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Smart and Resilient Material Management for Transformers in the Era of Electricity

RGI Webinar: Circular transformers for secure grid supply chains (Sept’ 26)

Dr. Ghazi Kablouti – Global Portfolio Sustainability Lead (Hitachi Energy/Transformers)

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Agenda

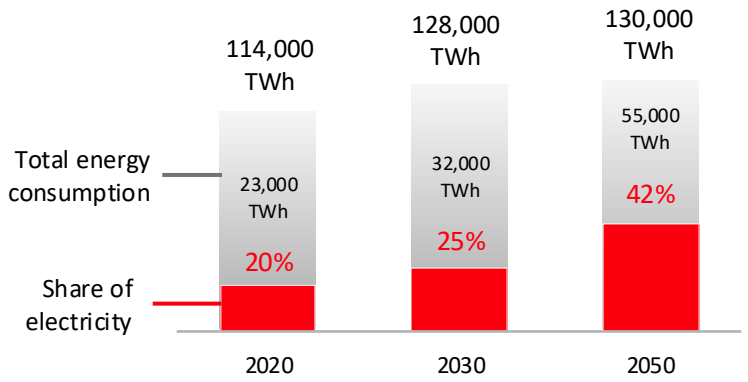
1. Materials in transformers for the “Era of Electricity”
2. Transformers and circularity: applying the 5R’s framework
3. Transformer material circularity in Europe: progress and outlook under current sourcing practices
4. Piloting a new value chain for material security and sustainability: drivers, objectives and key learnings
5. From pilots to scalable circular values chains: key recommendations for leading the transition in Europe

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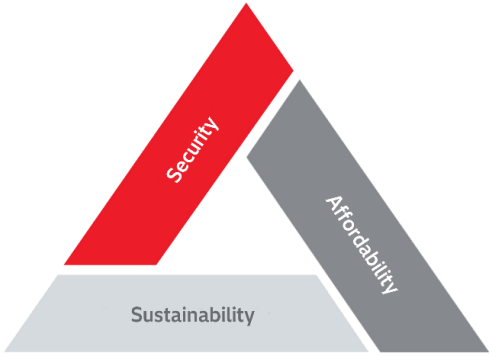
Transformers and their materials power the “Era of Electricity”

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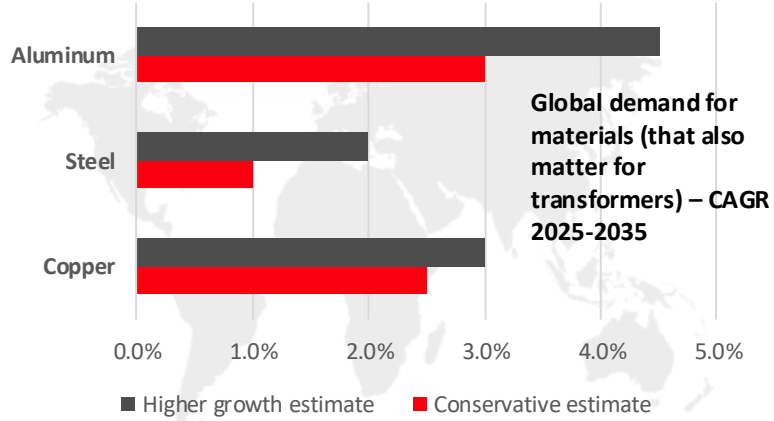
Living in the “Era of Electricity”



Balancing Security, Affordability and Sustainability in developing grids



More Electricity → More Transformers → More Materials



Source: Hitachi Energy Analysis (IEA Global Critical Minerals Outlook 2024/2025; International Aluminium Institute (IAI)/CRU; World Steel Association; McKinsey Global Materials Perspective 2025

Key growth drivers

- Grid expansion and electrification
- Renewables and energy storage
- EVs and charging infrastructure
- AI data centers (particularly copper)
- Defense spending and reindustrialization

Growth in demand 2020-2050

Transformers	HV Switchgear	HVDC	BESS*1	STATCOM*2	Power electronics	Software solutions	Service
3x	3-5x	4x	>10x	5-10x	6-8x	>10x	>6x

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Advancing circularity across the transformers value chain: – A 5R's framework

RETHINK

Rethink the way we deliver value to customers to design waste out of the equation.

REDUCE

Reduce consumption/ reduce reliance on virgin resources and reduce waste generated throughout our value chain

REUSE

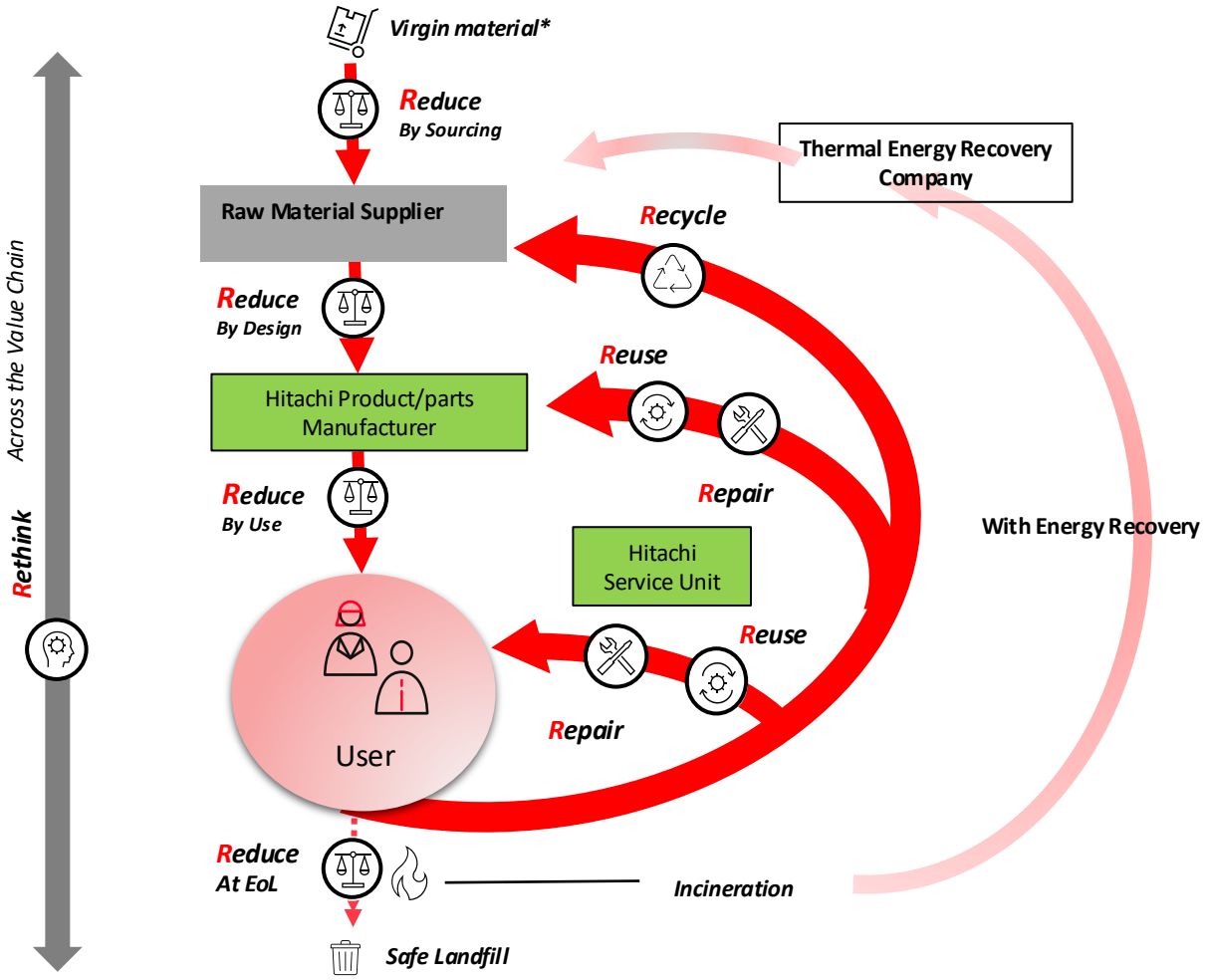
Reuse products, components and materials where possible. Design for reuse and modularity.

REPAIR

Repair equipment and parts to extend the valuable lifetime for as long as possible.

RECYCLE

Recycle materials from products that no longer can be reused or repaired. Strive for closed loop recycling where possible, else open loop recycling.



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Transformers circularity across the transformers value chain: – Applying the 5R's framework

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Lever	Objective	State-of-Play	Our approach for further improvement
REDUCE	Reduce reliance on virgin resources and reduce waste generated throughout our value chain	Yes – by superior transformer design: compact and lower weight transformers (while meeting expected operational energy efficiency requirements/standards when applicable)	• Design & testing excellence (rules, safety margins) • Advanced materials (e-steel grades, higher temperature insulation) reducing total material use • Sourcing of materials with higher share of recycled content
REUSE	Reuse products, components and materials where possible. Design for reuse and modularity.	Limited direct reuse of complete transformers: • Long lifetimes (20 to 40+ years) often result in outdated specifications and regulatory compliance gaps. • Component reuse (e.g., bushings) is possible but typically limited to spare-part applications. • Logistics, liability, certification, and warranty requirements restrict reuse in new units.	
REPAIR	Repair equipment and parts to extend the valuable lifetime for as long as possible	Yes – Hitachi Energy offering complete suite of services including life cycle extensions	
RECYCLE	Recycle materials from products that no longer can be reused or repaired. Strive for closed loop recycling where necessary, else open loop recycling.	Potential to increase consumption of recycled raw materials and participate in recycled material value chain in collaboration with other players	• End of Life guidance document (materials recovery guidelines) – available upon request • Establishing pilots with customers on circular material loops (e.g. copper, mineral oil, steel…)
RETHINK	Rethink the way we deliver value to customers to design waste out of the equation.	Potential in future with product as service business model	

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Transformer material circularity: Progress and outlook under current sourcing practices

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Transformers: Material-intensive, long-lasting products



Example –
Large Power transformer 420/120/30 kV,
380 MVA, EU-Tier 2 Operational efficiency level,
Total weight: ~470 tons

Main material	Material weight
Electrical Steel	~134 tons
Steel	~150 tons
Copper	~62 tons
Mineral Oil	~98 tons
Others	~21 tons

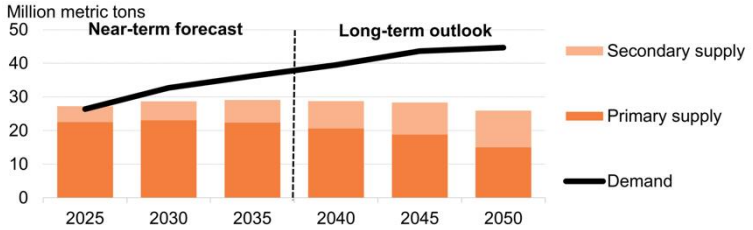
Recycled content in new power transformers (main) materials* (Focus: Europe)

	TODAY	INCREASING RECYCLED CONTENT? CHALLENGES
E-Steel 	10-15% (100% recycled label based on mass-balance credit system)	• Very niche material with a limited number of European suppliers. • Highly sensitive to scrap purity and contamination, making recycling and upgrading energy-intensive • Sustainability roadmaps primarily focused on decarbonization, with H_2-DRI/EAF routes as key levers
Carbon steel 	~10-90%	• Scrap-based EAF routes can maximize recycled content, but deployment in Europe remains limited due to economics and energy costs • Higher recycled content typically comes with a “green premium” • Process efficiency requires a stable supply of high-purity steel scrap • Europe remains a net exporter of steel scrap, reducing availability for domestic circular value chains
Copper conductor 	~35% (100% recycled label based on mass-balance credit system)	• Highly recyclable material, but greater use of recycled content is constrained by the availability of high-purity scrap • Europe remains a net exporter of copper scrap • European copper producers are expanding recycling capacity and capabilities • Alternative conductor technologies enabling up to 90+% scrap input still require broader technical and commercial validation
Mineral Oil 	0/99% Commercially available recycled mineral oil from old transformer oils	• Limited supplier base for recycled and re-refined mineral oil solutions • Market acceptance is still developing, technical confidence achieved • Scalability depends on the availability and quality of end-of-life oils (e.g., PCB contamination risks) • Cross-border transport and import/export requirements create additional administrative burdens

The strategic case for reducing dependence on virgin copper in transformers for the "Era of Electricity"

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The global perspective



Source: BloombergNEF. Note: Supply is based on BNEF's announced asset-level supply analysis and benchmarking, and represents risk-adjusted capacity. Secondary supply includes collected scrap and battery recycling material availability. Demand is under BNEF's Economic Transition Scenario.

Source: Bloomberg

- **Structural supply deficit:** Demand projected to increase by +20% by 2030 and +40% by 2040
- **Rising mining concentration:** Top three producing countries could account for 48% of global supply by 2030 – geopolitical risks
- **Declining mining productivity:** Lower ore grades and increasing extraction complexity
- **Longer mine development cycles:** New capacity takes longer to permit and bring online, ESG risks…
- **China-centric refining:** 40-50% of global refining capacity concentrated in China
- **Virgin copper dominates impacts:** Largest contributor to most material-related environmental impacts in transformers (second to steel on carbon impacts)

The European perspective

Most of EU copper demand is met by domestic smelting, refining and recycling capacity



BUT…

The race for copper is no longer only about mining. It is increasingly about who can secure, recover, and retain high-quality scrap within regional value chains



Germany Urges Europe to Halt China's Copper Scrap Buying

The market perspective



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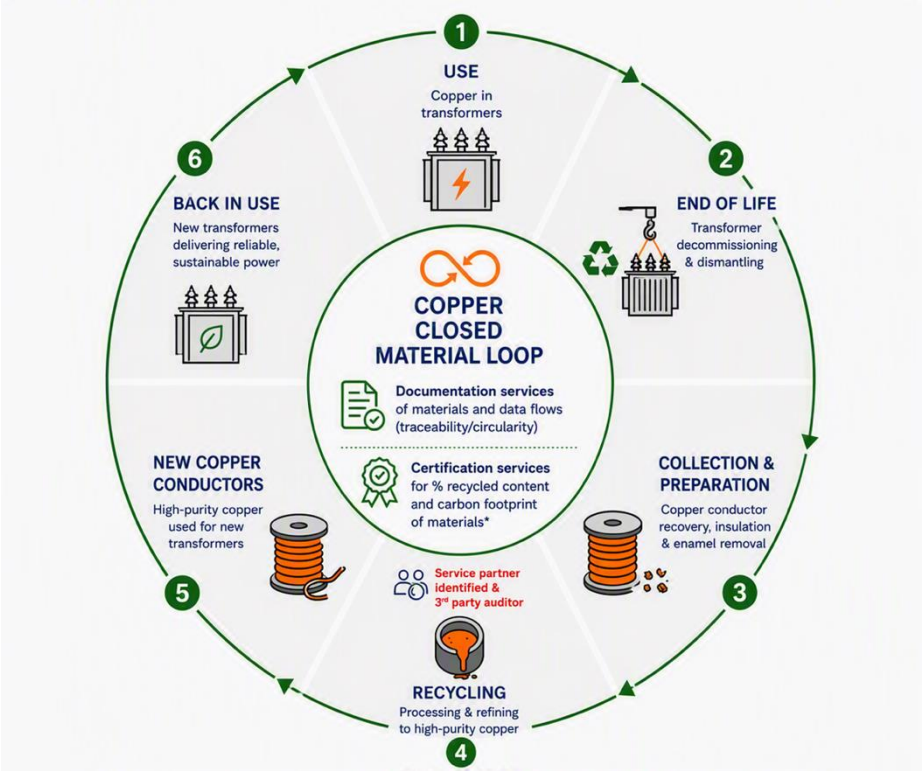
Hitachi Energy & Elia Group piloting a closed material loop – Pioneering a new value chain for material security and sustainability

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DRIVERS & CONTEXT

- **Growing urban mine**: Europe's aging transformer fleet is unlocking increasing volumes of valuable recoverable materials.
- **Limited traceability**: Utilities often lack visibility into recycling outcomes, material flows, and retention within Europe.
- **Rising demand**: Grid expansion and fleet replacement are driving growing demand for transformer materials.
- **Circular materials at a premium**: Recycled materials frequently re-enter the market at higher costs for new transformer production.

Pilot started in 2025



OBJECTIVES

- **Pilot a circular ecosystem** linking end-of-life transformers to new transformer production
- **Validate the business case** for copper and steel circularity (cost drivers and effectiveness vs. business-as-usual sourcing)
- **Test traceability and material flow transparency**
- **Quantify environmental and economic benefits** (vs. business-as-usual sourcing today)

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Hitachi Energy & Elia Group piloting a closed material loop – Key learnings

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1. High recovery & quality potential

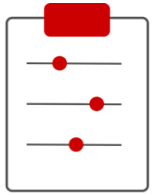
- Copper conductors from end-of-life transformers show very high recovery rates at high purity, enabled by insulation removal and enamel separation processes.

2. Strong market tailwinds:

- Demand and price premiums for high-purity copper scrap are increasing, driven by:
  - Supply chain investments in recycling infrastructure
  - Growing need for low-carbon secondary materials

3. Traceability potential

- Physical traceability is feasible upstream, before smelting
- Downstream, mass-balance approaches can ensure equivalent volumes of recycled copper re-enter the value chain (with expected process losses)



1. Challenges of project-specific CML pilots

- Dismantling and new manufacturing timelines rarely align
- Early design freeze for units under manufacturing (materials, suppliers, specifications)
- Need for alignment across ecosystem partners
- However, great learnings on feasibility, cost effectiveness, environmental impacts

2. Ownership constraints

when utilities sells unit to dismantles (transfer of ownership of old materials)

- Optimization of total cost of ownership is limited
- Control over reintegration pathways is reduced

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Enabling scalable circular transformer value chains in Europe: Key Recommendations and call to action

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Together, We can create a more circular future

A more circular, resilient and competitive transformer value chain is possible. Let's combine our efforts and lead the transition.

Standardization bodies

1 Harmonize material traceability

Create common standards for material origin, recycled content and end-of-life flows to increase transparency, support compliance and enable consistent circularity measurement.

2 Harmonize Grid's asset ratings

Create common standards to define harmonized assets ratings for the grids (transformers, switchgears, etc..) to optimize use of material and reduced variety for each specific applications (e.g., Data Center, Renewables, ..)

Transformer owners

3 Retain material value in Europe

Use procurement and end-of-life contracts to improve visibility over recovered-material destinations and encourage recycling and reintegration within European value chains, where feasible.

Policy makers

4 Enable high-quality circular loops

Promote material purity, segregation and traceability to preserve functionality, enable higher-value recycling and maximize economic and environmental benefits.

5 Remove regulatory barriers

Address regulatory, fiscal and administrative requirements that disadvantage circular materials (particularly on recycled mineral oil). Apply clear, risk-based and harmonized cross regions European borders' rules while maintaining safety, quality and environmental standards.

Industrial organizations

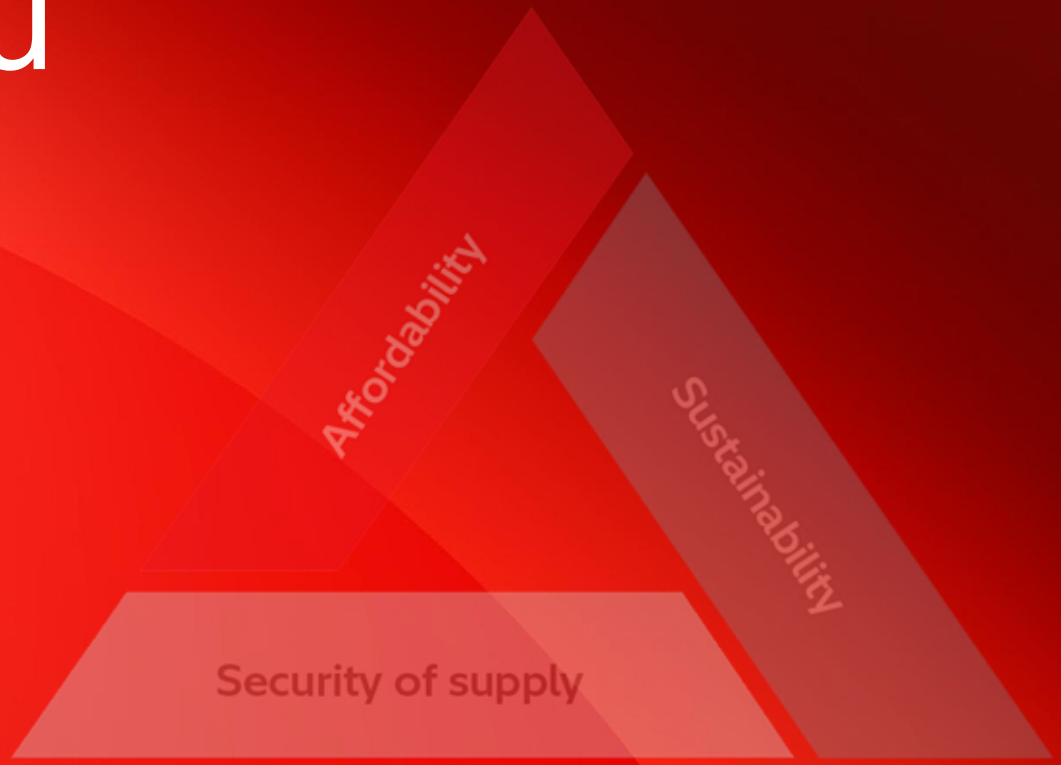
6 Strengthen value-chain collaboration

Create a dedicated forum connecting utilities, dismantlers, recyclers and manufacturers to share best practices, improve recovery outcomes and develop common end-of-life approaches.

7 Promote specification harmonization across transformer applications

- Create a dedicated forum connecting utilities and other transformers segments customer to normalize and standardize ratings
- Reduce unnecessary product variants
- Increase spare-part interchangeability and repairability (greater refurbishment and component reuse opportunities).

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