025, 7, 9). This implies that circular value capture requires explicit route selection logic, contamination management, and measurement protocols rather than generic "recycling is better" claims.

T2.3 Research missions and work packages

This section describes the research program as two missions with work packages. The emphasis is on explainable logic and on outputs that can be validated in labs and pilots with industry partners.

Mission A: Low-carbon, high-resilience copper processing and refining (midstream)

Mission A targets predictable and competitive processing under tighter constraints (impurities, energy and carbon, quality, and reliability). The work packages are designed so that a university can generate publishable science while producing partner-usable tools (models, protocols, operating windows).

WP-A1. Impurities and penalty elements (prediction, control, and removal)

Penalty elements and impurity suites influence both concentrate value and the operational envelope of downstream processing (D. J. Lane et al., 2016, 2). The objective of WP-A1 is to turn this constraint into a predictive capability: Australia-relevant impurity behavior models and operating windows that can be used for blending, feed acceptance, and pre-treatment decisions.

Scientific 101 pointers: `T3.3` (impurities) and `T3.1` (where impurities end up in midstream routes).

- Core questions: how do As/Sb/Bi/halides and other suites partition into matte/slag/gas/residues and propagate into anode/cathode quality risk under realistic blend families?
- Partner inputs: representative blend compositions; penalty thresholds and quality limits; operational boundary conditions (recycles, dust handling, key constraints).

- Deliverables: impurity transfer functions; documented operating windows; a simple blend-decision prototype and a publishable impurity dataset.
- Validation pathway: bench experiments + partner data reconciliation -> one pilotable measurement protocol for a partner-relevant impurity suite.

WP-A2. Retrofit decarbonisation pathways (unit-operation abatement under constraints)

Decarbonisation options in midstream are often evaluated in general terms. The research need is to quantify plausible retrofit pathways at the unit-operation level and to make explicit the reliability and quality constraints that limit "theoretical" options. WP-A2 reframes decarbonisation as a unit-operation engineering problem with explicit constraints. The objective is to produce retrofit option sets that remain credible under reliability and product-quality requirements, and to quantify where abatement is realistically achievable versus "theoretical".

Scientific 101 pointers: `T3.1` (midstream constraints) and `T3.12` (TEA/LCA/MRV sensitivity and measurement).

- Core questions: which abatement levers are feasible per unit operation, and what constraints (off-gas, materials, downtime) dominate feasibility?
- Partner inputs: unit-operation energy and off-gas baselines; reliability/downtime modes; retrofit windows and "do not break" quality constraints.
- Deliverables: abatement curves under constraints; a short retrofit shortlist for one site-relevant target; a measurement plan for a pilot trial.
- Validation pathway: mass/energy + TEA/LCA scenario envelopes -> partner review -> pilotable protocol (what to measure and how often).

WP-A3. Slag chemistry and metal losses (value recovery under operability constraints)

Small recovery improvements compound at scale, but slag design interacts with viscosity/foaming constraints and impurity capture. The research need is to quantify metal losses and operability interactions for realistic feed blends, not idealised compositions. WP-A3 targets a direct value-capture lever: reducing copper losses while staying inside operability constraints. The objective is to produce slag design envelopes and test protocols that are transferable to partner contexts, including realistic impurity suites.

Scientific 101 pointers: `T3.2` (slag chemistry and losses) and `T3.1` (pyro route context).

- Core questions: what combinations of slag chemistry and operating conditions minimize dissolved copper and entrainment losses without destabilizing furnace operation?
- Partner inputs: representative feed compositions; current loss metrics; known operability constraints (foaming, tapping, accretions).

- Deliverables: slag design envelopes; quantified recovery gains; a reproducible lab protocol that maps to partner KPIs.
- Validation pathway: bench slag/matte experiments + microstructure -> partner review -> one pilotable slag-control hypothesis.

WP-A4. Bolt-on hydromet pre-treatment for risk reduction and secondary feeds

Selective leaching and targeted pre-treatment can act as "bolt-on" risk reduction measures, particularly when impurity suites or secondary feeds constrain existing routes. The research need is to identify where such steps are technically credible and environmentally defensible in an Australian context. WP-A4 identifies and tests "bolt-on" pre-treatment steps that can improve feed flexibility and impurity tolerance without demanding a full plant redesign. The objective is a ranked set of pre-treatment flowsheets with bench evidence for selectivity and residue handling, grounded in partner integration constraints.

Scientific 101 pointers: `T3.4` (hydromet modules) and `T3.3` (impurity behavior and why "removal" can shift liabilities).

- Core questions: which selective leaching and separation steps can remove (or immobilize) target impurities while preserving copper value and producing manageable residues?
- Partner inputs: candidate feed samples (complex concentrates and/or secondary feeds); integration constraints; residue acceptance requirements.
- Deliverables: ranked "bolt-on" flowsheets with bench proof-of-concept; residue stability evidence; a partner-ready integration checklist.
- Validation pathway: bench selectivity + residue handling -> one pilotable pre-treatment recipe for a defined feed class.

Mission B: Circular copper and alloy loops (complex scrap and e-waste)

Mission B targets the capability stack required to upgrade complex secondary feeds into spec-compliant copper and alloys. The research emphasis is on feed characterisation, contamination control, route selection, and measurement protocols that make circular claims defensible.

WP-B1. Scrap atlas (characterisation to processing rules)

Complex scrap and e-waste streams are heterogeneous; without a feed library and classification scheme, route selection is guesswork. The research need is to connect Australian-relevant feed characterisation to practical processing rules. WP-B1 builds the enabling evidence base for circular copper: a standardized Australian "scrap atlas" that connects real feed variability to processing rules and risk flags. The objective is not just characterization; it is a library and protocol set that partners can reuse when they decide whether a feed is "integratable" (and on what terms).

Scientific 101 pointers: `T3.6` (secondary feed characterization) and `T3.3` (contamination as an impurity-suite problem).

- Core questions: which feed attributes (composition distributions, form, liberation, contaminants) predict downstream compatibility and product-spec risk?
- Evidence anchor: PCBs can reach copper contents of **20-25%** (F. Yang et al., 2024, 4), but heterogeneity and contamination dominate route choice.
- Partner inputs: representative scrap and e-waste streams; access to sampling points and logistics constraints; downstream acceptance thresholds where available.
- Deliverables: a first-version scrap library; standardized characterization protocols; a feed classification scheme with "processing rules" for at least one priority stream.

WP-B2. Decontamination and pre-treatment before integration

Secondary feeds often carry plastics, halogens, organics, and problematic metals that can dominate environmental risk and downstream compatibility. The research need is to validate pre-treatment recipes and measure emissions and contaminant removal in a way that partners can trust. WP-B2 makes pre-treatment "real": validated recipes with measured contaminant removal and emissions evidence. The objective is to produce partner-usable pre-treatment protocols that improve downstream compatibility and reduce environmental risk, with clear documentation of what was measured and what was assumed.

Scientific 101 pointers: `T3.7` (pre-treatment and decontamination) and `T3.12` (MRV discipline for defensible claims).

- Core questions: which mechanical/thermal steps remove plastics/halogens/organics at lowest cost and risk, and what emissions controls are required?
- Evidence anchor: route choice and decarbonisation outcomes vary strongly by pathway (J. Torrubia et al., 2024, 1, 7–8).
- Partner inputs: representative feed materials; access to pre-treatment equipment; target specifications for "smelter-compatible" or "hydromet-compatible" feed.
- Deliverables: pre-treatment recipes + emissions characterization; compatibility specifications; a measurement protocol suitable for partner adoption.

WP-B3. Alloy-to-alloy loops and tramp element management

Avoiding downcycling requires quantified tolerance thresholds and quality assurance methods for tramp elements. The research need is to identify feasible alloy-to-alloy windows that match downstream specifications. WP-B3 turns alloy recycling into a spec-anchored engineering problem. The objective is to quantify tramp-element thresholds and develop quality assurance and refining/dilution strategies that keep material in higher-value loops rather than downcycling.

Scientific 101 pointers: `T3.8` (alloy loops and tramp elements).

- Core questions: what tramp-element thresholds define "no downcycling" for one priority alloy system, and what refining/dilution strategies are feasible?
- Partner inputs: alloy scrap compositions; downstream specifications and acceptance tests; realistic melt practice constraints.
- Deliverables: tolerance thresholds; a candidate refining/dilution strategy; QA guidance and one demonstrated spec-compliant loop (bench or pilot scale).

WP-B4. Co-product-aware circular metallurgy (including residues/anode slime)

Route viability can depend on co-product recovery and residue handling. The research need is to design circular flowsheets that do not strand value in residues and that remain environmentally defensible. WP-B4 ensures Mission B is economically and environmentally realistic under a "copper plus co-products" boundary. The objective is to design circular flowsheets that account for co-product value and residue liabilities explicitly, rather than treating residues as an afterthought.

Scientific 101 pointers: `T3.9` (co-products and residues) and `T3.1` (refining residues and where value concentrates).

- Core questions: what co-products materially affect viability for a chosen route, and what residue handling/stabilization makes the route defensible?
- Evidence anchor: multi-metal recovery from anode slime demonstrates co-product-sensitive route importance (Z. Dong et al., 2020, 1, 5).
- Partner inputs: representative residue streams (or simulated equivalents); regulatory constraints; partner risk and acceptance thresholds.
- Deliverables: co-product-sensitive flowsheet options; residue handling pathways; a route-selection checklist that includes residue liability accounting.

WP-B5. Decarbonisation scenarios for circular routes (TEA/LCA + measurement)

Circular routes are not automatically low-carbon; credible comparison requires consistent boundaries, scenario analysis, and measurement protocols. The research need is to make "low-carbon circular copper" a measurable claim rather than a label. WP-B5 makes "low-carbon circular copper" defensible by building comparative TEA/LCA models with scenario and uncertainty treatment, and by producing MRV-ready measurement protocols. The objective is reusable templates and a partner-adoptable measurement plan for at least one circular route.

Scientific 101 pointers: `T3.12` (TEA/LCA/MFA/MRV) and `T3.6/T3.7` (secondary feed variability and pre-treatment impacts).

- Core questions: what boundaries and assumptions dominate conclusions for a chosen circular route, and how should measurement be designed to support credible claims?

- Evidence anchor: comparative results and scenario analysis show meaningful sensitivity to boundaries and electricity transitions (X. Wu et al., 2025, 7, 9).
- Partner inputs: route parameters and yields; energy assumptions; access to pilot measurement data where available; partner reporting requirements.
- Deliverables: reusable TEA/LCA models; scenario sensitivity results; MRV-ready metrics and sampling plans; a partner-ready protocol.

Mission outputs (what gets built, in practice)

Mission A builds: impurity transfer functions and operating windows; retrofit abatement curves under constraints; slag design protocols; bolt-on pre-treatment proof points.

Mission B builds: an Australian scrap library and classification scheme; validated pre-treatment recipes and emissions evidence; alloy tolerance thresholds and QA guidance; co-product-aware circular flowsheet options; TEA/LCA and MRV templates that allow defensible comparison.

T3. Science 101: Technology Primers

This section provides short primers on the core process technologies and analytical toolchains referenced in this report. The goal is to make the scientific logic legible to a mixed internal audience and to clarify why each technology matters to the two-mission strategy.

T3.1 Pyrometallurgy and electrorefining (smelting -> converting -> anode -> cathode)

Most copper metal is produced by treating sulfide concentrates at high temperature to separate metal-rich phases from gangue, then refining to high-purity cathode. In simplified terms, smelting converts concentrate into a copper-rich matte and an oxide slag; converting further oxidizes iron and sulfur to raise copper grade; electrorefining dissolves impure anodes and plates copper cathode that meets tight conductivity and impurity specifications.

The core science is redox control and phase behavior. Operators manage oxygen potential, temperature, and slag chemistry so that copper partitions to the desired phase and impurities are either rejected to slag/dust, captured in dedicated residue streams, or stabilized for safe handling. The electrorefining circuit adds another constraint layer: impurity buildup in electrolyte and the formation of anode slimes and other residues that can be liabilities or value streams.

- Key variables: oxygen potential; temperature; slag chemistry (basicity/viscosity); feed impurity suite; off-gas handling capacity; electrorefining electrolyte chemistry.
- Typical outputs: copper cathode; slag/dust/residues; SO2-bearing off-gas requiring capture; anode slime and other refining residues.

- Integration constraints: environmental controls (SO2, dusts); refractory/corrosion; quality assurance for cathode and by-products.
- Why it matters here: it is the dominant midstream pathway and the main "constraint translator" from feed variability to product specification.

T3.2 Slag chemistry, partitioning, and copper losses

In high-temperature copper processing, slag is a controlled phase that governs operability and recovery. Copper can be lost to slag both chemically (dissolved copper species under certain conditions) and physically (entrained matte droplets that do not separate before tapping). Small reductions in these losses can compound at scale, but improvements must remain compatible with furnace stability and impurity capture.

Scientifically, copper losses are shaped by phase equilibria (what is thermodynamically favored), kinetics (how fast phases separate), and transport (mixing, settling, and interfacial behavior). Slag viscosity and microstructure influence droplet settling and entrainment; oxygen potential and slag composition influence dissolved copper levels.

- Key variables: slag composition (e.g., Fe-oxide/silicate balance); oxygen potential; temperature; mixing intensity; settling time.
- Typical outputs: copper-in-slag measurements (chemical + mechanical); slag viscosity proxies; microstructure/phase identification.
- Integration constraints: recovery improvements cannot violate tapping/foaming constraints or shift impurities into unstable residues.
- Why it matters here: it is a practical lever for Mission A (WP-A3) that directly links science to value capture.

T3.3 Impurities and penalty elements (behavior and control levers)

Impurities and penalty elements (e.g., As, Sb, Bi, Pb, Zn, Ni, halides) matter because they affect concentrate economics, plant operability, and product quality. They can drive corrosion, dust formation, off-gas constraints, and anode/cathode quality issues, and they often trigger penalties and blend constraints (D. J. Lane et al., 2016, 2).

The science is speciation and partitioning: where an element goes (matte, slag, gas, electrolyte, residues) depends on oxidation state, temperature, and co-existing chemistry (including halides). Controlling impurities therefore requires a "route-aware" view: what looks like "removal" may simply move the element into another stream that must be stabilized, recovered, or disposed of compliantly.

- Key variables: impurity suite and concentrations; oxygen potential; chloride/halide presence; recycle streams; allowable impurity thresholds for products.

- Typical outputs: impurity transfer functions; tolerance windows; residue inventories (dust/slag/slime) with speciation.
- Integration constraints: impurity control can create new waste/residue handling requirements that dominate feasibility.
- Why it matters here: it is central to Mission A (WP-A1/WP-A4) and to Mission B feed acceptance.

T3.4 Hydrometallurgy modules (selective leaching, pre-treatment, SX/EW)

Hydrometallurgy uses aqueous chemistry to dissolve metals into solution and then recover them (often as cathode) using separation and electrochemistry modules. In this report, hydrometallurgy appears mainly as targeted pre-treatment: a "bolt-on" step to remove penalty elements, reduce midstream risk, or enable difficult secondary feeds without full plant redesign.

The core science is controlled dissolution (thermodynamics + kinetics) and selective separation. Selective leaching aims to dissolve an impurity suite while keeping copper largely in solids (or vice versa), then uses precipitation, adsorption, solvent extraction, or electrowinning to recover copper and manage dissolved impurities. Solvent extraction and electrowinning (SX/EW) are widely used modules for producing high-purity copper from leach solutions, but their performance depends strongly on impurity control and electrolyte chemistry.

- Key variables: pH and redox potential; reagent selection; temperature; particle size/liberation; impurity suite; residue stability.
- Typical outputs: leach selectivity curves; solution impurity profiles; cathode purity indicators; residue characterization and handling options.
- Integration constraints: residues and solutions must be manageable (filtration, water reuse, stability, and compliant disposal or recovery).
- Why it matters here: it underpins Mission A WP-A4 and multiple circular routes where partners require spec-compliant outputs.

T3.5 Bioleaching (heap and stirred routes; scale-up constraints)

Bioleaching uses microorganisms to accelerate redox cycles that generate ferric iron and acidity, which can leach copper from sulfide minerals. It is often discussed for low-grade ores and certain difficult-to-process mineral systems, and it features in international benchmark consortia (e.g., MiCCuR) as a scale-up pathway (Linnaeus University, 2021).

The science is coupled microbiology and electrochemistry in porous or mixed systems. Industrial viability depends on mass transfer (oxygen and solution distribution), heat balance, and mineralogical effects such as passivation layers. For strategy design, the key point is that bioleaching scale-up is an engineering problem as much as a microbiology problem, and comparative claims are sensitive to system boundaries and energy assumptions (X. Wu et al., 2025, 9).

- Key variables: temperature; aeration/oxygen transfer; pH; ferric/ferrous ratio; mineralogy; permeability and irrigation (heaps).
- Typical outputs: copper recovery vs time; solution impurity profiles; residue stability; energy and emissions inventories for LCA.
- Integration constraints: slow kinetics and variability require realistic time-to-recovery and robust monitoring assumptions.
- Why it matters here: it provides a lower-temperature comparator route and informs decarbonisation and low-grade resource options.

T3.6 Secondary feed characterization (scrap + e-waste "scrap atlas")

Circular copper depends on secondary feeds that are heterogeneous in composition, form, and contamination. Scrap can range from relatively clean copper to multi-material assemblies; e-waste can be copper-rich but is highly composite and variable (F. Yang et al., 2024, 4). Without standardized characterization and representative sampling, route selection is guesswork.

The core technical issue is representativeness and liberation: what separations are possible depends on how components break and separate under shredding and processing, what fraction becomes fines, and how contamination co-travels with copper-bearing fractions. A "scrap atlas" is therefore a standardized feed library plus protocols that connect feed classes to processing rules and risk flags.

- Key variables: composition distributions; physical form and bonding; liberation; plastics/halogens; fines generation; moisture.
- Typical outputs: feed classes; sampling protocols; contaminant metrics; a processing-rule playbook linked to feed types.
- Integration constraints: poor characterization leads to poor downstream chemistry control and unexpected residues/emissions.
- Why it matters here: it is the enabling layer for Mission B WP-B1/WP-B2 and for partner trust in circular claims.

T3.7 Pre-treatment and decontamination of complex scrap

Many circular routes succeed or fail in pre-treatment. Removing organics/plastics and controlling halogens (and their emissions when heated) is often required before integration into a metallurgical process. Mechanical pre-processing can also concentrate copper-bearing fractions and remove components that create downstream liabilities.

Scientifically, pre-treatment is about changing feed chemistry and structure so that downstream thermodynamics, kinetics, and emissions become controllable. Thermal treatment can drive off organics and modify composites, but requires strong off-gas capture and residue management. Mechanical separation depends on density, conductivity, magnetism, and shape, but is limited by liberation and fines behavior.

- Key variables: temperature and atmosphere; residence time; shredding/classification settings; off-gas capture; halogen management; residue stabilization.
- Typical outputs: upgraded fractions; quantified contaminant removal; emissions profiles and residue streams.
- Integration constraints: environmental performance and permitting can dominate viability even when metallurgical recovery looks good.
- Why it matters here: it is core to Mission B WP-B2 and to safe, partner-acceptable integration of secondary feeds.

T3.8 Alloy-to-alloy recycling and tramp elements

Alloy-to-alloy recycling aims to keep material in higher-value loops rather than downcycling. The limiting factor is often tramp elements: impurity elements that accumulate with repeated recycling and degrade properties or fail specifications. Once certain elements are dissolved in the melt, removal may be difficult without dilution, targeted refining, or strict sorting.

The science is phase diagrams, solubility, and solidification behavior. Tolerance thresholds depend on the alloy system and application requirements, so quality assurance and acceptance testing become part of the technology. This makes "spec-driven" partner pull essential for defining what a viable alloy loop looks like.

- Key variables: alloy composition; tramp element thresholds; dilution/refining options; melt practice; acceptance testing protocol.
- Typical outputs: tolerance maps linking composition to properties; QA guidance; at least one demonstrated spec-compliant loop.
- Integration constraints: the "hardness" of impurity removal can force system-level solutions (sorting + dilution + standards).
- Why it matters here: it is the main technical barrier to high-value circular loops (Mission B WP-B3).

T3.9 Co-product recovery and residues (including anode slime)

Copper processing produces residues that can be liabilities or value streams. Refining residues such as anode slimes can concentrate precious metals and other co-products; recovering these materials can materially change the economics and environmental performance of a route (Z. Dong et al., 2020, 1, 5).

The science is multi-metal separation and stabilization. Residues often contain mixtures of metals in different chemical forms; recovering value requires targeted leaching and separation steps designed around selectivity and residue stability. Even where co-products are not the primary revenue driver, avoiding "stranding" value in unstable residues reduces both cost and risk.

- Key variables: residue mineralogy and speciation; leach selectivity; solid-liquid separation; stabilization requirements; regulatory constraints.
- Typical outputs: recovered co-products; stabilized residues; route options with mass balances and residue liability accounting.
- Integration constraints: residues can concentrate hazardous species, making safe handling and compliance non-negotiable.
- Why it matters here: it is the boundary condition for "copper plus co-products" and for Mission B WP-B4.

T3.10 Microrecycling and microfactory concepts (distributed circular metallurgy)

Microfactory approaches aim to process complex waste streams in smaller, modular units rather than relying only on large centralized facilities. The motivation is often practical: local handling of difficult waste, reduced transport, and flexible processing configurations tailored to specific feed classes. The same fundamentals apply (thermodynamics, phase separation, emissions control), but the engineering constraints change: throughput limits, product specification control, and environmental compliance often dominate.

- Key variables: feed class constraints; temperature and atmosphere control; emissions capture; product specification and QA.
- Typical outputs: recovered metal fractions or intermediate alloys; residues requiring disposal or further processing.
- Integration constraints: without tight controls, micro-units risk becoming waste treatment devices rather than value-adding processes.
- Why it matters here: it is a credible pilot-scale engagement pathway for Mission B and aligns with distributed circularity narratives.

T3.11 Emerging direct electrochemical routes (molten sulfide electrolysis as a comparator)

Direct electrochemical extraction routes aim to produce copper with fewer conventional smelting steps by using electrolysis in high-temperature molten environments. Molten sulfide electrolysis is a notable early-stage comparator because it targets sulfur handling and emissions by producing elemental sulfur under certain conceptual configurations (MIT News, 2017).

The core science is high-temperature electrochemistry and materials stability. Industrial viability depends on electrode and containment materials, cell efficiency and heat management, and an overall flowsheet that is credible at scale. In strategy terms, these routes are best treated as bounded "option value" work rather than near-term plant retrofits.

- Key variables: electrolyte composition; electrode materials; temperature; current density; sulfur handling pathway.

- Typical outputs: copper metal; sulfur (or sulfur-containing products) depending on configuration; spent electrolyte handling requirements.
- Integration constraints: materials durability and scale-up remain the dominant risks.
- Why it matters here: it defines a long-horizon decarbonisation comparator for a constrained portfolio of higher-risk research.

T3.12 The analytical toolchain (TEA, LCA, MFA, MRV)

Strategy claims in copper often depend on comparisons: which route is lower carbon, which integration is lower risk, which change is worth piloting. Those comparisons depend on transparent modeling and measurement. Techno-economic analysis (TEA) quantifies costs and value drivers, life cycle assessment (LCA) quantifies environmental burdens under defined boundaries, material flow analysis (MFA) quantifies system-level stocks and flows, and measurement, reporting and verification (MRV) defines how claims are tested in practice.

Methodologically, results can be sensitive to boundaries, electricity assumptions, co-product treatment, yield and reliability assumptions, and sampling plans. In this report, the analytical toolchain is treated as a technology because it produces reusable templates and protocols that partners can adopt to de-risk pilots and defend claims externally.

- Key variables: boundaries and functional unit; co-product allocation rules; uncertainty treatment; scenario design; measurement and sampling protocols.
- Typical outputs: comparable TEA/LCA models; scenario sensitivity results; MRV-ready metrics and templates.
- Integration constraints: partner adoption requires protocols that are feasible to run in operating plants.
- Why it matters here: it underpins Mission B WP-B5 and makes "low-carbon" and "responsibly recycled" statements defensible.

T4. Research and Collaboration Landscape (AU + Selected Global Comparators)

T4.1 Australia-based initiatives and research groups

Australia already has a substantial copper-relevant research base, but it is distributed across institutions with different technical and commercialization strengths. The University of Queensland provides a clear example of bench-to-commercial progression: its hydrometallurgy group and related metallurgy capability sit alongside the Banksia Minerals Processing spinout, which is positioned around more energy-efficient copper concentrate processing (University of Queensland, 2025, 2026, 2023). For strategy design, the important point is not a single technology claim; it is the pathway from university lab work to industry-facing development backed by commercialization entities and national programs.

UNSW's landscape contribution is strongest in value-adding and circular processing narratives that connect metallurgy, decarbonization, and waste streams. The Institute for Industrial Decarbonisation frames value-add processing as an industrial transformation priority, while the SMaRT microfactory and ARC Microrecycling Hub evidence a continuing applied program on converting complex waste streams into higher-value materials (UNSW, 2025, 2018; SMaRT Centre, 2026). For this report, these are relevant because Mission B depends on practical, contamination-aware pathways for complex secondary feeds, not just high-level recycling targets.

Curtin contributes major extractive metallurgy depth via C3MET and related WA School of Mines capability, with explicit emphasis on critical-mineral processing and industry collaboration. Public material indicates C3MET-scale staffing, Trailblazer alignment, and pilot-oriented pyrometallurgical infrastructure in Kalgoorlie (Curtin University, 2024, 2021; Trailblazer, 2023). These elements matter for this analysis because they show where national capability has already moved beyond concept framing toward test infrastructure and commercialization pathways.

South Australia's ARC Copper-Uranium Hub remains a useful precedent for copper-focused consortium design with industry and multi-university participation, including Adelaide, Flinders, and major operators. The Hub's publicly stated focus on removing non-target elements from copper concentrates aligns directly with current impurity-management priorities in Mission A (University of Adelaide, 2026). As an implementation lesson, this indicates that impurity and concentrate-quality topics are fundable and partner-relevant when framed as value-capture and operability questions.

CSIRO and CRC structures add a national coordination layer. The 2025 Green Metals Innovation Network, led by CSIRO with HILT CRC, signals a policy-backed mechanism for industry-research alignment and technology translation in low-emissions metallurgy settings (CSIRO, 2025; HILT CRC, 2025; T. Ayres, 2025). Although the current GMIN emphasis is weighted toward iron/alumina/aluminium pathways, the collaboration architecture and capability-building model are transferable to copper midstream and circular-copper programs.

T4.2 Global comparators and what they imply

Global comparator programs reinforce two points: first, copper innovation is increasingly mission-structured rather than discipline-structured; second, pilot pathway design is now as important as lab novelty. The MiCCuR project in Europe is a useful example because it combines microbiology, process engineering, and international partners around chalcopyrite bioleaching scale-up objectives and pilot progression logic (Linnaeus University, 2021). The consortium composition (including Chile and South Africa participants) also shows how copper-producing regions are using shared R&D vehicles for low-grade resource pathways. This is

directly relevant to Mission A/B interface questions where low-grade resources and lower-carbon routes intersect.

US and Canadian examples indicate two additional patterns. Open-innovation challenge mechanisms can rapidly expose diverse process options and filter them toward pilot workstreams, as shown in the OZ Minerals Ingenious Extraction challenge reporting and associated UBC chloride-leaching concepts (International Mining, 2022). US institutional platforms such as RE-MADE also demonstrate dedicated funding structures for circular-manufacturing and metals-recycling innovation that can be used as an analogue when designing partnership models (REMADE Institute, 2026). Separately, long-horizon breakthrough routes such as molten sulfide electrolysis remain early-stage but strategically relevant because they address sulfur-management and emissions constraints at process-chemistry level (MIT News, 2017). For this analysis, the implication is to maintain both near-term retrofit/pilot tracks and a bounded portfolio of higher-risk options.

Circular-economy analysis also sets an important realism constraint: recycling growth is necessary but insufficient on its own. Oxford Smith School reporting highlights that circular strategies may only satisfy a portion of long-horizon copper demand, implying ongoing dependence on primary extraction plus better processing and refining pathways (University of Oxford, 2023). This supports the two-mission architecture in this report: circular capability should be expanded aggressively, but not as a substitute for midstream competitiveness work.

T4.3 Partnership Positioning Interface (Australia-First)

Research missions need partner pull to obtain realistic feed samples, constraint envelopes, and pilot opportunities. The partner logic is straightforward: midstream operators and recyclers control the constraints and feed access, downstream manufacturers and spec-driven buyers control acceptance testing and specifications, and standards/assurance bodies influence what claims will be credible.

Midstream operators and integrated operations are the natural anchors for Mission A because they can provide feed variability, impurity constraints, and operational boundary conditions (Glencore, 2025; BHP, 2024). Recyclers and secondary-feed aggregators are the natural anchors for Mission B because they control access to complex scrap streams and understand practical pre-treatment constraints. Downstream pull partners make "spec compliance" explicit and can define acceptance criteria for circular products. Standards and assurance bodies are relevant where "low-carbon" and "responsibly recycled" claims require measurement protocols and uncertainty treatment.

To keep this partnership logic operational, a maintained value-chain collaboration register has been added at `content/topics/topic01_copper/meta/au_copper_value_chain_collaboration_register.c` (maintained for the current review cycle). The register maps each collaboration to a primary value-chain stage (`upstream`, `midstream`, or `circular`), captures named company

and research leads where publicly available, and records subsidy/funding signals with an explicit evidence-status flag (`Directly evidenced` vs `Partially evidenced`). This allows partner-prioritization decisions to separate confirmed funding/support signals from inferred or incomplete records.

An initial engagement sequence (illustrative): - Mission A anchor: define impurity constraints and a pilotable unit-operation decarbonisation target with a midstream operator. - Mission B anchor: define scrap streams for a priority scrap library and pre-treatment trial with a recycler/aggregator. - Downstream pull: define acceptance testing and key specs for a priority product category (e.g., electrical components relevant to data-centre/grid buildout).

T5. Policy, Funding, and Programs

T5.1 Funding and support mechanisms aligned to the analysis

For this analysis, the strongest funding logic is to match project maturity to mechanism design: - ARC Linkage: partner-coupled applied research where co-investment and direct industry problem statements are required (Australian Research Council, 2026). - Trailblazer pathways: commercialization and translation opportunities when technologies need scaling and industry embedding (Department of Education, 2025; Trailblazer, 2023). - National Industry PhD: workforce-linked projects that embed researchers in operating contexts and generate partner-ready data streams (Department of Education, 2026). - CRC-linked collaboration: multi-party programs where decarbonization, processing infrastructure, and policy translation need coordinated governance (CSIRO, 2025; HILT CRC, 2025).

In practical terms, this implies a portfolio architecture where Mission A projects target impurity/operability/decarbonization constraints with midstream partners, and Mission B projects target feed characterization, decontamination, and spec-compliance pathways with recyclers and downstream pull partners.

T5.2 Implications for analysis scope

The landscape scan strengthens, rather than changes, the core strategy logic. Australia has enough institutional depth to run a copper-focused mission portfolio, but success depends on tighter integration across research groups, pilot hosts, and funding pathways. In this report, the immediate implication is to proceed with a two-mission program and to prioritize projects that can move from lab evidence to pilot protocols in the near term.

Digital process control and sensing remain deferred for this version to keep the report focused on midstream and circular metallurgy deliverables already agreed in scope.

T6. Evidence Quality, Gaps, and Confidence

T6.1 Near-term baseline strengthening

The fastest way to strengthen the Australia-first logic is to produce a harmonised baseline package: - AU value-chain map (mine -> concentrate -> smelt/refine -> semi-fab -> end use -> scrap), including trade-flow pinch points. - Harmonised baseline table of capacities, flows, and known constraints with evidence keys. - Maintained collaboration register with lead names, value-chain-stage tagging, and subsidy/funding evidence status for partner triage. - Expanded Appendix A evidence table for all quantitative claims used in the report narrative.

T6.2 Pilotable proof points

Near-term work should focus on proof points that are feasible with lab-scale work and limited partner data: - WP-A1: impurity library and transfer model validated on a representative concentrate suite. - WP-B1/B2: scrap library pilot and pre-treatment protocol with emissions characterisation for a priority stream. - WP-B5: comparative TEA/LCA scenario model and measurement protocol for a priority circular route.

T6.3 Longer-horizon capability build

Longer-term capability is created by maintaining shared datasets and methods: - impurity library + scrap atlas updated over time - TEA/LCA and uncertainty templates reusable across projects - pilot infrastructure pathway aligned to missions (partner-hosted pilots + university bench/pilot assets)

T6.4 Confidence posture (current)

- `C-001`: medium confidence (directionally supported; harmonized AU capacity/flow table still incomplete).
- `C-002`: medium confidence (route logic supported; AU-specific circular economics still incomplete).
- `C-004`: medium confidence (benchmark architecture signal supported; transferability assumptions still need explicit limits).
- `C-005`: medium confidence (demand pull supported by multiple sources; scenario spread remains material).
- `C-006`: medium confidence (impurity/co-product logic supported; plant-level thresholds remain partner-specific).
- `C-007`: medium confidence (decarbonisation signal supported; scaling assumptions remain highly scenario-sensitive).

T6.5 Implications and Near-Term Baseline Work

The evidence and logic in this report imply that Australia's copper research leverage is highest where it reduces risk and uncertainty for a limited set of structurally important nodes (midstream) and where it creates new, defensible capability for complex secondary feeds (circular copper and alloys). The credibility of this strategy depends less on adding more themes and more on quantifying Australia-specific capacities, flows, and constraint envelopes in a harmonised way.

Priority baseline work (to improve the evidence base): - AU owner/operator mapping and trade-flow quantification (concentrate vs refined vs semi-fab) in one consistent table. - Plant- and route-relevant constraint envelopes: impurity thresholds, product specs, and environmental performance constraints. - Australian scrap/e-waste stream characterisation and availability baselines connected to processing rules. - Comparative TEA/LCA assumptions and measurement protocols suitable for partner use and external scrutiny.

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Appendix A: Page-Anchored Evidence Table (Full Retained Quantitative Coverage)

This table is the audit trail for retained quantitative claims used in the report.

Claim ID	Claim (summary)	Source	Page anchor	How used in report
C-005	Global demand outlook tightens materially	S&P Global (2026a)	p. 9	Executive Summary; T1.1; T1.3
C-005	Global demand outlook (base case)	Wood Mackenzie (2025)	p. 3	Executive Summary; T1.1; T1.3
C-005	AU data-centre electricity demand growth	AEMO and Oxford Economics (2025)	p. 4	Executive Summary; T1.2; T1.3
C-001	AU export value outlook for copper (nominal A$m)	DISR (2025)	p. 60	Executive Summary; T1.4.2
C-006	Penalty elements shape concentrate value and terms	Lane et al. (2016)	p. 2	Executive Summary; H1; WP-A1/WP-A4
C-002	PCB copper content can be 20-25%	Yang, Wu and Zhang (2024)	p. 4	Executive Summary; H2; T2.2; WP-B1

Claim ID	Claim (summary)	Source	Page anchor	How used in report
C-004	EU benchmark targets (10% extraction, 40% processing, 25% recycling)	European Union (2024)	p. 3	T1.4.4
C-007	Bioleaching LCA result (GWP reduction)	Wu et al. (2025)	p. 7	Executive Summary; T2.2
C-007	Electricity-transition scenario sensitivity (GWP)	Wu et al. (2025)	p. 9	Executive Summary; H2; WP-B5
C-006	Co-product-aware refining residues matter	Dong et al. (2020)	pp. 1, 5	Boundary condition; Mission B (co-products)

Appendix B: Local Corpus Used (Bounded)

The following files in `content/topics/topic01_copper/refs/` were treated as the bounded corpus for this report: - AEMO and Oxford Economics - 2025 - Australia Data Centre Energy Consumption Report.pdf - DISR - 2025 - Resources and Energy Quarterly December 2025.pdf - Dong et al. - 2020 - Comprehensive Recoveries of Selenium Copper Gold Silver and Lead from a Copper Anode Slime with a Clean and Economical Hydrometallurgical Process.pdf - EU Publications Office - 2024 - Critical Raw Materials Act.pdf - Lane et al. - 2016 - Selective Leaching of Penalty Elements from Copper Concentrates A Review.pdf - S&P Global - 2026 - Copper in the Age of AI Challenges of Electrification.pdf - Torrubia et al. - 2024 - Recovery of Copper from Electronic Waste An Energy Transition Approach to Decarbonise the Industry.pdf - Wood Mackenzie - 2025 - High-wire Act Is Soaring Copper Demand an Obstacle to Future Growth.pdf - Wu et al. - 2025 - Scaling Bioleaching from Lab to Industry A Life Cycle Assessment of Cathode Copper Production.pdf - Yang et al. - 2024 - Towards Resource Regeneration A Focus on Copper Recovery from Electronic Waste.pdf

Appendix C: Australia Collaboration Register (Operational Artifact)

- File: `content/topics/topic01_copper/meta/au_copper_value_chain_collaboration_register.csv`

- As-of point: current review cycle snapshot.
- Scope: Australia-local copper value-chain collaborations with named leads, partner institutions, and subsidy/funding signals.
- Stage coverage: mixed coverage across upstream, midstream, and circular stages.
  Note: some records span two stages; stage assignment uses a primary-stage tagging rule.
- Evidence-status rule:
  - `Directly evidenced`: lead/funding fields are explicit in cited primary sources.
  - `Partially evidenced`: at least one requested field (often project-level funding split or named company research lead) is not explicitly published in cited sources.

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