Schneider Electric™
Sustainability Research Institute

# Copper Dynamics and Horizons

## Building Sector Mitigation and Electric Vehicle-Driven Growth

Life Is On | Schneider Electric

# The Present and Future Role and Fate of Copper

## Forward

Copper is our oldest metallic companion, the first metal we ever extracted and worked. And this multi-secular companionship is not close to an end. To the opposite, copper is the most indispensable metal of the energy and digital transitions. Excellent conductor of heat and electricity, it enters in all the important technologies we are deploying on a large scale to mitigate climate change: solar panels, wind turbines, power grids, electric batteries and motors, heat exchangers and heat pumps… Copper is the king of electrification.

Will we have enough copper for our goals? The layperson wonders. He/she reads that we will need, in the next twenty-five years, to extract as much copper than we ever have. He reads that we are exploiting copper deposits with 0.6% grade, while half a century ago we used deposits with 1.7% grade.  Isn't this the proof that the end of copper is close, and that we will need ever more energy to extract copper, maybe enough to cancel out the whole benefits of low-carbon electrification.

The reality is very different. Technical improvements during half a century have allowed to move from high-grade deposits to low-grade deposits with comparable energy use. And low-grade deposits are larger and more abundant than high-grade deposits. As a result, the world copper reserves (economically exploitable), estimated in 1970 at 280 million tons (Mt), have jumped to 890 Mt today… after we extracted 650 Mt in between. Similarly, the world's resources jumped from 1.6 to 5.6 bn tons…

We need indeed as much copper in the next decades than we have extracted so far – but this is not the first time, it has already been the case in the last decades, it's a mathematical law that a growth of 3 percent per year leads to a doubling in 25 years, and that the cumulative extraction during these 25 years equals the cumulative extraction of all previous periods.

Furthermore, this will not continue forever. The global demographic transition is close to its end. The saturation of basic needs and the energy efficiency improvements slows the growth of the energy demand in China today, as it did already in the most industrialized countries. In this context, with a growing base of used items with high copper content, the recycling will increase from providing only 20% of the copper we use every year, to much higher levels, and thus finally reduce the need for primary, virgin metal.

The present report draws a very informed, fact-based – and much more detailed – picture of the present and future role and fate of copper in our societies in transition. A must-read!

Cédric Philibert
Energy and Climate Change Analyst
Former International Energy Agency (IEA)

# Beyond Extraction: Approaches to Copper Demand Management

## About the Research

The global move towards new energy systems has brought about unprecedented demand for critical minerals, with copper of particular significance. The metal's exceptional conductivity, corrosion resistance, and ductility have made it indispensable to electrification efforts that underpin innovation and decarbonization strategies. This research complements our previous study, "Copper 4.0," which examined digital technologies, sustainable mining, and international collaboration mechanisms.

The analysis presented here is motivated by our systems approach and curiosity, asking what sectors could and would move to non-copper solutions should the anticipated price hikes and tight market unfold this decade. To answer this, we first set the foundation for copper demand across all sectors and compared that to different supply trajectories. With no surprise, we join the chorus of concerns about a market imbalance in copper. Like others, our modeling shows demand outpacing supply this decade. With this set, we dove deeper into copper demand and emerged with critical new insights from the study.

Most consequentially, we show the buildings sector as presenting a critical but underexplored opportunity for demand reduction. In this sector, targeted interventions could potentially decrease global copper demand by 5.4-8.1% by 2050. Because the industry has readily available solutions for such interventions, such actions would 'free up' global copper for technologies primed to reduce emissions. Further, should high copper prices hit the market, the segment will naturally adopt known, non-copper solutions for plumbing, façade, and electrical infrastructure.

The implications extend beyond academic discourse to inform practical decision-making across multiple domains, especially for policymakers. Our findings suggest opportunities for coordinated approaches to resource management, including strategic incentives for copper intensity reduction in construction. As it turns out, efficiency, this time material efficiency, is a 'first fuel' worth considering, but now in an adjacent sector. The challenges illuminated by this research are substantial but not insurmountable.

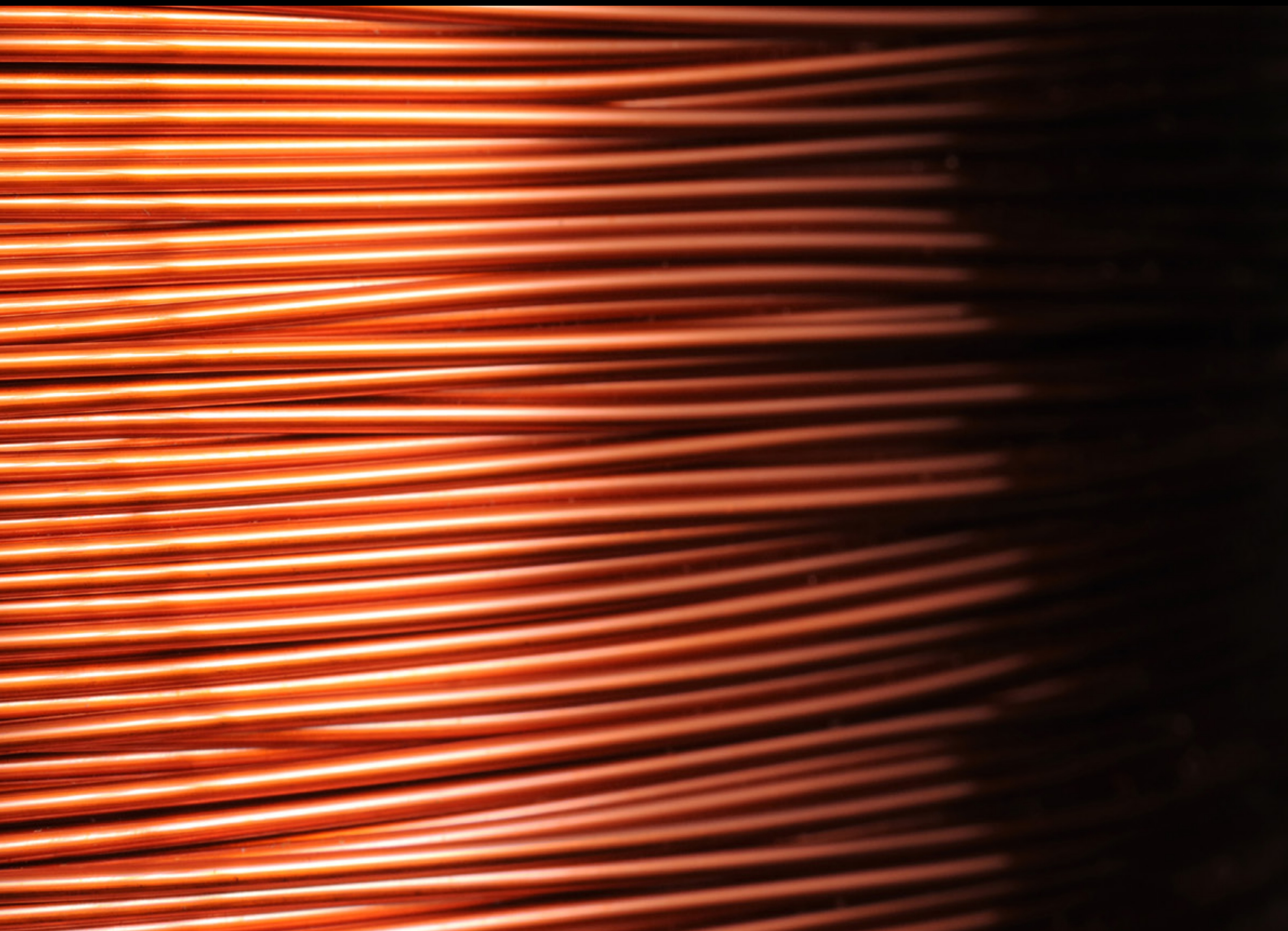
Demand management – not only in building construction but also vehicle design and recyclability enhancement, offers feasible routes to help ensure copper supply does not short-circuit critical growth in new energy technologies.

As we progress toward an electrified future in which solar and wind energy continue to undercut all other forms of energy in terms of costs, demand management is important not only from an economic perspective but also from an environmental one.

Dr. Thomas Alan Kwan

Vice President Sustainability Research, Schneider Electric

# Executive Summary



# Key Insights

### Buildings Present a Critical but Underexplored Opportunity for Copper Demand Reduction

The analysis reveals that reducing copper intensity in buildings by 20-30% could decrease total global copper demand by 5.4-8.1% by 2050, representing a significant but previously understudied opportunity for demand management. This sector offers particularly viable substitution options through alternatives like PEX/PVC piping and aluminum wiring that could alleviate pressure on copper supplies while maintaining functionality.

### Electric Vehicle Adoption Represents the Most Significant Driver of Copper Demand Within Clean Technologies

The research demonstrates that transportation electrification will generate substantially higher copper demand than renewable power generation, with potential EV-related copper requirements ranging from 96 to 160 Mt cumulatively by 2050, depending on adoption rates. This finding provides nuance to 'clean technology' as a whole driving copper demand and the relative impact compared to wind and solar power generation.

### Energy Transition Scenarios Show Relatively Modest Differences in Copper Demand for Power Generation

Contrary to common assumptions, the research reveals surprisingly small variations in copper demand across different projections for power generation falling within a narrow range of 0.8 million tonnes per year by 2050 despite different renewable energy deployment trajectories. This finding suggests that power generation infrastructure may have less impact on copper markets than previously thought, regardless of which energy transition pathway is pursued.

# Executive Summary

## Copper's Role in the Global Economy and Energy Transition

Copper underpins the global transition toward an electrified future. This report presents a comprehensive analysis of copper's pivotal role in enabling decarbonization efforts, examining current demand-supply dynamics, forecasting future requirements through sophisticated modeling, and evaluating potential strategies for sustainable copper management. The findings presented herein are particularly significant given copper's unparalleled combination of electrical conductivity, corrosion resistance, and ductility that positions it as an indispensable material for electrification and renewable energy systems.

### Current Landscape

Copper's significance in the global economy extends across diverse sectors. As of 2022, global refined copper consumption reached approximately 25.6 million tonnes, with demand distributed across construction (28-30%), electrical and electronic equipment (27-29%), transportation (12-14%), and industrial machinery (12%). This sectoral distribution underscores copper's versatility and critical importance to both traditional industries and emerging technologies.

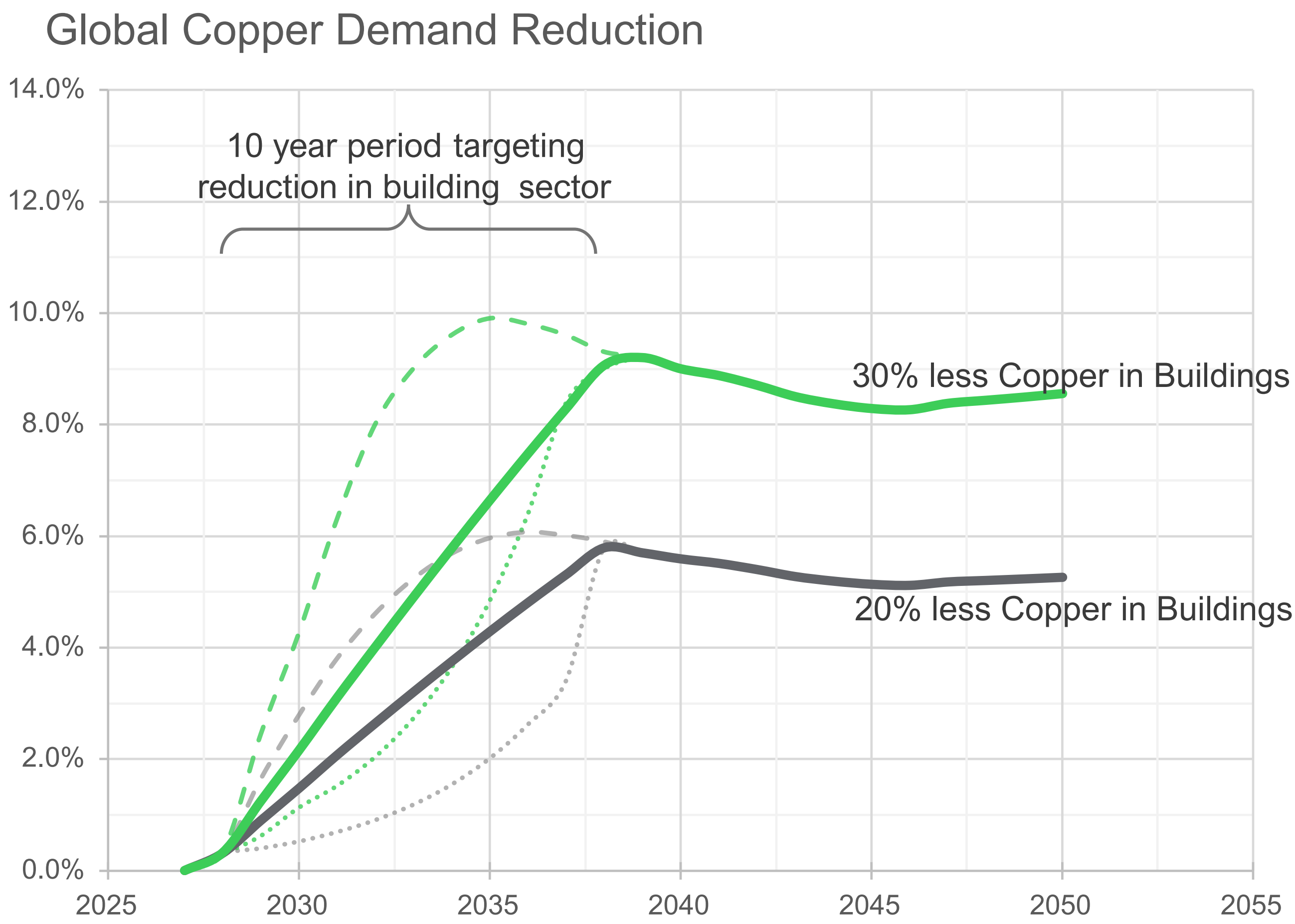
The supply side is characterized by significant geographical concentration, with Chile accounting for approximately 24% of global mined output in 2022, followed by Peru and the Democratic Republic of Congo. This concentration introduces vulnerability to geopolitical tensions, labor disputes, and natural disasters. Additionally, China's emergence as a dominant refining hub, responsible for over 40% of global refined copper production, highlights the shifting landscape of global copper processing.

Despite steady production growth, several factors constrain the industry's ability to meet projected demand increases. These include declining ore grades in existing mines, environmental pressures on water usage and emissions, and a slowdown in the development pipeline for major new projects. These constraints have contributed to concerns about potential supply-demand imbalances, with forecasts suggesting that copper demand could outstrip supply as early as 2025.

### Demand Drivers

The research identifies three primary drivers of future copper demand: the clean energy transition, urbanization and infrastructure development, and technological advancements.

The clean energy transition represents a transformative force in shaping copper demand. Renewable energy technologies demonstrate significantly higher copper intensity compared to conventional power generation. Solar photovoltaic systems require approximately 2.8-3.2 tonnes of copper per megawatt (MW) of installed capacity, while




**The study demonstrates the effect of reducing copper intensity in buildings by 20% and 30% over a ten-year period starting in 2026 on global copper demand. The graph shows the potential for significant demand reduction through efficiency measures and material substitution in the construction sector**

wind energy installations demand between 2.5-3.0 tonnes per MW for onshore and approximately 8 tonnes per MW for offshore deployments. These figures contrast sharply with conventional fossil fuel-based power generation, which typically uses only 0.5-2.0 tonnes of copper per MW.

Electrification of transportation emerges as a particularly significant demand driver. Electric vehicles (EVs) require substantially more copper than internal combustion engine vehicles—approximately 60 kg per vehicle compared to 18 kg—primarily in electric motors, batteries, wiring harnesses, and charging infrastructure. The research reveals that EV adoption rates will critically influence future copper demand, with cumulative requirements ranging from 96 to 160 million tonnes by 2050, depending on the pace of adoption.

Urbanization and infrastructure development constitute another major demand driver, with the construction sector remaining the largest consumer of copper. A typical single-family home uses approximately 199 kg of copper, while larger structures such as office buildings and hospitals require significantly more. The United Nations projects that by 2050, 68% of the world's population will live in urban areas, necessitating massive investments in new buildings and infrastructure.

Technological advancements across various sectors further contribute to copper demand growth. Data centers can use between 20 to 40 tonnes of copper per megawatt of power capacity, with North American data centers alone consuming 197,000 tonnes in 2020. The rollout of 5G networks, expansion of consumer electronics, and developments in industrial automation and artificial intelligence all point toward increasing copper intensity in technological applications.

## Modeling Methodology and Projections

To forecast future copper demand, the research employs a sophisticated bottom-up stock dynamics model that disaggregates demand into six main categories: building construction, infrastructure, industrial durables, transportation, consumer durables, and commercial durables. This methodological approach enables detailed examination of copper demand across various end-use sectors while incorporating technological changes and market dynamics.

The model integrates projections of socioeconomic indicators such as population growth, urbanization rates, and GDP per capita, based on United Nations projections.

For power generation, the study models four energy transition scenarios: Schneider Electric's Back to 2050 and New Normal scenarios, and the International Energy Agency's Announced Pledges Scenario (APS) and Net Zero Emissions by 2050 Scenario (NZE).

The supply projection methodology utilizes a multi-scenario approach based on primary and secondary production estimates. The baseline Established Supply scenario builds on IEA's Base Case for mined output, with a 15% increase to account for recycled copper. Two growth scenarios—Moderate Growth (600,000 tonnes annual increase from 2025) and High Growth (1,200,000 tonnes annual increase from 2025)—capture potential supply expansions.

## Key Findings

The modeling results yield several significant insights with implications for resource management and policy development:

All scenarios project substantial growth in copper demand, reaching between 50 and 52 million tonnes annually by 2050—approximately double the current consumption of 25 million tonnes. This finding aligns with other studies, including S&P Global's projections.

Supply constraints appear likely in the short to medium term. After 2025 and by 2030, even under the High Growth supply scenario, production struggles to keep pace with projected demand, suggesting potential market tightness.

The sectoral composition of copper demand is expected to evolve significantly. While the buildings sector remains the largest consumer throughout the projection period (28% of total demand in 2050), the transportation sector shows substantial growth from 11% in 2025 to 24% in 2050, driven primarily by electric vehicle adoption.

The analysis of copper demand for power generation yields particularly significant insights. Despite varying levels of renewable energy deployment across scenarios, the differences in copper demand for this sector are relatively small, with all projections falling within a range of 0.8 million tonnes by 2050.

Electric vehicles emerge as the most critical component of "clean technology" demand for copper. The difference in cumulative copper demand between linear and exponential EV growth scenarios reaches 64 million tonnes by 2050, underscoring the potential for rapid technological adoption to dramatically impact resource requirements.

The buildings sector presents significant opportunities for demand reduction. A 20% reduction in copper use in buildings could decrease total annual global copper demand by 5.4% by 2050, while a 30% reduction could lead to a decrease of 8.1%. This finding is particularly noteworthy as buildings have been understudied in relation to clean energy technologies despite representing a substantial portion of copper demand.

## Strategies for wwCopper Management

The research identifies two key approaches to managing copper demand sustainably: efficiency and substitution strategies, and recycling and circular economy approaches.

In the construction sector, several substitution options show promise, including plastic piping systems (PEX and PVC), which have gained substantial market share in residential applications; aluminum wiring for certain electrical applications; and composite materials for specific uses. These substitutions must carefully balance performance, safety, and sustainability considerations.

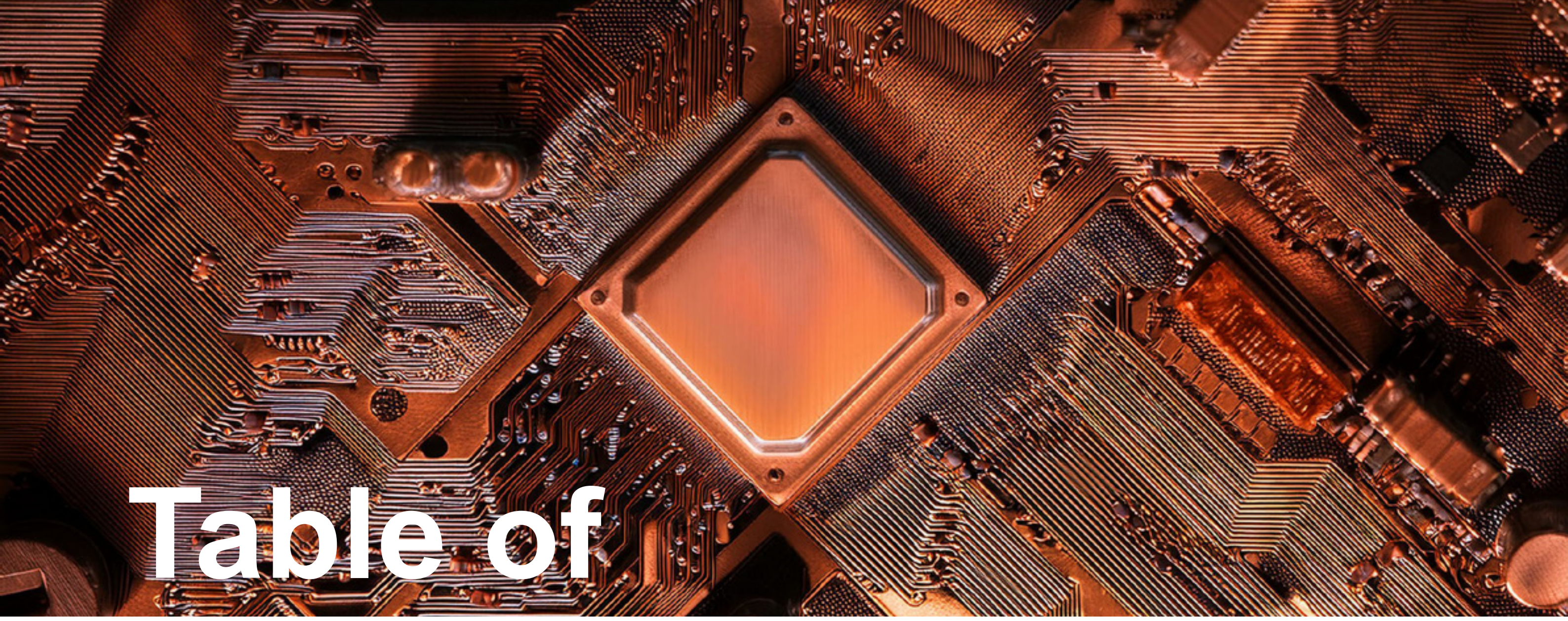
For the transportation sector, aluminum is increasingly being used in EV wiring harnesses, which can account for up to 50% of a vehicle's copper content. Research is also advancing on aluminum windings in electric motors and more efficient motor designs to reduce copper intensity without compromising performance.

Recycling and circular economy approaches offer particular promise for copper, given its infinite recyclability without loss of properties. The recovery rate for copper at the end of a building's life can reach 95%, though rates in consumer electronics are generally lower (40-50%). Enhanced collection systems, advanced sorting technologies, design for disassembly, and innovative business models such as leasing and take-back programs can significantly increase copper recycling rates.

## Implications

This analysis demonstrates that copper will play a vital role in enabling the transition to a sustainable, electrified economy. However, the projected doubling of demand by 2050 presents significant challenges for ensuring adequate and sustainable supply.

The findings have important implications for policymakers, industry stakeholders, and researchers. For policymakers, they highlight the need for coordinated approaches to resource management, including incentives for material efficiency, substitution research, and recycling infrastructure. For industry, they underscore the importance of investing in efficiency improvements, circular business models, and supply chain resilience. For researchers, they point to critical areas for further investigation, including regional demand-supply dynamics, technological innovations, and policy mechanisms.



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# Introduction

## Introduction

Copper, which has been integral to human civilization for millennia, stands at the forefront of our transition to a sustainable, electrified future. As global economies grapple with the urgent need to decarbonize and modernize infrastructure, copper's unique properties make it an indispensable material in this transformation. Examining the critical role of copper in the global economy and energy transition, exploring demand-supply dynamics, and projecting scenarios that will shape the copper landscape in the coming decades framed the approach of this research towards bridging knowledge gaps and elucidating systemic insights to the copper centered dialogue.

### Copper's role in the global economy and energy transition

Copper's exceptional electrical conductivity, second only to silver, combined with its corrosion resistance, ductility, and relatively low cost, has cemented its position as the metal of choice for electrification and energy systems. As the world pivots towards renewable energy sources and electrified transportation to combat climate change, copper's importance is set to grow exponentially.

Copper plays a vital role in renewable energy technologies, particularly in solar photovoltaic (PV) systems and wind turbines. The copper intensity varies depending on the specific technology and installation type. Looking ahead, the copper intensity for solar PV is estimated to be as low as 2.8-3.2 tonnes per megawatt (MW) of installed capacity. In wind energy, onshore turbines can be as minimal as 2.5-3.0 tonnes of copper per MW, while offshore wind installations have a higher copper intensity, approximately 8 tonnes per MW due to additional cabling requirements [1-3]. Although exact amounts may vary based on factors such as system design, location, and technological advancement this high copper intensity in renewable energy technologies is a stark contrast to conventional fossil fuel-based power generation, which uses significantly less copper, even when considering the low values and estimates for copper intensities of renewable energy technologies. For instance, coal and natural gas power plants typically require only 0.5-2.0 tonnes of copper per MW [3, 4].

The electrification of transportation, a key component of the energy transition, is significantly driving up copper demand. Electric vehicles (EVs) require substantially more copper than internal combustion engine vehicles. According to recent studies, an EV typically needs about 132 pounds (60 kg) of copper, which is roughly three to five times more than the 40 pounds (18 kg) needed for a conventional vehicle [4,5]. This increased copper content is primarily found in the electric motors, batteries, wiring harnesses, and charging infrastructure. As global automakers commit to electrifying their fleets, the copper intensity in the transportation sector is poised for significant growth.

Beyond renewable energy and electric vehicles, copper plays a critical role in upgrading and expanding electricity grids. The push for smarter, more resilient power infrastructure to support increased electrification and renewable energy integration will require substantial copper investments. High-voltage power lines, transformers, and other grid components all rely heavily on copper for efficient electricity transmission and distribution.

The importance of copper in the energy transition is further underscored by projections from the International Energy Agency (IEA). Under their Net Zero Emissions by 2050 Scenario, which aligns with limiting global warming to 1.5°C, copper demand for power generation and electric vehicle infrastructure is expected to rise from around 5 million tonnes today to approximately 14 million tonnes by 2035. This represents a near tripling of copper demand in these sectors alone over a 15-year period.

However, copper's significance extends far beyond the energy and transportation sectors. Its antimicrobial properties make it valuable in healthcare settings, while its thermal conductivity is utilized in heat exchangers and cooling systems. In the construction industry, copper is essential for plumbing, roofing, and increasingly, in smart building technologies [6].

While copper's role in enabling a low-carbon future is clear, it's important to note that copper production itself faces sustainability challenges. The energy-intensive nature of copper mining and processing contributes to greenhouse gas emissions, and declining ore grades in existing mines may exacerbate this issue [7]. As such, improving the efficiency of copper production and increasing recycling rates are crucial considerations in ensuring that copper can fulfill its role in the energy transition sustainably.

The geopolitical landscape of copper production adds another layer of complexity to its future availability. Chile and Peru, which together account for about 40% of global copper production, have faced political instability and social unrest that could impact copper supply

[8, 9]. This concentration of production in a few key regions highlights the need for diversification of supply sources and increased attention to responsible mining practices.

The interplay between increasing demand from the energy transition and the challenges in scaling up production sustainably will be a critical factor in the global copper market. Innovations in copper mining techniques, such as in-situ leaching and the potential for deep-sea mining, may help address supply concerns, but these technologies also come with their own environmental considerations [10, 11].

The circular economy concept is gaining traction as a means to mitigate some of the challenges associated with primary copper production. Copper's infinite recyclability without loss of properties makes it an ideal candidate for closed-loop systems. Currently, about 30% of global copper demand is met through recycling, but there is significant potential to increase this proportion [12, 13]. Improving collection systems, developing new recycling technologies, and designing products for easier disassembly and material recovery could all contribute to higher recycling rates and reduced reliance on primary copper production.

Copper stands as a linchpin in the global transition to a sustainable, electrified economy. Its unparalleled combination of electrical conductivity, durability, and versatility makes it essential for renewable energy systems, electric vehicles, and the modernization of power grids. As the world accelerates its efforts to combat climate change, the demand for copper is expected to surge, potentially doubling by 2050 according to some estimates. This projected growth presents both opportunities and challenges for the copper industry, policymakers, and technology developers. Balancing the need for increased copper production with environmental and social considerations will be crucial in ensuring that copper can continue to play its vital role in shaping a sustainable future for generations to come.

## Overview of copper demand and supply landscape

The global copper market is characterized by a complex interplay of increasing demand, supply constraints, and evolving end-use sectors. As of 2022, global refined copper consumption reached approximately 25.6 million tonnes, marking a significant increase from the estimated 5 million tonnes consumed in 1950 [14]. This growth trajectory underscores copper's expanding role across various industries and the global economy at large.

Copper's end-use consumption patterns demonstrate its versatility and importance across various sectors of the global economy. The construction industry remains the largest consumer of copper, accounting for approximately 28-30% of global demand. This sector utilizes copper extensively in electrical wiring, plumbing systems, and architectural applications. Following closely is the electrical and electronic equipment sector, which represents about 27-29% of copper consumption. This category encompasses a wide range of applications, from consumer electronics to industrial machinery, underscoring copper's crucial role in our increasingly digital world. The transportation sector, including electric vehicles, is also a significant consumer, accounting for roughly 12-14% of global copper demand [15-17]. These figures highlight copper's integral role in both traditional industries and emerging technologies, particularly in the context of the ongoing global energy transition.

The transportation sector, encompassing both conventional vehicles and the growing electric vehicle market, accounts for approximately 12% of global copper demand. As mentioned earlier, the shift towards electric vehicles is expected to significantly increase the copper intensity in this sector in the coming years. Industrial machinery and equipment constitute another major end-use category, representing about 12% of copper consumption [18, 19]. This sector includes a wide range of applications, from manufacturing equipment to HVAC systems, all of which rely on copper's excellent thermal and electrical properties.

On the supply side, global copper mine production has expanded steadily over the past decades, reaching about 21.9 million tonnes in 2022. This represents a 4% increase from the previous year, driven by the commissioning of new projects and the expansion of existing mines [20].

Geographically, copper production remains highly concentrated. Chile continues to be the world's largest copper producer, accounting for approximately 24% of global mined output in 2022. Peru and the Democratic Republic of Congo are closely the second and third largest producers of copper both having the output approximately half that of Chile [21, 22].

This concentration of production in a handful of countries presents both opportunities and risks. On one hand, it allows for economies of scale and specialized expertise in these regions. On the other, it makes the global copper supply vulnerable to geopolitical tensions, labor disputes, or natural disasters in these key producing areas. For instance, Chile's output is at risk due union strikes and social unrest [23, 24].

In terms of refining capacity, China has emerged as a significant player, responsible for over 40% of global refined copper production. This shift in refining capacity towards China reflects the country's growing importance in global manufacturing and its strategic focus on securing critical raw materials [25].

Despite the steady growth in copper production, there are concerns about the industry's ability to keep pace with projected demand increases. The development pipeline of major new greenfield projects has slowed, with most copper production growth now expected to come from incremental expansions of existing mines and restarts of idled capacity rather than large new operations [25, 26].

Several factors contribute to this slowdown in new project development. Declining ore grades in existing mines mean that more material must be processed to yield the same amount of copper, increasing production costs and environmental impacts. The average copper ore grade has declined over the past 15 years. Additionally, new copper deposits are often located in more remote or politically unstable regions, increasing the risks and costs associated with their development [25].

Environmental and social considerations are also playing an increasingly important role in copper production. Stricter regulations on water usage, emissions, and land reclamation are impacting the economics of copper mining projects. For instance, in water-scarce regions like Chile's Atacama Desert, copper mines are increasingly turning to desalination plants to meet their water needs, adding to production costs [27, 28].

The growing emphasis on responsible sourcing and sustainability in supply chains is prompting the copper industry to adopt more rigorous environmental, social, and governance (ESG) standards. Initiatives like the Copper Mark are gaining traction, providing a framework for responsible production practices across the copper value chain [23].

Recycling plays a crucial role in the copper supply landscape, currently meeting approximately 30% of global copper demand. The high recyclability of copper, with recovery rates often exceeding 95% for high-grade copper scrap, makes it an attractive option for reducing reliance on primary production. However, the long lifespan of many copper-containing products means that there is often a significant lag between initial use and availability for recycling [29].

The copper market faces a potential, if not likely,

supply-demand imbalance. Forecasts suggest that copper demand could outstrip supply as early as 2025, with the gap widening in subsequent years if significant new production capacity is not brought online. This looming supply gap has led to concerns about potential copper shortages and price volatility, which could impact the pace of the global energy transition and broader economic development.

## The Imperative

Copper stands at a critical juncture in the global economy and energy transition. Its unparalleled properties make it an essential material for electrification, renewable energy technologies, and modern infrastructure. As the world accelerates its efforts to combat climate change and upgrade aging infrastructure, the demand for copper is projected to surge, potentially doubling by 2050.

However, meeting this increased demand presents significant challenges. The copper industry must navigate declining ore grades, environmental pressures, and geopolitical risks while scaling up production sustainably. Innovations in mining technologies, increased recycling rates, and the development of a more circular economy for copper will be crucial in bridging the potential supply gap.

The current copper demand and supply landscape reflects these complexities. While production has steadily increased over the past decades, concerns about the industry's ability to keep pace with future demand growth are mounting. The concentration of production in a few key regions and the slowdown in new project development add further uncertainty to the supply outlook.

As we move forward, balancing the need for increased copper production with environmental and social considerations will be paramount. The copper industry's ability to adapt to these challenges, coupled with policy support for responsible production and recycling, will play a crucial role in determining whether copper can fulfill its potential as a key enabler of the global energy transition and sustainable economic development.

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# 2
# Demand Factors

## Factors Influencing Future Copper Demand

In the near future and long-term outlook, several key factors are poised to significantly influence the demand for copper. These drivers are complex and interconnected, reflecting the multifaceted role that copper plays in our evolving global economy. Understanding these factors is crucial for policymakers, industry leaders, and investors as they navigate the challenges and opportunities in the copper market. We focus on three primary drivers of future copper demand: the clean energy transition, urbanization and infrastructure development, and technological advancements.

### I. Energy Transition

The global push towards a low-carbon future is perhaps the most recognized factor driving the projected increase in copper demand. The clean energy transition encompasses a wide range of technologies and infrastructure changes, all of which rely heavily on copper's unique properties. This shift is not just a matter of environmental concern; it represents a fundamental restructuring of the global energy landscape, with copper at its core.

#### Renewable Energy Systems

At the forefront of the clean energy transition are renewable energy systems, particularly solar photovoltaics (PV) and wind power. These technologies are substantially more copper-intensive than traditional fossil fuel-based power generation, primarily due to the need for efficient electricity conduction and distribution from relatively more decentralized generation points.

Solar PV systems utilize the metal in various components due to its excellent electrical conductivity properties and the demand for installations is growing. According to the International Energy Agency (IEA), the annual global copper demand in the solar PV sector is projected to increase from approximately 750 kilotons in 2022 to 2,060 kilotons in 2035 [1]. This growth reflects the expanding role of solar energy in the global transition to renewable power sources and supported by factors such as improving solar cell efficiencies, expanding utility-scale projects, and the integration of energy storage systems.

Copper is integral to the functionality of solar PV systems, being used in wiring and cabling, ribbon cables, bus bars, heat exchangers, inverters, and the extensive wiring networks that connect individual panels to the grid. The IEA notes utility-scale PV installations can use approximately 2.5 tonnes of copper per megawatt (MW) of capacity while the commonly referenced intensity is 5 tonnes per MW.

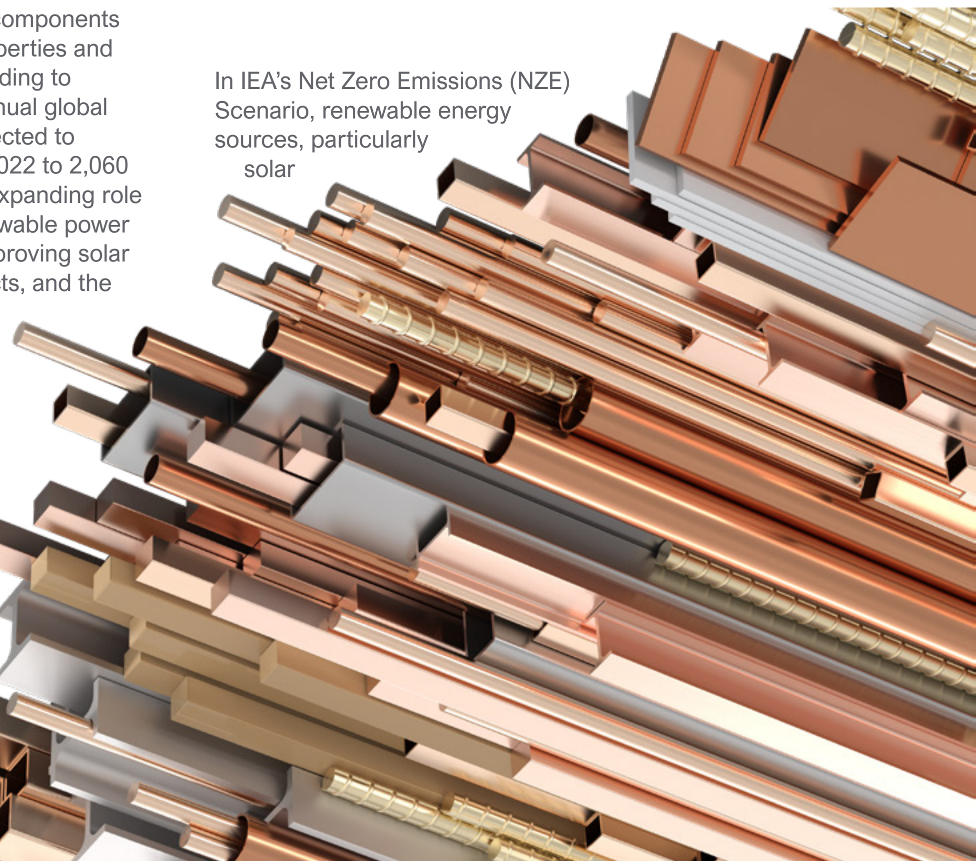
It's worth noting that while copper demand is increasing, technological advancements may lead to more efficient use of the metal. For instance, some manufacturers are exploring ways to reduce copper content in solar modules, potentially decreasing copper intensity by up to 30% through efficiency improvements [1, 2]. However, these reductions may be offset by the overall growth in solar PV deployments.

Wind power installations, both onshore and offshore, are also drivers of copper demand in the renewable energy sector. The copper intensity of wind turbines varies depending on their size, location, and specific design. Onshore wind turbines typically contain between 2.5 and 6.4 tonnes of copper per megawatt (MW), with an average of about 3.6 tonnes per MW. Offshore wind installations, however, require substantially more copper, ranging from 8 to 10 tonnes per MW, primarily due to the extensive cabling needed to transmit electricity back to shore [5-7].

The higher copper content in offshore turbines is attributed not only to the longer cables required for power transmission but also to the more robust equipment necessary to withstand harsh marine environments. As wind turbine technology advances, with larger and more powerful units being developed to capture energy more efficiently, their copper requirements are likely to increase proportionally [7].

The growing trend towards larger offshore wind farms located farther from shore is expected to further intensify copper demand. Some projections suggest that copper demand from the wind energy sector could reach 2 million tonnes per year by 2040, representing a nontrivial portion of the current global copper production [5].

In IEA's Net Zero Emissions (NZE) Scenario, renewable energy sources, particularly solar



PV and wind, are expected to dominate the electricity generation mix by 2050 and the corresponding copper demand is projected to rise by 50% by 2040 in the NZE Scenario [8].

The IEA's report on copper highlights that in the Announced Pledges Scenario (APS), which aligns more closely with current policy commitments, clean technology demand for copper is expected to nearly double from about 6,300 kilotonnes in 2023 to 12,000 kilotonnes by 2030 and highlights the natural demand for copper in the energy sector, even in less ambitious scenarios than the NZE.

The rapid deployment of clean energy technologies, including solar PV, wind power, and electric vehicles, is the primary driver behind the increasing copper demand. As discussed for solar PV and wind turbines, these technologies typically require more copper than their conventional counterparts.

## Electric Vehicles and Charging Infrastructure

The electrification of transportation, particularly the shift to electric vehicles (EVs), represents another significant driver of copper demand within the clean energy transition. EVs require substantially more copper than their internal combustion engine (ICE) counterparts due to their electric motors, batteries, and charging systems.

On average, a battery electric vehicle (BEV) contains approximately 83 kg of copper, which is more than triple the amount found in a conventional ICE vehicle (about 23 kg) [4]. This increased copper content is distributed throughout the vehicle's components, with major contributions from the electric motor, power electronics, and the extensive wiring harness required to connect the battery to various vehicle systems [9].

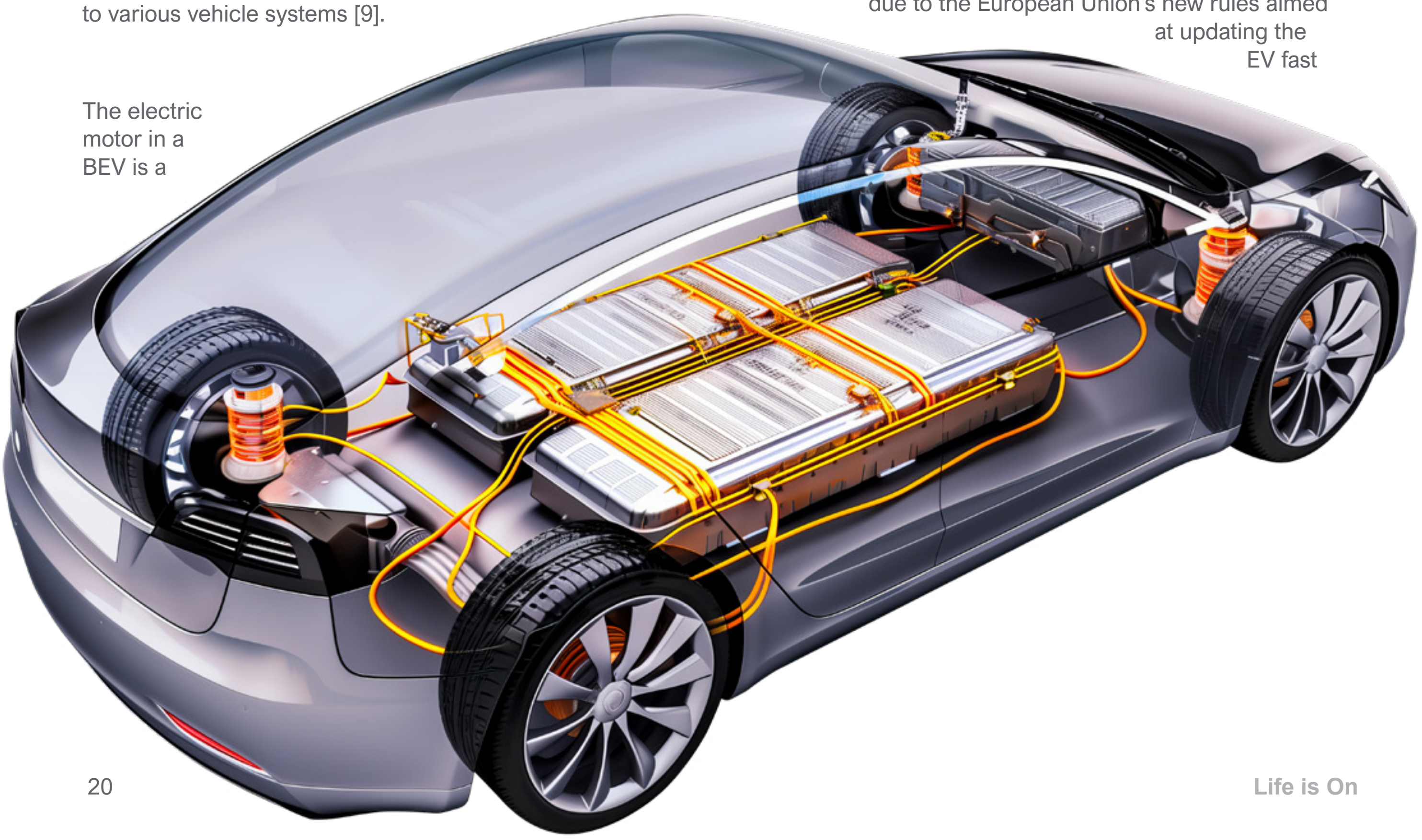
The electric motor in a BEV is a significant consumer of copper, potentially containing up to 23 kg of the metal [10]. Other copper-intensive components include the inverter, which converts DC power from the battery to AC power for the motor, and the charging system. The wiring harness in a BEV is particularly copper-intensive, as it must carry high currents between the battery, motor, and other electrical systems [11].

The exact amount of copper used in EVs can vary depending on the vehicle's size, type, and specific design. For instance, larger electric buses or trucks may contain even higher quantities of copper, with some estimates suggesting up to 369 kg in electric buses [12].

The increased use of copper in EVs is not limited to the vehicles themselves. The charging infrastructure required to support the growing EV fleet also relies heavily on copper, further driving demand for this critical metal in the transition to electric mobility.

Fast-charging stations, which are essential for long-distance travel and reducing charging times, are particularly copper-intensive due to their high-power requirements. The International Copper Association estimates that each EV charger needs an average of 0.7 kg of copper, while fast chargers can require up to 8 kg of copper each. Industry experts suggest that megawatt chargers used to power heavy-duty EV trucks may potentially use more than 10 kg of copper per unit [13].

The expansion of EV charging infrastructure is expected to drive substantial copper demand in the coming years. Some projections estimate that by 2032, a total of 71,000 tons of copper will be needed for EV charging stations in Europe alone, with the global figure reaching 314,000 tons. This significant increase in copper demand is partly due to the European Union's new rules aimed at updating the EV fast



charging network, which require charging facilities with a minimum output of 400 kW every 60 km along core Trans-European Transport Network corridors by 2026 [13].

According to the IEA Global EV Outlook 2023, under current policy settings, electric vehicles could account for 35% of global car sales by 2030. This projection aligns with the IEA's Stated Policies Scenario (STEPS), which reflects existing policies and firm objectives. However, in more ambitious scenarios, such as the NZE Scenario, the share of EV sales could reach up to 60% by 2030 [14].

The rapid growth of the EV market is expected to have profound implications for copper demand, more than power generation over the course of the energy transition. However, the IEA warns that there is a substantial gap between prospective supply and demand for copper, with anticipated mine supply from announced projects meeting only 70% of copper requirements by 2035 [8].

The increasing importance of copper in the energy transition is reflected in market projections. The IEA estimates that the combined market value of key energy transition minerals, including copper, could more than double to reach USD 770 billion by 2040 in the NZE Scenario, and along with the power generation, EV and EV charging stations, the grid infrastructure needed to deliver the electricity will also demand copper in and of itself.

## Grid Infrastructure

The transition to a clean energy system requires not just new generation sources and end-use technologies, but also a fundamental transformation of the electricity grid. This transformation is necessary to accommodate the intermittent nature of renewable energy sources and the changing patterns of electricity demand brought about by electrification.

Global electricity grids are likely needed to double in capacity by 2050 to meet the anticipated 86% increase in electricity demand. This expansion is estimated to require a significant annual investment, reaching over $600 Billion US by 2030 annually, accumulating to tens of trillions by 2050 [4]. Such a massive undertaking will inevitably drive-up copper demand, as it is a crucial component in various grid infrastructure elements.

High-voltage transmission lines, transformers, and substations are copper-intensive components of the electrical grid. The IEA estimates that annual copper demand for electricity grids is set to increase from 5 million tonnes (Mt) in 2020 to nearly 10 Mt by 2040 in their ambitious Sustainable Development Scenario (SDS) where the annual pace of grid expansion more than doubles in the period to 2040.

Other estimates provide a wider range of copper demand for electrical grids associated and show they could require between 27 and 81 Mt of copper cumulatively by 2050, depending on the energy scenario considered [15] and the management of the grid.

Smart grid technologies play a crucial role in managing the complexities of renewable-heavy power systems, and copper is a key component in their implementation. These advanced grid systems utilize extensive sensor networks and communication infrastructure, which, no surprise, heavily rely on copper for wiring and various components [4]. The superior conductivity and durability of copper make it an ideal material for the intricate web of connections required in smart grids.

The integration of smart grid technologies is essential for efficiently managing the intermittent nature of renewable energy sources. Copper's role in this context extends beyond simple conductivity; it enables the real-time monitoring and control systems that are fundamental to smart grid operations. These systems require a vast network of sensors and communication devices, all of which depend on copper's unique properties to function effectively [10].

Additionally, the demand for copper in smart grid applications is expected to grow significantly as countries worldwide accelerate their transition to renewable energy. While smart grid technologies are copper-intensive, they also contribute to overall system efficiency. By optimizing power distribution and reducing losses, smart grids can help mitigate some of the increased copper demand associated with the expansion of renewable energy capacity [16]. This efficiency gain, however, is unlikely to fully offset the growing copper requirements of the energy transition. Other technologies are part of the new energy systems that are part of the renewable energy infrastructure.

## Policy Implications and Market Dynamics

The clean energy transition is not occurring in isolation; it is being driven and shaped by policy decisions at local, national, and international levels. Government commitments to reduce greenhouse gas emissions, such as those made under the Paris Agreement, are translating into concrete policies that stimulate the deployment of clean energy technologies. These include renewable energy targets, EV incentives, energy efficiency standards, and carbon pricing mechanisms.

These policies have direct implications for copper demand. For example, the European Union's Green Deal, which aims to make Europe climate-neutral by 2050, is expected to drive significant investments in renewable energy, energy efficiency, and sustainable transport – all of which will require substantial amounts of copper.

The interplay between policy decisions, technological advancements, and market dynamics will ultimately determine the trajectory of copper demand in the clean energy transition. As the transition accelerates, it may create feedback loops that further drive demand. For instance, as renewable energy becomes more cost-competitive, it may be deployed at even faster rates than currently projected, potentially accelerating copper demand beyond current forecasts.

The clean energy transition represents a transformative force in shaping future copper demand. From renewable energy systems and electric vehicles to grid infrastructure and energy storage, copper plays a crucial role in enabling the technologies that will power a low-carbon future. As the world accelerates its efforts to combat climate change, the demand for copper is set to rise dramatically, presenting both opportunities and challenges for the copper industry and global sustainability efforts.

## II. Urbanization and Infrastructure Development

Urbanization and the associated infrastructure development represent another significant driver of future copper demand. As the global population continues to grow and concentrate in urban areas, the need for copper in construction, transportation systems, and urban technologies is set to increase substantially.

The United Nations projects that by 2050, 68% of the world's population will live in urban areas, up from 55% in 2018 [17]. This rapid urbanization, particularly in developing countries, necessitates massive investments in new buildings, transportation networks, and utility systems – all of which require significant amounts of copper.

The role of copper in construction and buildings represents a significant source of copper demand. As urbanization accelerates and the built environment evolves to meet new sustainability and technological standards, the importance of copper in construction is set to increase further but may also represent an opportunity to reduce demand.

Copper's versatility makes it a crucial material for various applications. Its primary uses include electrical wiring, plumbing systems, heating and cooling equipment, and architectural elements. The copper intensity of buildings varies widely depending on their size, type, and level of technological sophistication.

A typical single-family home is estimated to use about 439 pounds (199 kg) of copper. However, this figure can increase significantly for larger or more advanced buildings. For instance, a mid-size office building might require 2,000 to 3,000 pounds (907 to 1,361 kg) of copper, while a large hospital could use up to 200,000 pounds (90,700 kg) [18, 19].

A significant portion of copper used in buildings is for electrical systems. Copper's excellent conductivity makes it the preferred material for wiring and cabling. In residential construction, which accounts for about two-thirds of the building construction market, electrical applications are a major use of copper. Additionally, as buildings become 'smarter' and more connected, the amount of copper required for wiring is likely to increase. Smart building technologies, such as advanced energy management systems, security systems, and building automation, all require extensive wiring networks. The global smart building market has been projected to grow at a CAGR of 10.5% from 2020 to 2025, suggesting a concurrent increase in copper demand for these applications [20, 21].

Plumbing is another major use of copper in buildings, accounting for approximately 34% of copper use in a typical single-family residential structure. Copper pipes are valued for their durability, corrosion resistance, and ability to withstand high pressures and temperatures. Moreover, copper's natural antimicrobial properties make it particularly suitable for potable water systems, contributing to better water quality and public health [22].

The trend towards green building design and construction is influencing copper demand in the sector. Copper's recyclability and long lifespan align well with sustainability goals. Copper plays a crucial role in many green building technologies, particularly in solar water heating systems. These systems, which are increasingly common in green buildings, rely heavily on copper for their collectors, absorber sheets, and tubing due to excellent thermal conductivity and durability [23].

Energy efficiency is a key focus of modern building design, and copper contributes significantly to this goal. High-efficiency HVAC systems, which often use copper in their heat exchangers and cooling coils, are becoming standard in new construction and renovations. The global HVAC systems market has been estimated to grow at a CAGR of 7.4% from 2024 to 2030, potentially driving increased copper demand in this application [24].

The rise of net-zero energy buildings presents another potential growth area for copper use in construction. These buildings, which produce as much energy as they consume over the course of a year, often rely on a combination of energy-efficient design, on-site renewable energy generation, and advanced energy management systems - all of which can be copper-intensive.

Renovation and retrofitting of existing buildings, another focus of global decarbonization, may also contribute significantly to copper demand in the construction sector. In many developed countries, a large proportion of the building stock is aging and in need of upgrades. Retrofitting older buildings with modern electrical systems, energy-efficient HVAC, and smart building technologies often involves substantial copper use. For example, the European Commission's Renovation Wave Strategy aims to at least double renovation rates in the next ten years, which could drive significant copper demand in the region.

In the context of urbanization, the trend towards taller buildings in city centers is another factor influencing copper demand. Skyscrapers and high-rise buildings generally require more copper per square meter than low-rise structures due to their more complex electrical, mechanical, and plumbing systems. As cities grow vertically to accommodate increasing urban populations, this could lead to higher copper intensity in construction.

The growing adoption of Building Information Modeling (BIM) and other digital technologies in construction may also indirectly influence copper demand. These technologies allow for more precise material planning and can potentially reduce waste in construction processes. However, they also enable more complex and sophisticated building designs, which could lead to increased copper use in advanced building systems.

While copper demand in construction is generally projected

to increase, efforts to improve material efficiency and the development of alternative materials could moderate this growth. For instance, aluminum is sometimes used as a substitute for copper in certain electrical applications where size and portability are not an issue.

The construction and building sector represent a major and growing source of copper demand. This demand is driven not only by the sheer volume of new construction associated with global urbanization but also by the evolving nature of buildings themselves. As buildings become larger, taller, smarter, and more energy-efficient, their copper intensity is likely to increase. However, buildings present a unique opportunity to reduce demand because the two primary uses are for electrical infrastructure, where aluminum may be considered as a substitute or partial substitute, and plumbing, where existing substitutes are readily available. Though not all urban infrastructure is immobile like buildings.

Alongside EVs, other urban transportation infrastructure is anticipated to be another major consumer of copper. Subway systems, for instance, use copper extensively in their power distribution systems, signaling equipment, and rolling stock. Electrically powered subway cars use an average of 2,300 pounds (approximately 1.04 tonnes) of copper each [25]. As cities worldwide expand their mass transit systems to accommodate growing populations and reduce carbon emissions, this will drive significant copper demand.

The development of smart cities represents a confluence of urbanization and technological advancement that is substantially boosting copper consumption. Smart city technologies, such as intelligent traffic management systems, smart street lighting, and municipal Wi-Fi networks, all rely heavily on copper for their communication and power infrastructures. In addition to advanced digital technologies, basic services also utilize copper in the urban environment.

Water infrastructure is another critical area where urbanization drives copper demand. As cities grow, they require expanded and upgraded water distribution and treatment systems. Copper pipes are often preferred in these applications due to their corrosion resistance and antimicrobial properties. The need for reliable water infrastructure is particularly acute in rapidly developing regions of Asia and Africa, where large-scale urbanization is ongoing.

The renovation and upgrading of aging infrastructure in developed countries also contribute to copper demand. Many Western cities are facing the need to replace century-old water pipes. These renovation projects often involve replacing older materials with copper.

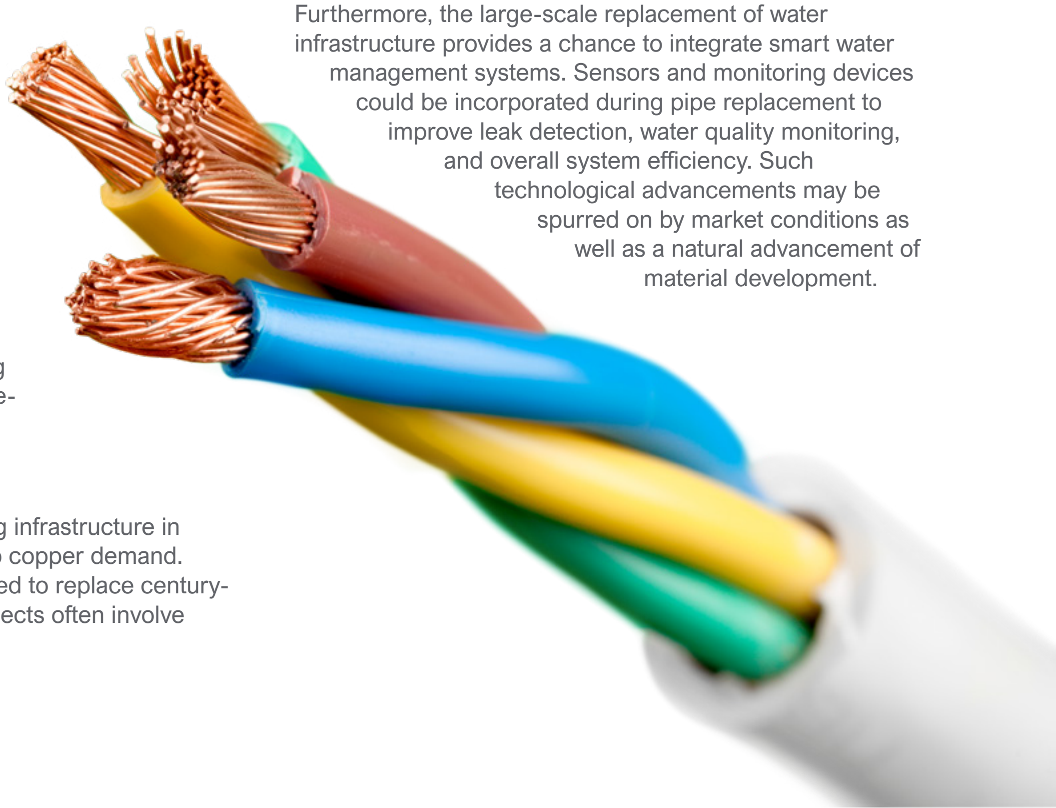
For example, in Fall 2024 the U.S. Environmental Protection Agency (EPA) has issued a landmark final rule requiring the replacement of all lead drinking water pipes across the nation within 10 years [26]. This ambitious initiative aims to eliminate a major source of lead exposure, particularly for children and disadvantaged communities. The rule, known as the Lead and Copper Rule Improvements (LCRI), mandates that water utilities identify and replace lead service lines, conduct more rigorous water testing, and improve communication with residents about lead risks and pipe replacement plans [27].

To support this effort, the EPA is providing $2.6 billion in new funding through the Bipartisan Infrastructure Law, with 49% of these funds earmarked for disadvantaged communities [28]. This builds upon the $15 billion allocated for lead pipe replacement under the infrastructure law. The EPA estimates that up to 9 million homes across the country still receive water through lead pipes, with many of these in lower-income areas and communities of color.

The implications of this rule for copper demand are significant. Copper tubing has emerged as the primary material for replacing lead service lines due to its durability, corrosion resistance, and antimicrobial properties. If the estimated 12 million lead and galvanized service lines in the U.S. were to be replaced, it would require approximately 180,000 tonnes of copper [29]. For comparison, this would represent about one-quarter of all the copper used globally for solar PV in 2022 but still a fraction of the total global demand of 24.8 Mt that year.

The lead pipe replacement initiative also presents an opportunity to innovate in water infrastructure. While copper is currently the preferred replacement material, research into new materials or technologies that offer similar benefits could emerge. This could include advanced composites or other suitable materials.

Furthermore, the large-scale replacement of water infrastructure provides a chance to integrate smart water management systems. Sensors and monitoring devices could be incorporated during pipe replacement to improve leak detection, water quality monitoring, and overall system efficiency. Such technological advancements may be spurred on by market conditions as well as a natural advancement of material development.



## III. Technological Advancements

Technological advancements across various sectors are set to play a crucial role in shaping future copper demand. As innovation continues to accelerate, new applications for copper are emerging, while existing uses are becoming more copper intensive.

The ongoing digital transformation is a key driver of copper demand in the technology sector. The expansion of data centers, cloud computing, and 5G networks all require significant amounts of copper. Data centers can use between 20 to 40 tonnes of copper per megawatt of power capacity. North American data centers consumed 197,000 tons of copper in 2020, with consumption projected to reach almost 300,000 tons by 2040 [30]. As global internet traffic continues to grow exponentially, driven by trends such as video streaming, online gaming, and the Internet of Things (IoT), the demand for data center capacity – and consequently, copper – is expected to rise.

The rollout of 5G networks represents a copper-intensive technological advancement. 5G infrastructure requires a significant amount of copper for antennas, cables, and other components, contributing to increased copper demand in the telecommunications sector [31]. As 5G becomes the standard for mobile communications globally, it will drive significant copper demand.

In the consumer electronics sector, the trend towards miniaturization and increased functionality is driving up the copper content of devices. While individual devices may be getting smaller, they often contain more complex circuitry, which requires more copper. Additionally, the proliferation of electronic devices in everyday life – from smartphones and tablets to smart home devices – is increasing the overall demand for copper in this sector.

Advancements in industrial automation and robotics are contributing to increased copper demand. While the exact copper content in industrial robots compared to traditional equipment varies, the automation of industries is expected to drive up copper demand. Recent estimates suggest the flourishing activity in sectors including automation will lead to at least 10 million metric tons of additional copper demand by 2030 [33].

The development of artificial intelligence (AI) and machine learning technologies is another area with implications for copper demand. These technologies require substantial computing power, driving the need for more data centers and high-performance computing hardware, all of which use copper extensively as noted above.

## Chapter Summary

The future demand for copper will be shaped by a complex interplay of factors, with the clean energy transition, urbanization and infrastructure development, and technological advancements serving as the primary drivers. These forces are not acting in isolation but are deeply interconnected, often reinforcing and accelerating each other's impact on copper demand.

The clean energy transition stands out as perhaps the most visible factor, with the potential to dramatically increase copper demand across multiple sectors. From renewable energy generation and electric vehicles to grid infrastructure and energy storage, copper is integral to the technologies that will power a low-carbon future. The pace and scale of this transition, influenced by policy decisions and technological progress, will be a key determinant of future copper demand. Of these, EVs represents the most critical due to its potential growth and subsequent significant impact on copper demand.

Urbanization and infrastructure development, particularly in developing economies, represent another major driver of copper demand, in particular buildings. The massive construction and infrastructure projects required to support growing urban populations will consume significant quantities of copper. Moreover, the trend towards smart cities and intelligent infrastructure is likely to increase the copper

intensity of urban development further. Yet, buildings remain the core copper sink and opportunity concerning the built environment. It represents a traditional and substantial portion of copper demand will continue to do so in the future. At the same time, some uses, such as building façade, may be avoided, and others, such as in-place electrical infrastructure and plumbing, have readily available substitutes.

Importantly, though from a sheer volume perspective not as demanding, technological advancements across various sectors are also set to boost copper demand. The digital transformation, encompassing developments such as 5G networks, data centers, and the Internet of Things, is creating new applications for copper and increasing its use in existing ones. Industrial automation, artificial intelligence, and advancements in consumer electronics all point towards a future where copper plays an even more crucial role in our technological infrastructure.

These drivers of demand are set against a backdrop of challenges in copper supply, including declining ore grades, environmental concerns, and geopolitical risks. This tension between rapidly growing demand and constrained supply underscores the critical importance of sustainable practices, including improved recycling and resource efficiency, in the copper industry.

It is clear copper will play a vital role in shaping our world. Its unique properties make it indispensable for the technologies and infrastructure that will define the 21st century. However, meeting this demand sustainably will require innovative approaches to production, use, and recycling of this essential metal [33]. The decisions made by policymakers, industry leaders, and technologists in the coming years will be crucial in determining whether copper can fulfill its potential as a key enabler of a sustainable, high-tech future.

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# 3
# Copper Dynamics

# Modeling Copper Dynamics

Forecasting copper demand is a critical endeavor for policymakers, industry leaders, and researchers as they navigate the complexities of resource management in an increasingly copper-intensive global economy. The importance of such projections has grown significantly in recent years, driven by the metal's crucial role in the clean energy transition, urbanization, and technological advancement. Accurate demand modeling not only informs strategic decision-making in the mining and manufacturing sectors but also guides policy formulation aimed at ensuring sustainable resource use and mitigating potential supply challenges.

The methodology employed in copper demand forecasting has evolved considerably over the past decades, reflecting the growing sophistication of modeling techniques and the availability of more granular data. While top-down approaches using historical trends and macroeconomic indicators have been widely used, bottom-up methods that analyze demand at the level of individual applications and technologies have gained prominence for their ability to capture technological shifts and sector-specific dynamics [1-5].

These bottom-up approaches are particularly valuable in the context of rapid technological change, where traditional extrapolation methods may fail to capture emerging trends. For instance, the accelerating adoption of electric vehicles and renewable energy technologies introduces new patterns of copper use that may not be evident in historical data. By disaggregating demand into specific end-use categories and incorporating technological parameters, bottom-up models can provide nuance and potentially reveal long-term insights that would otherwise not be possible.

Nonetheless, the complexity of global copper flows and the interconnectedness of various economic sectors present significant challenges to demand modeling. Factors such as material substitution, efficiency improvements, and the development of circular economy practices can have profound impacts on future demand trajectories. The long lifespan of many copper-containing products means that today's consumption patterns will influence recycling potential and secondary supply for decades to come.

The present study builds upon copper demand modeling while incorporating the latest data and methodological advances. By employing a bottom-up stock dynamics model across multiple energy transition scenarios, we aim to provide a nuanced view of potential copper demand trajectories to 2050. This approach not only allows for the exploration of sector-specific trends but also facilitates the examination of critical issues such as the impact of substitution in traditionally copper-intensive sectors like construction, which we notably explore.

As our projections and findings are presented, it is important to recognize that while such research offers valuable insights, they are inherently subject to uncertainty. The interplay of technological innovation, policy decisions, and market forces can lead to outcomes that deviate from even the most carefully constructed models. The value in our demand forecasting is as an indispensable tool for informing long-term strategy and policy.

## I. Methodology

### Copper Demand Projections

To project future copper demand, this study employs a bottom-up stock dynamics model adapted from the methodology developed by Schipper et al. [6]. This approach allows for a detailed examination of copper demand across various end-use sectors while incorporating technological changes and market dynamics.

The model disaggregates into six main categories: building construction, infrastructure, industrial durables, transportation, consumer durables, and commercial durables. Each category is further divided into subcategories to capture specific applications and technologies and their respective material stock dynamics. For instance, the transportation sector includes cars, trains, aircraft, vessels, and heavy-duty vehicles, with further refinement into internal combustion engines (ICE) and EV's for land transport. Table 1 lists the categories and subcategories.

The fundamental principle of the stock dynamics model is that copper demand is driven by two factors: the growth and decline of in-use stock and the replacement of end-of-life products. The general equation for calculating copper demand in a given year is:

$$D_a = \sum(N_{i_a} - N_{i_{a-1}}) + (\frac{N_{i_{a-1}}}{r_i * m_i})$$

Where $D_a$ is the copper demand in year a, $N_{i_a}$ is the stock of application i in year a, mi is the copper content per unit of application i, and $r_i$ is the average residence time of copper in application i.

For each end-use category, the model calculates both the inflow of new copper (driven by stock growth and replacement) and the outflow of end-of-life copper as well as evolving copper intensity improvements. The outflow calculation is based on the average lifespan of copper in each application, providing insights into potential secondary copper supply from recycling.

The model also incorporates the concept of stock saturation, recognizing that the per capita ownership of certain copper-containing products may plateau as markets mature. This is particularly relevant for consumer durables and some infrastructure categories. For instance, the model assumes that after a household obtains certain products, the demand will be met until the product needs replacement.

A key enhancement in this study is the update of copper intensity factors for emerging technologies, particularly in the electric vehicle and renewable energy sectors. For example, the copper content of electric vehicles has been revised to reflect the latest designs and manufacturing practices. Similarly, the copper intensity of renewable energy technologies such as solar photovoltaics and wind turbines has been updated to account for recent technological advancements.

The model's flexibility allows for the analysis of specific subsectors, such as transmission and distribution infrastructure, which are critical in the context of grid modernization and renewable energy integration. Furthermore, the model enables the exploration of substitution effects, particularly in sectors like construction that have received less attention in previous copper demand studies.

Aside from power generation, future stock levels were modeled by incorporating projections of socioeconomic indicators such as population growth, urbanization rates, and GDP per capita. These were based on the United Nations projections [7].

For power generation, projections from previous energy scenarios from Schneider Electric (SE) and the International Energy Agency (IEA) were modeled: Back to 2050 and New Normal from SE and IEA's Announced Pledges Scenario (APS) and Net Zero Emissions by 2050 Scenario (NZE) [8, 9]. These scenarios differ in the amount and rate of clean energy technology, notably for power generation, which served as the differentiating factor for the projections. Both Back to 2050 and New Normal are demand based scenario's and comparable to the consumption data in IEA's scenario's. Both Back to 2050 and NZE are normative whereas New Normal and APS are more indicative of the natural unfolding of the energy transition.

To account for the differences between demand-side and supply-side perspectives of the energy transition, the study compares results from Schneider Electric's scenarios (Back to 2050 and New Normal) with both the consumption and production projections from IEA's scenarios (APS and NZE). This cross-examination approach provides a comprehensive view of potential copper demand across a spectrum of energy transition pathways.

While the model provides detailed projections, it's important to note its limitations. The accuracy of long-term projections depends on the reliability of data input and assumptions about technological development, economic growth, and policy changes. Additionally, the model does not explicitly account for price elasticity of demand or potential supply constraints, which could influence future copper consumption patterns.

**Table 1** – **Categories and subcategories of copper containing goods.**

| Category | Subcategories | |
|---|---|---|
| Infrastructure | **Power Generation** | |
| | | Nuclear |
| | | Oil |
| | | Coal |
| | | Gas |
| | | Hydro |
| | | Biomass |
| | | Wind |
| | | Solar |
| | **Transmission and Distribution** | |
| | | Agriculture |
| | | Households |
| | | Services |
| | | Industry |
| | | Transportation |
| | **Rail Systems** | |
| | | Conventional |
| | | High Speed |
| | **Traffic and Street Lights** | |
| | | Traffic |
| | | Street |
| Building and Construction | **Residential** | |
| | **Service** | |
| Industrial durables | **Agriculture** | |
| | **Industrial** | |
| Transportation | **Motorcycles** | |
| | | ICE Motorcycles |
| | | e-Motorcycles |
| | **Heavy Duty Vehicles** | |
| | | ICE HDV |
| | | EV HDV |
| | **Light Duty Vehicles** | |
| | | ICE Cars |
| | | EV Cars |
| | **Buses** | |
| | | ICE Buses |
| | | E-Buses |
| | **Aircraft** | |
| | **Trains** | |
| | **Vessels** | |
| Durable Goods | **Consumer Durables** | |
| | | TVs |
| | | Refrigerators |
| | | Air Conditioners |
| | | Washing Machines |
| | | Computers |
| | | Heat Pumps |
| | | Microwaves |
| | | Home Devises |
| | | Mobile Devices |
| | | Landline |
| | | Others |
| | **Commercial Durables** | |

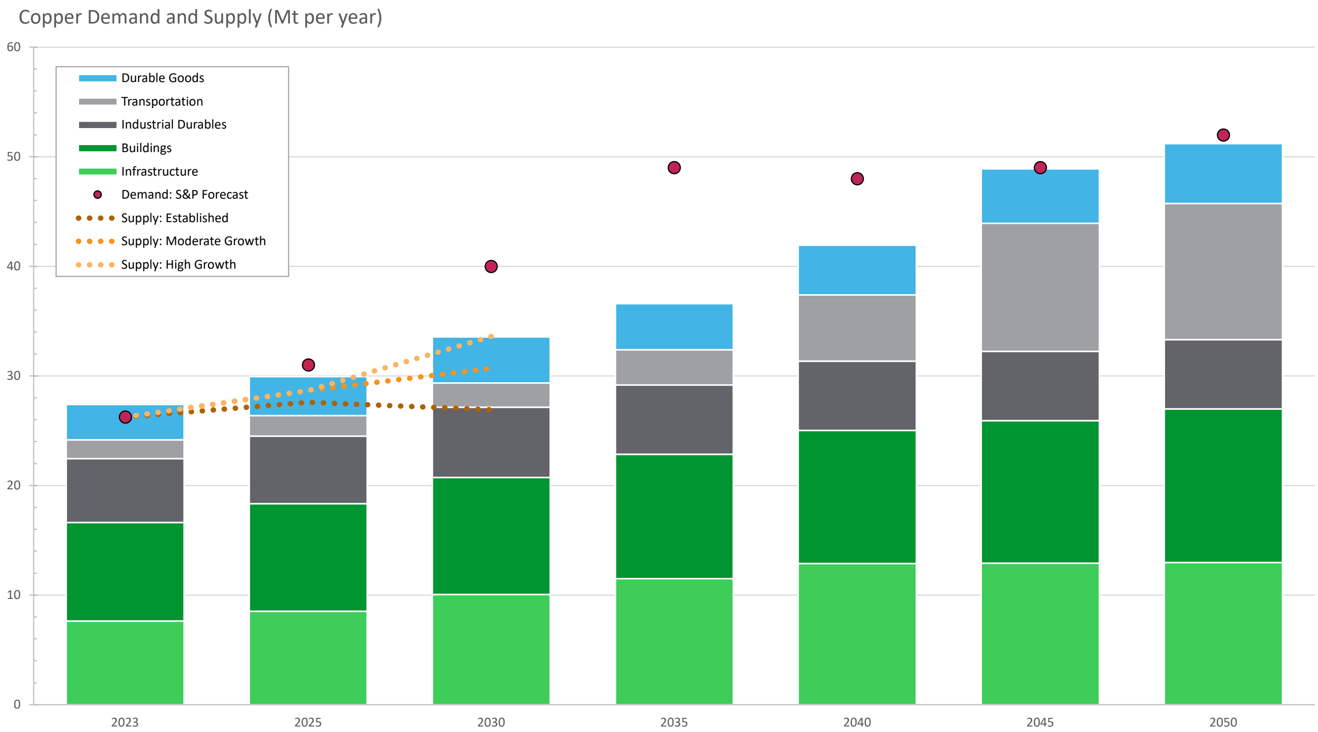



**Figure 1 – Supply and demand projections for copper. The supply accounts for both primary and secondary production. Demand is based on the New Normal scenario for power generation. Compared to S&P numbers, the demand converges to a few Mt over 50 by 2050. However, between 2025 and 2035 S&P shows a high demand largely due to EV's whereas the model employed in this study accounts for that growth in demand later, from 2035 to 2045.**

### Copper Supply Projections

To project total copper supply, we employed a multi-scenario approach based on primary and secondary production estimates. Here, we emphasize the importance of considering both mined output and recycled copper in supply forecasts. We exclude from the outlook processing and supply chain dynamics.

Our scenario utilizes mined output projections from IEA's Base Case as a foundation, reflecting mining from operating and announced projects [10]. To account for secondary supply, we applied a 15% increase to IEA's projection for the Established Supply scenario, reflecting a set base and conservative approach of recycled copper to total supply.

In addition to the Established Supply, we projected two growth scenarios to capture potential supply expansions. Both scenarios expand supply from Established Production by 500,000 tons per year from 2023 to 2025. From 2025, the increased supply scenarios model:

*Moderate Growth: An annual increase of 600,000 tonnes*

*High Growth: An annual increase of 1,200,000 tonnes*

Due to the inherent uncertainties in long-term forecasts and the dynamic nature of the copper market, we limited our supply projections to 2030. This aligns with the timeframe used in recent studies that highlights the challenges in predicting supply beyond this point [11].

It is important to note that this methodology simplifies complex market dynamics. Factors such as geopolitical risks, technological advancements, and environmental regulations can significantly impact supply and are not fully captured in these projections [10]. Additionally, the fixed annual growth rates in our scenarios may not accurately reflect the non-linear nature of supply expansions in the copper industry. Future research could enhance these projections by incorporating more granular data on individual mining projects, regional variations in recycling rates, and potential disruptive technologies in copper production and recycling.

## II. Results

Our analysis of copper demand to 2050 and supply projections to 2030 reveal several key findings with significant implications for the global energy transition and sustainable development. For reference and comparison, we have selectively included comparisons to S&P's impactful study The Future of Copper [5].

By 2050, all scenario's result in a copper demand between 50 and 52 Mt per year. This long-term outlook is not unique and converges with S&P's study as well as others in the literature. It provides credence to the notion the world will need to 'double copper supply by 2050' to keep pace, approximately going from 25 to 50 Mt per year. Figure 1 shows the supply scenarios in comparison with the demand projections from the New Normal scenario as well

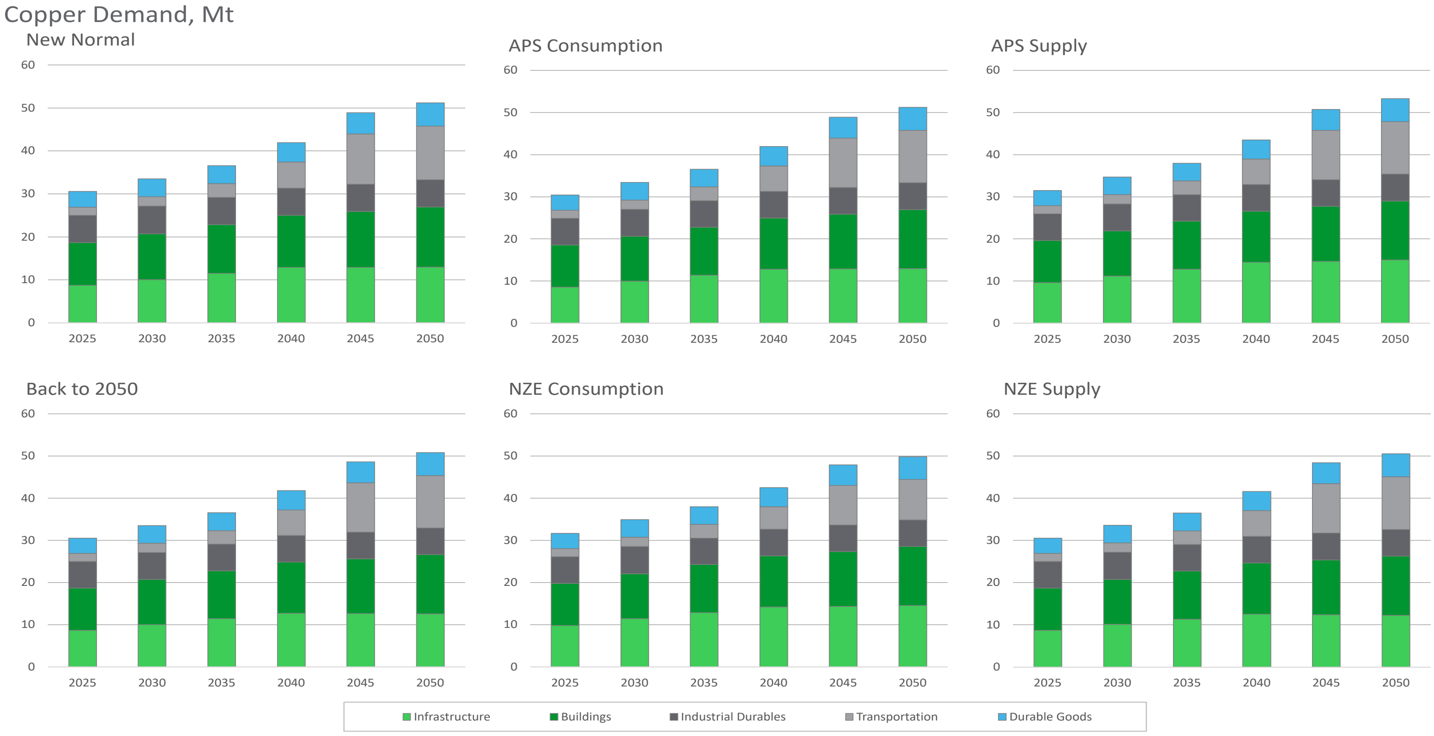



**Figure 2** – **Copper demand with power generation as only variable. The projected global copper demand from 2020 to 2050 was evaluated under four scenarios: Back to 2050, New Normal, IEA Announced Pledges Scenario (APS) and IEA Net Zero Emissions by 2050 Scenario (NZE). All scenarios indicate substantial growth in copper demand, with IEA variations based on supply or consumption perspective of the relative scenario.**

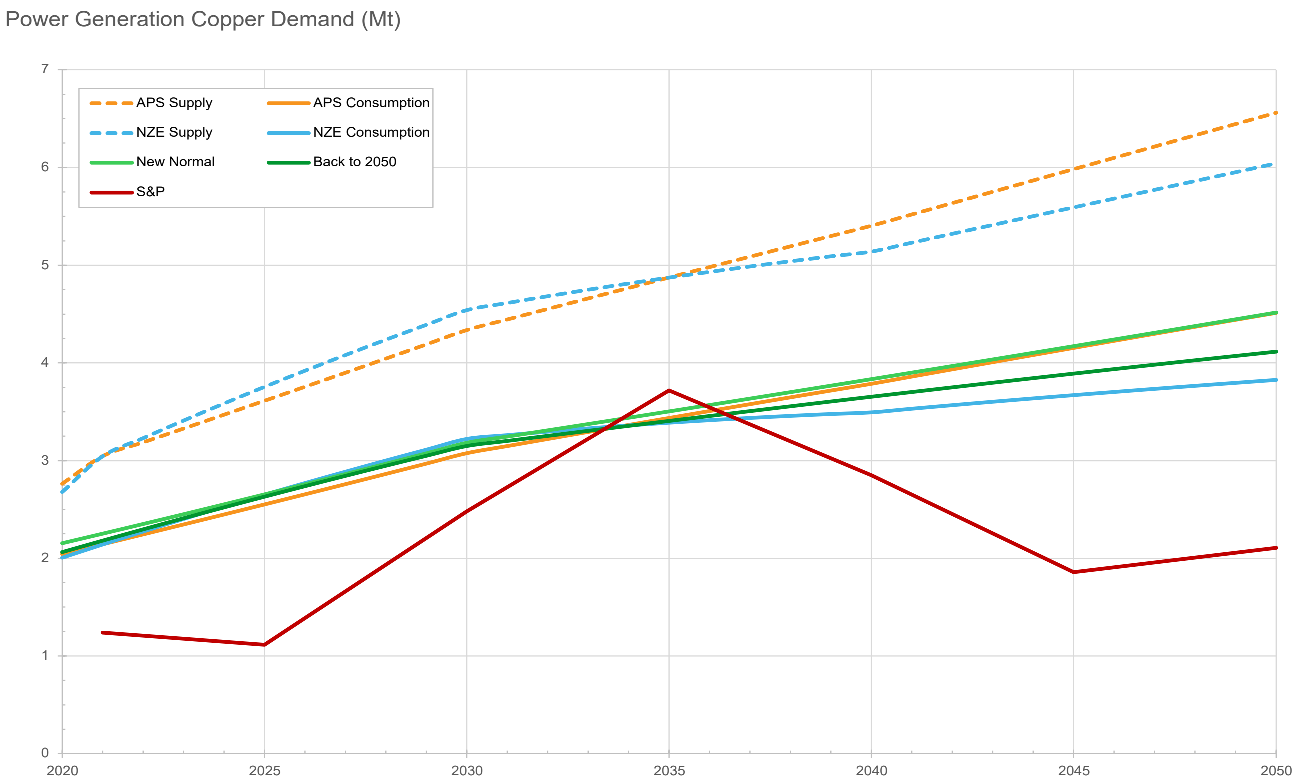
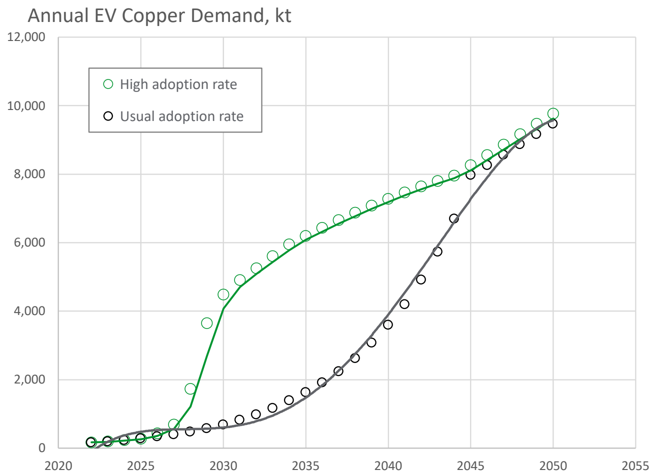



**Figure 3** – **Annual copper demand projections for power generation from 2020 to 2050 across scenarios. IEA's supply scenarios are larger than the demand based scenarios because they account for energy losses and need to overbuild whereas the consumption results do not. New Normal and Back to 2050 are demand based scenarios and similar in approach to IEAs consumption scenarios. The graph illustrates the relatively modest differences in copper demand for power generation between scenarios despite varying levels of renewable energy deployment. Because of the similarities in the consumption scenarios, the results are interpreted to indicate the actual deployment of various power generation mixes would result in the range between APS supply and NZE supply. S&P values from their respected study are provided for additional comparison.**



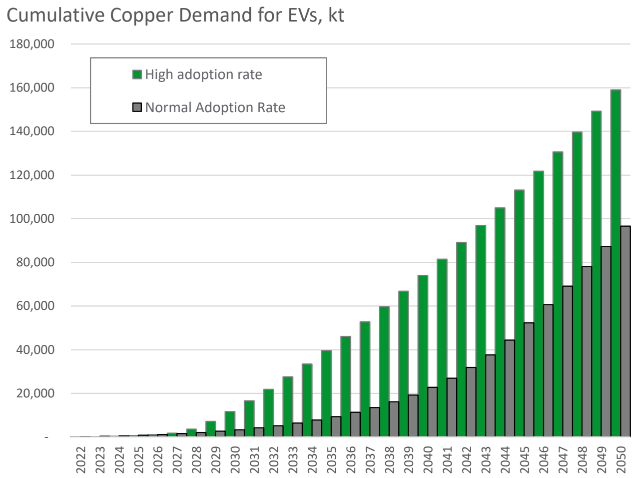




**Figure 4 – EV Copper demand for two adoption rate scenarios, high and normal. Their impact is shown in annual (left) and cumulative (right) demand. The graphs demonstrate the potential for significant increases in the amount of copper needed for transportation with the time frame and rate of penetration being critical factors.**

as S&P's numbers. The New Normal scenario represents a continuation of current trends without additional policy interventions. The graph demonstrates the relative contributions of each sector to overall copper demand growth.

After 2025 and by 2030, supply struggles to keep pace with demand, with High Growth maintaining a balance but the range between Established Supply and the optimistic growth scenario is below demand outlook.

The buildings sector remains the largest consumer of copper throughout the projection period, accounting for 28% of total demand in 2050. The transportation sector, which includes electric vehicles, shows significant growth from 11% in 2025 to 24% in 2050. From 2035 to 2045, a large increase in demand occurs due to the wide adoption of EVs over internal combustion engines. Interestingly, the transportation impact is similar to S&P's projections aside from the time frame. S&P models the electrification of transportation earlier, from 2025 to 2035. The comparative analysis further establishes the understanding that when/if the widescale adoption of EV occurs, the copper demand will be significant, and the category grow to be as big as other, traditional categories in buildings and infrastructure. The demand for power generation is also significant but less so than EVs when considering clean technologies.

All scenarios show a significant upward trend in copper demand, with projections ranging from approximately 30 million tonnes per year in 2025 to over 50 million tonnes per year by 2050. Figure 2 shows the similarities between the scenarios. Because the only variation between scenarios was power generation, the only differences seen in Figure 2 is that of infrastructure and analyzed deeper in Figure 3. The consumption results from IEAs scenarios represent the energy that is consumed and analogous to the demand scenarios from SE in New Normal and Back to 2050. However, losses in the energy system will necessarily mean the infrastructure needed to meet the demand will need to be greater than the consumption.

Therefore, we modeled and presented the supply numbers from IEA for the relative scenarios.

Our results indicate that the differences in copper demand between scenarios are less pronounced than might be expected, particularly in the near term. Up to 2035, the copper demand trajectories for all scenarios remain within a range of 2 million tonnes of each other. This suggests that regardless of the energy pathway being taken, a substantial increase in copper supply will be necessary to meet growing demand of energy in the coming decade.

Our analysis of the power generation sector yields particularly intriguing results. Figure 4 compares copper demand for power generation across all modeled scenarios.

Notably, the differences in copper demand for power generation between scenarios are relatively small, with all projections falling within a range of 0.8 million tonnes by 2050. The Back to 2050 scenario projects the lowest demand at 3.2 million tonnes, while the NZE scenario projects the highest at 4.0 million tonnes. Because of their similarity and fact they are built on power demand rather than supply, the APS and NZE consumption results are more indicative of how much cooper is needed. These estimates are similarly within 0.8 Mt/year of each but require between 6 and 6.6 Mt/year of copper.

## EVs

As noted, the results highlight the critical role of electric vehicles (EVs) in shaping future copper demand. With the understanding the rate of adoption of EVs is a key driver for copper demand, we modeled two scenarios in which the unit per capita is 0.18 by 2050 but achieve that under different adoption rates. The unit per capita number was chosen to reflect the internal combustion engine unit per capita for 2022; essentially, we conceptually model a target future in which every ICE vehicle today is an EV in 2050 and vice versa. Figure 4 illustrates two potential trajectories

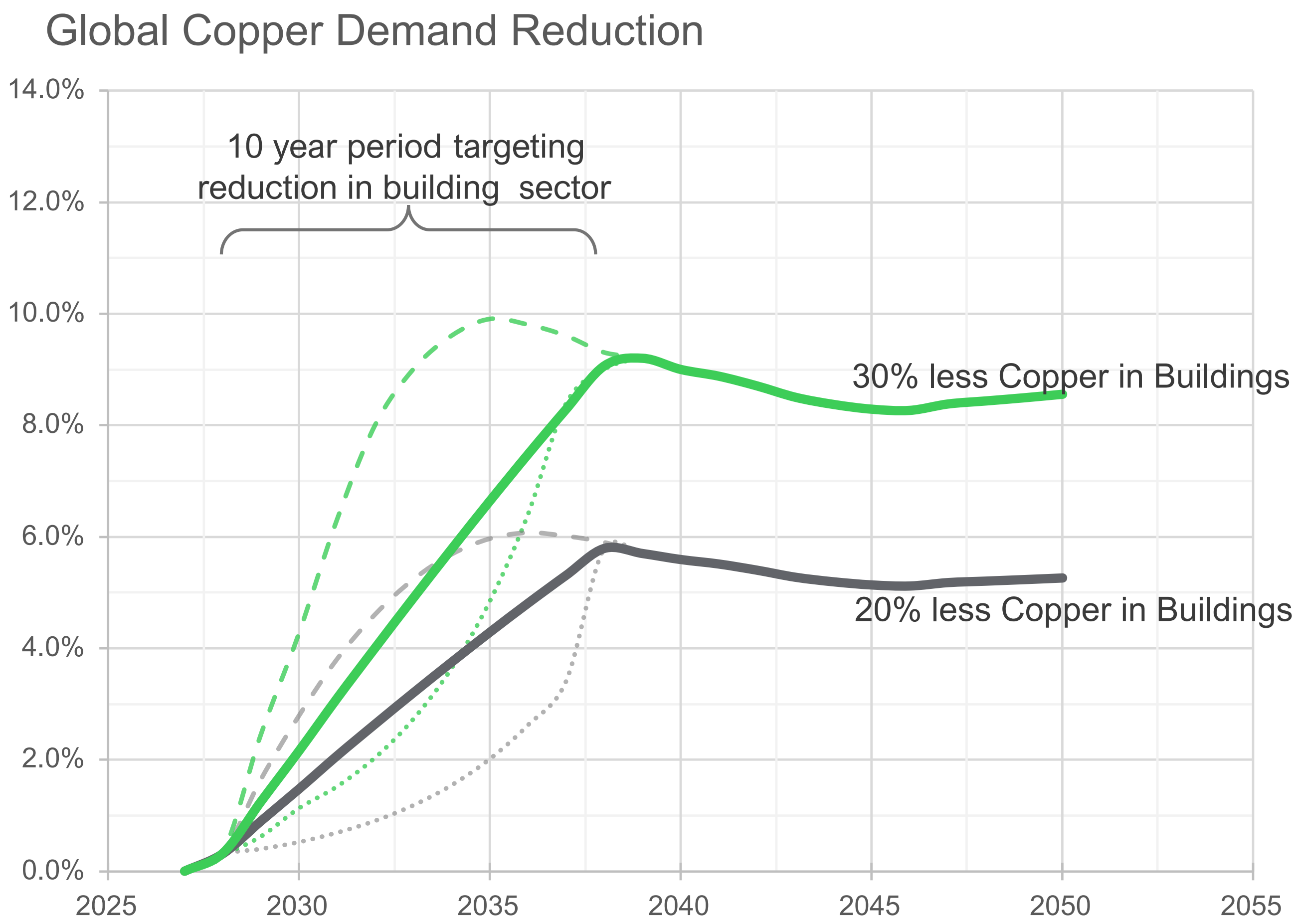



**Figure 5 – Copper demand mitigation potential from buildings. The figure demonstrates the effect of reducing copper intensity in buildings by 20% and 30% over a ten-year period starting in 2026 on global copper demand. The potential reduction is significant and an intriguing analysis because of known solutions of alternative materials and efficiency measures possible in the construction sector.**

and their corresponding impact on cumulative copper demand.

The scenario for EV's results in a cumulative copper demand between 96 Mt to 160 Mt by 2050. This represents a range of 64 Mt of copper needed for EVs and dependent on the penetration rate. Annually, the demand begins to converge with 9.4 Mt/year for normal adoption and 9.7 Mt/year for high adoption rates. However, the range between the two adoption rates is critical, with a difference of over 4 Mt/year in 2030 implying the annual demand for copper can potentially account from around 1% to 13% of the global demand solely due to EVs.

## Buildings

Another crucial finding of our analysis relates to the potential for demand reduction in the construction sector. Figure 5 illustrates the impact of reducing copper intensity in buildings by 20% and 30% over a ten-year period starting in 2026.

A 20% reduction in copper use in buildings could decrease total annual global copper demand by 5.4% by 2050, while a 30% reduction could lead to a decrease of 8.1% relative to the New Normal results. The importance of buildings relative to copper, especially towards demand reduction, has largely been understudied in relation to clean energy technologies. However, because alternatives are readily available, standing installation, and potential for regulations to impact the sector, it is a critical consideration. Mitigation is discussed in the next chapter.

## Transmission and Distribution

Lastly, our analysis of copper demand for transmission and distribution (T&D) infrastructure reveals a range of potential outcomes depending on the degree of grid centralization or decentralization. Figure 6 presents copper demand projections for T&D across various scenarios.

The projections for T&D copper demand in 2050 range from 7.3 Mt/year to 12.7 Mt/year when extrapolating the IEA NZE numbers which were taken directly from their outlooks and not the modeling in this study. Overall, results from IEA, S&P, and the baseline of this study are within 2.5 Mt/year of each other until 2040. However, projections

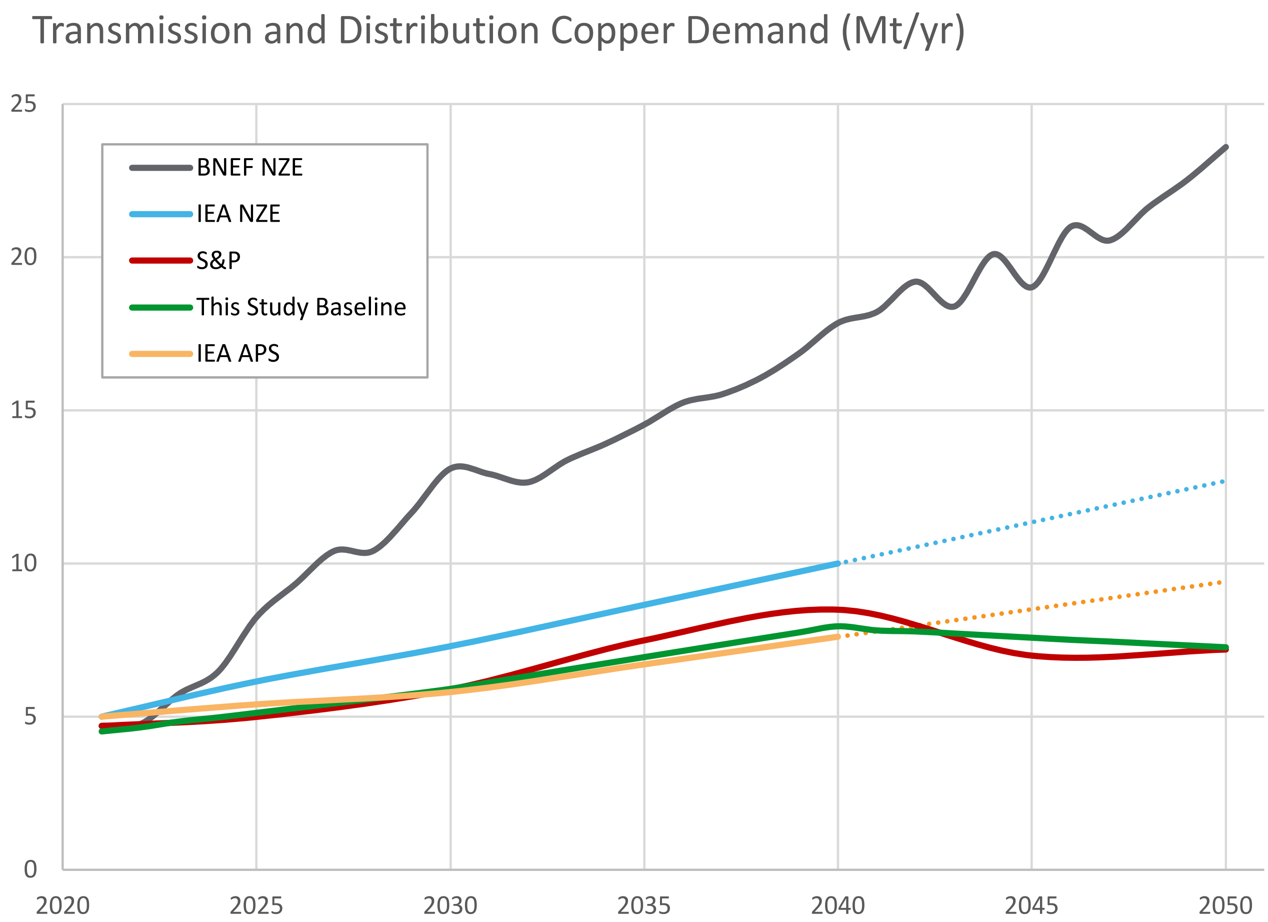



**Figure 6** – **Transmission and Distribution demand projections. The green line represents the modeling for this study and all other results come directly from the respective studies listed from BNEF, IEA, and S&P. The graph illustrates the range of potential outcomes based on different assumptions about grid centralization and renewable energy integration, representing a significant uncertainty about future copper demand. Dotted lines for IEA scenarios represent a linear extrapolation of their published projections.**

from Bloomberg New Energy Finance (BNEF) [12] are also presented for context, highlighting the significant uncertainty in this sector. Drivers such as new infrastructure vs upgrading vs decentralization will determine the actual copper demand which may be in the range presented in Figure 6.

## III. Discussion

Projections of copper demand and supply through 2050 provide a key insights on the role of buildings, EV's, and power generation in the complex picture facing the copper market. These findings have significant implications for policymakers, industry stakeholders, and researchers, and warrant consideration. The relative similarities in copper demand for power generation across all scenarios leads to a refined understanding of 'clean technology' demand for copper. Decoupling EV's from renewable energy generation demonstrates how the transportation sector is, by far, the largest component of the 'clean technology' appetite for copper.

In the same vein, the ranges provided for copper demand across EV adoption rates, less use in buildings, and uncertainty for transmission and distribution point to a nuanced understanding of the dynamics of copper. These ranges and relative timeframes provide more value than the absolute numbers output from the model which, as are all outlooks, imperfect.

Overall, and as expected, the results project an increase in global copper demand across all scenarios, in agreement with a concert of other copper forecasts over the past several years. The consistency of this upward trend, regardless of the specific pathway taken, underscores the critical role that copper will play in shaping our future energy systems and infrastructure. This growth in demand is not solely driven by the transition to clean energy technologies, as one might initially assume. Rather, it reflects a broader trend of increasing copper intensity across multiple sectors of the global economy.

The similarity in demand trajectories across different scenarios up to 2035 is particularly noteworthy. This convergence suggests that in the near to medium term, the copper market will face significant pressure regardless of the pace of the energy transition. This finding has important implications for supply chain planning and investment decisions. It indicates that efforts to increase copper production and improve recycling rates will be crucial in the coming decade, irrespective of the specific policy choices made regarding climate change mitigation.

## Sectors

The sectoral breakdown of copper demand provides insights into the drivers of future demand growth. The continued dominance of traditional copper-intensive sectors such as construction puts into perspective the notion that the energy transition will be the primary driver of increased copper demand. Aside from EV's and the uncertainty around transmission and distribution, clean technologies, namely renewable energy, largely follow natural growth and demand for copper. While the evolution in copper demand for transportation is significant, it does not exceed the established building sector but instead grows to become a similar by 2050.

This finding has important implications for strategies to manage copper. It suggests that efforts to reduce copper intensity or find alternative materials should not focus solely on emerging technologies but should also target traditional applications.

### Buildings

Our analysis shows that even modest reductions in copper intensity in the building sector could have a substantial impact on overall copper demand. A 20% reduction in copper use in buildings could decrease total global copper demand by 5.4% by 2050, while a 30% reduction could lead to a decrease of 8.1%. These figures highlight the significant potential for demand management through improved efficiency and material substitution in this sector.

The potential for demand reduction in the construction sector is particularly relevant in the context of the broader sustainability challenges we face. Buildings are a major contributor to global carbon emissions and resource consumption. Reducing copper intensity in buildings could therefore have multiple benefits, contributing to both resource conservation and climate change mitigation through direct and indirect effects. Directly through improved material utilization and indirectly by copper demand reduction, freeing up the metal for clean technologies like EV's, renewable power, and transmission and distribution infrastructure to support electrification. This aligns with the principles of the circular economy, where the focus is on maximizing resource efficiency and minimizing waste.

### Power Generation

Our analysis of power generation yields some surprising

results. The relatively small differences in copper demand for power generation between scenarios, despite varying levels of renewable energy deployment, challenge some common assumptions about the resource implications of the energy transition. This finding suggests that while renewable energy technologies like wind and solar are indeed more copper-intensive than conventional power generation, their overall impact on copper demand may be moderated by factors such as improving efficiency and the gradual nature of the energy transition.

### EVs

The role of electric vehicles (EVs) in shaping future copper demand emerges as a critical factor in our analysis. The significant difference in cumulative copper demand between our linear and exponential EV growth scenarios underscores the potential for rapid technological adoption to dramatically impact resource requirements. This finding has important implications for both the copper industry and the automotive sector.

For the copper industry, it highlights the need for flexibility and responsiveness in production planning. The potential for rapid growth in EV adoption could lead to sudden and substantial increases in copper demand, requiring rapid scaling of production capacity. This aligns with the concerns raised about the challenges of scaling copper production sustainably [13].

For the automotive sector, our findings underscore the importance of considering resource availability and sustainability in technology development and deployment strategies. The copper intensity of EVs is significantly higher than that of conventional vehicles. While this supports the transition to low-carbon transportation, it also creates potential vulnerabilities in the supply chain. Efforts to reduce the copper intensity of EVs or develop alternative technologies could therefore be crucial for ensuring the long-term sustainability of the electric mobility transition.

### Transmission and Distribution

Copper demand for transmission and distribution (T&D) infrastructure reveals significant uncertainty in this sector. The wide range of projections for T&D copper demand from the model employed in this study compared to others projections from BNEF, underscores the complexity of future grid development and the potential impact of factors such as distributed energy resources and smart grid technologies. This uncertainty presents both challenges and opportunities for the copper industry and energy sector planners.

On one hand, the potential for high copper demand in T&D infrastructure highlights the critical role of copper in enabling the integration of renewable energy sources and the electrification of various sectors. On the other hand, the lower end of the demand projections suggests that there may be opportunities for demand reduction through innovative grid designs and technologies.

The implications of our findings extend beyond the copper industry and energy sector. They touch on broader issues of resource management, sustainable development, and global equity. Copper plays a crucial role in many aspects of modern life, from infrastructure to consumer electronics. Ensuring its availability and affordability is therefore not just an economic issue, but also a matter of social equity and development.

The projected increase in copper demand, particularly from developing regions, raises important questions about global resource distribution and access. As countries seek to develop their infrastructure and improve living standards, their demand for copper is likely to grow. However, if supply constraints lead to price increases, this could potentially hinder development efforts. The need for global cooperation and equitable approaches to resource management can provide opportunities for more resilient supply chains and business models [13].

Our findings also have significant implications for environmental sustainability. While copper is essential for many clean energy technologies, its production can have substantial environmental impacts, particularly water use and habitat disruption [13]. The projected increase in copper demand therefore presents a paradox: it is both necessary for the transition to a low-carbon economy and a potential source of environmental harm.

The role of policy in shaping future copper demand and supply cannot be overstated. Our analysis of different scenarios demonstrates how policy choices regarding climate change mitigation and energy systems can significantly influence long-term copper demand. This suggests that policymakers need to consider resource implications when designing climate and energy policies not only for the targeted sectors but adjacent ones that are intrinsically linked by material dependencies.

Furthermore, policies to promote recycling, material efficiency, and circular economy principles could play a crucial role in managing copper demand. Extended producer responsibility schemes and landfill bans on recyclable materials have been effective in increasing recycling rates in many countries. Expanding and strengthening such policies could help to increase the share of secondary copper in the global supply.

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# 4

# Demand Management

# Copper Demand Management

As global copper demand continues to rise, driven by the clean energy transition, urbanization, and technological advancements, it becomes increasingly crucial to develop and implement strategies for managing this demand sustainably. This section explores two key approaches to copper demand management: efficiency and substitution, and recycling and circular economy approaches. These strategies aim to balance the growing need for copper with the challenges of supply constraints and environmental concerns.

## I. Efficiency and Substitution

Improving the efficiency of copper use and exploring viable substitutes are critical strategies for managing copper demand. These approaches can help reduce the pressure on primary copper production and mitigate potential supply shortages without compromising the functionality and performance of copper-dependent technologies and infrastructure.

Efficiency in copper use can be achieved through various means, including improved product design, advanced manufacturing techniques, and the development of high-performance copper alloys. Substitution, on the other hand, involves replacing copper with alternative materials that can perform similar functions, often in specific applications where copper's unique properties are not fully utilized or essential.

### Construction and Buildings

Copper is a critical element in housing, supporting global economic growth and human development, and is commonly used for electrical wiring and plumbing systems in buildings. Considering the increasing demand for copper and the energy-intensive processes required for its extraction and processing, implementing strategies to reduce its use in the building sector is critical. Copper is extensively used in various aspects of building construction and operation [1-3]:

Electrical Wiring: Copper's high electrical conductivity makes it ideal for electrical wiring throughout buildings. It is used in power distribution, lighting, and wiring devices.

Plumbing: is used in plumbing for water distribution, heating, gas, and sprinkler systems, its corrosion resistance and durability make it a preferred material for water pipes

Building Components: utilized in roofs, gutters, flashing, and architectural decorations (façade)

HVAC Systems: used in air conditioning tubes and other components of heating, ventilation, and air conditioning (HVAC) systems

Lead service line replacement: an ideal solution for replacing lead service lines because of its natural corrosion resistance, long lifespan, and recyclability

To mitigate copper demand in buildings, material substitution and efficiency strategies can be implemented [2, 4-6]:

**1. Plastic Piping Systems**: One of the most significant substitutions in building construction has been the shift from copper to plastic pipes for plumbing applications. Polyethylene crosslinked (PEX) and polyvinyl chloride (PVC) pipes have gained substantial market share, particularly in residential construction. These materials offer several advantages over copper, including lower cost, easier installation, and resistance to freezing and bursting. PEX, in particular, has seen rapid adoption due to its flexibility, ease of installation, and resistance to freezing. A study by the Plastics Pipe Institute found that PEX installation can be up to 60% faster than copper pipe installation, leading to significant labor cost savings. In North America, plastic pipes now account for over 60% of residential water distribution applications. However, copper remains preferred in certain applications, particularly where high temperature resistance or antimicrobial properties are required.

**2. Composite Pipes:** For more demanding applications, reinforced plastic and polymer composite pipes are emerging as alternatives to copper. These materials, which can include additives like graphite and carbon fibers, offer improved stiffness and temperature resistance, making them suitable for applications such as hydronic heating and fire suppression systems. While these materials are gaining traction, they often require specialized engineering and may face challenges in meeting building codes for large-scale commercial applications.

**3. Aluminum Wiring**: The use of aluminum for electrical wiring in buildings has a complex history. While it gained popularity in the 1960s and 1970s due to lower costs, safety concerns led to a decline in its use. However, modern aluminum alloy conductors, specifically engineered to meet current safety standards, are once again being considered as a viable alternative to copper, particularly for larger gauge wires where the lower ampacity density of aluminum is less problematic. The adoption of aluminum wiring faces several barriers, including lingering safety perceptions, the need for special installation techniques, and limitations in building codes. However, as copper prices rise and aluminum alloys improve, there is growing interest in revisiting aluminum as a partial substitute for copper in building electrical systems.

**4. Efficient Wiring Design**: Improved building design and wiring layout can reduce the total amount of copper required without compromising functionality. This includes strategies such as centralized wiring systems, the use of structured cabling for data networks, and the implementation of smart building technologies that can optimize power distribution.


**5. Copper-Clad Aluminum**: In some applications, copper-clad aluminum conductors are being used as a compromise solution. These conductors feature an aluminum core with a thin copper outer layer, providing some of the benefits of copper (such as corrosion resistance and ease of termination) while reducing overall copper content.

**6. Alternative Antimicrobial Surfaces**: Copper's natural antimicrobial properties have led to its increased use in high-touch surfaces in buildings, particularly in healthcare settings. However, alternatives are emerging, including silver nanoparticle coatings and certain polymer materials that can provide similar antimicrobial effects without relying on copper.

**7. Efficient HVAC Systems:** While copper remains crucial in HVAC systems due to its thermal conductivity, more efficient system designs can reduce the overall copper content. This includes the use of microchannel heat exchangers, which can achieve the same heat transfer with less material, and the development of alternative refrigerants that may allow for smaller diameter tubing. Research is also ongoing into alternative materials for heat exchangers. Aluminum is already used in some HVAC applications, particularly in residential air conditioning units. While less conductive than copper, aluminum's lighter weight and lower cost make it attractive for certain uses.

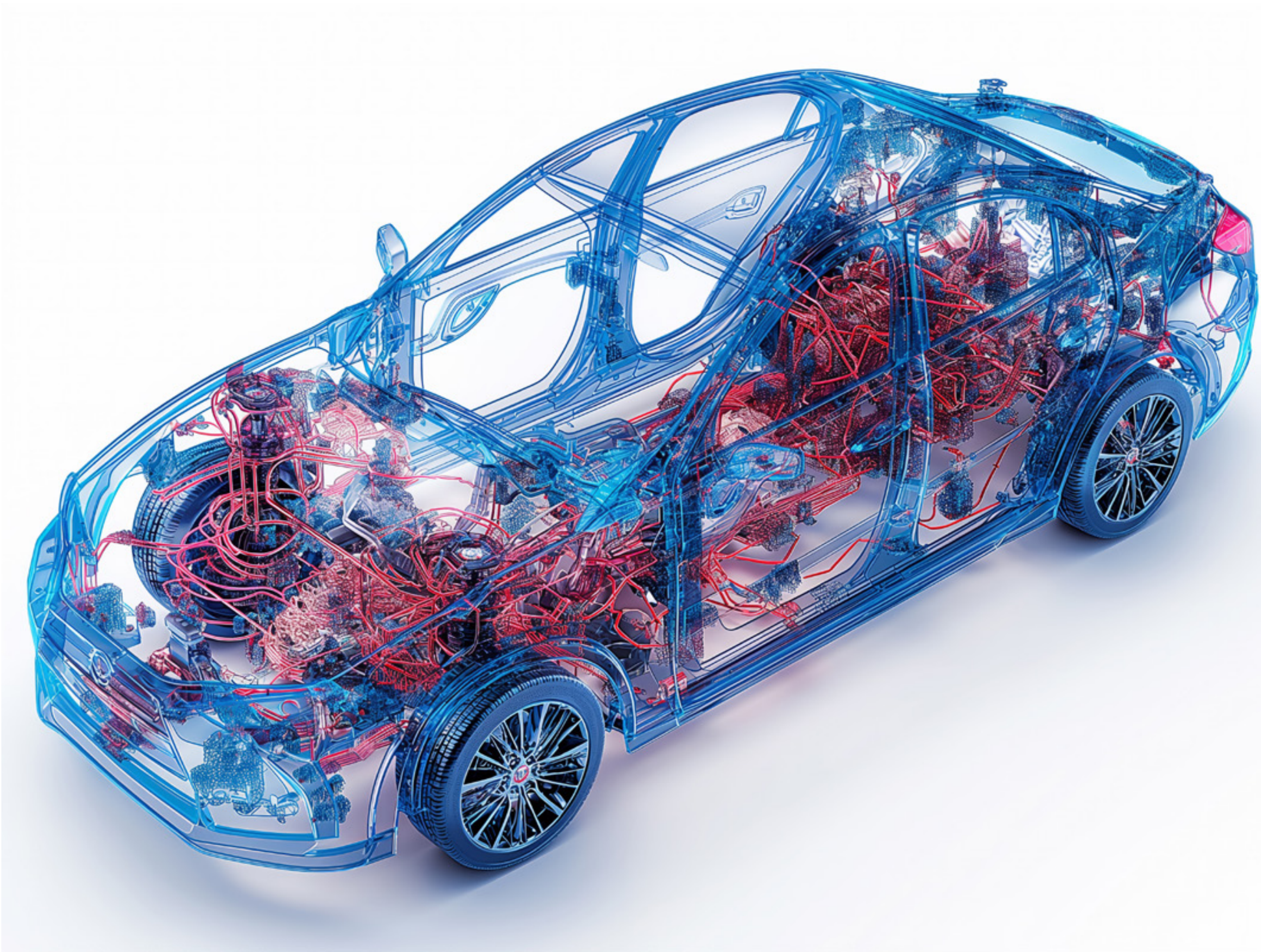
It's important to note that while these substitution and efficiency strategies can help manage copper demand in construction, they often come with trade-offs in terms of performance, longevity, or cost. The choice of materials and systems in building construction must balance these factors along with local building codes, climate considerations, and specific project requirements.

Furthermore, as buildings become more technologically advanced and energy-efficient, new applications for copper may emerge, potentially offsetting some of the reductions achieved through substitution and efficiency. For example, the growth of smart building systems and on-site renewable energy generation may increase copper demand in certain areas of building construction and operation.

## Transportation Sector

The shift towards electric vehicles (EVs) is driving up copper demand, but efficiency improvements and substitution strategies are being explored to mitigate this increase.

Aluminum is increasingly being used in EV wiring harnesses, which can account for up to 50% of a vehicle's copper content. While challenges remain in terms of corrosion resistance and connection reliability,



advancements in aluminum alloys and bonding techniques are making this substitution more viable.

In electric motors, which are a significant source of copper demand in EVs, research is ongoing into the use of aluminum windings. While aluminum windings typically result in slightly lower efficiency, design adaptations and cooling techniques can help minimize these losses. Some manufacturers claim to have already replaced significant amounts of copper in their EV motors with aluminum. The development of more efficient electric motor designs, such as axial flux motors, could also help reduce copper intensity in EVs without compromising performance.

### Industrial Equipment

Industrial applications, including motors, generators, and heat exchangers, offer several opportunities for efficiency improvements and substitution.

In electric motors and generators, die-cast aluminum rotors are gaining traction as a substitute for copper, particularly in smaller, lower-voltage applications. While this substitution may slightly increase energy losses, the cost savings can be significant.

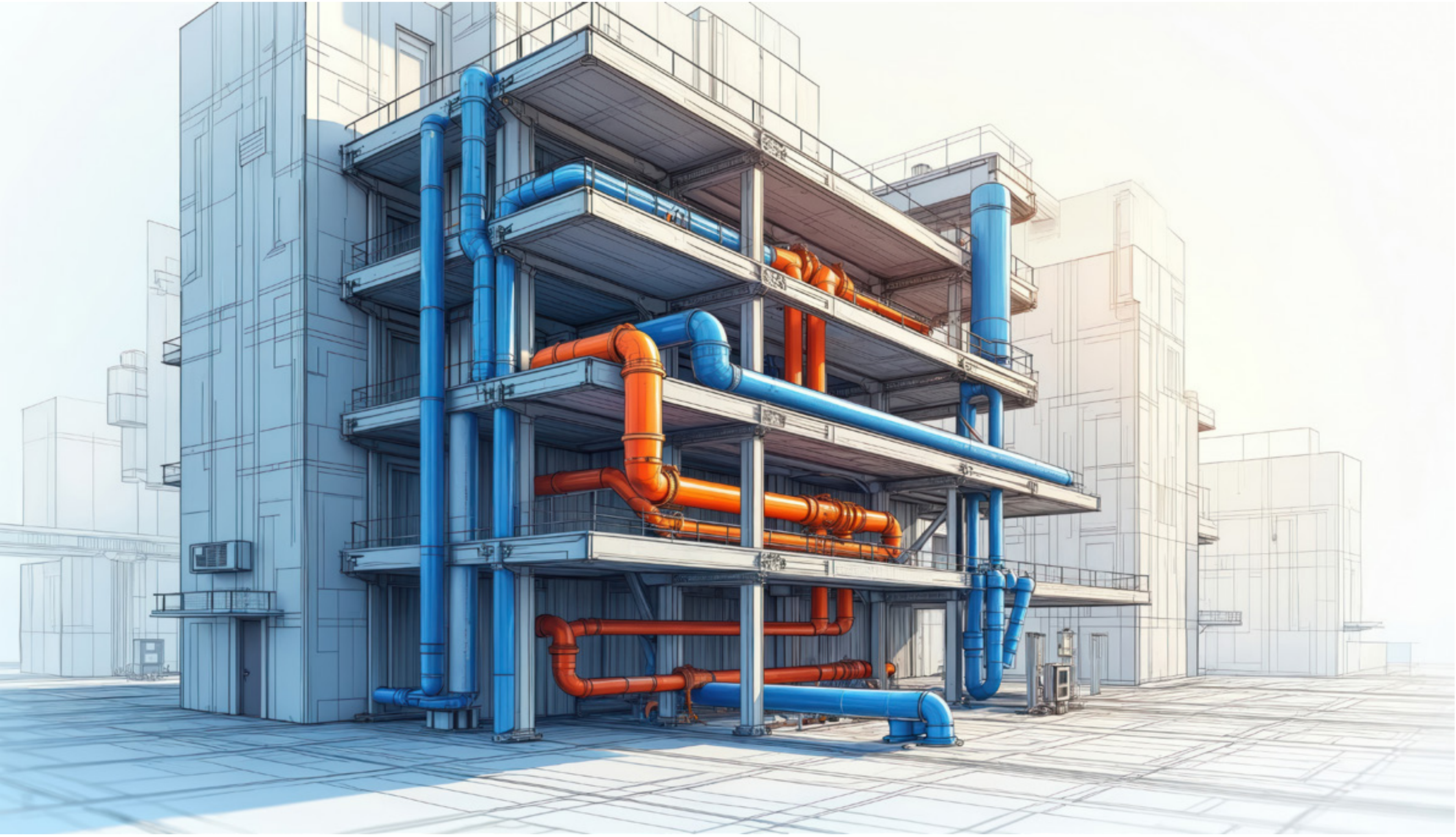
For heat exchangers, advances in polymer materials are enabling the development of plastic heat exchangers that can replace copper in certain applications, particularly in HVAC systems. While these plastic exchangers are currently limited to lower temperature and pressure applications, ongoing research may expand their range of use.

In large industrial condensers and heat exchangers, particularly in power plants and marine applications, titanium tubes are increasingly replacing copper-nickel alloys due to their superior corrosion resistance. While titanium is more expensive initially, its longer lifespan and reduced maintenance needs can make it cost-effective in the long run.

## II. Recycling and Circular Economy Approaches

### Buildings and Construction

The construction sector, being one of the largest consumers of copper, presents significant opportunities for implementing recycling and circular economy strategies. The long lifespan of buildings, often 50 years or more, means that a large stock of copper is locked up in the built environment, representing a valuable future resource.



## End-of-Life Recovery

At the end of a building's life, copper recovery rates can be exceptionally high, often exceeding 95% (International Copper Association 2017). This high recovery rate is facilitated by the relatively large quantities of copper used in buildings and the ease of separating it during demolition. Copper wiring, plumbing pipes, and roofing materials are typically easily identifiable and removable.

However, maximizing copper recovery from buildings necessitates careful planning and execution of demolition processes. Selective deconstruction, where buildings are carefully dismantled rather than demolished, can significantly improve the quality and quantity of recovered materials, including copper.

## Design for Disassembly and Recycling

Incorporating principles of design for disassembly into building construction can greatly facilitate future copper recovery. This approach involves designing building systems and components in ways that make them easy to separate and recycle at the end of the building's life. For copper, this might include:

1. Using standardized and easily separable electrical and plumbing systems.

2. Avoiding the permanent bonding of copper components to non-recyclable materials.

3. Providing clear labeling and documentation of copper-containing systems to aid future recycling efforts.

Building Information Modeling (BIM) technology can play a crucial role in this process by creating a digital twin of the building that includes detailed information about material composition and location. This information can be invaluable for future recycling efforts.

## On-Site Recycling and Reuse

During building renovations or partial demolitions, there are often opportunities for on-site recycling and reuse of copper components. For example, copper wiring or pipes removed during a renovation could potentially be reused in other parts of the building or in new construction on the same site. This approach reduces transportation needs and associated emissions while keeping valuable materials in use.

## Urban Mining and Material Banks

The concept of urban mining is particularly relevant to the construction sector. As cities grow and evolve, older buildings are often demolished to make way for new developments. These demolition sites can be viewed as urban mines, rich in copper and other valuable materials.

Some cities are taking this concept further by treating their building stock as a material bank. For instance, Amsterdam is piloting a "materials passport" system for buildings, which provides detailed information about the materials used in construction and their potential for future reuse or recycling. This approach facilitates more efficient recovery and reuse of materials, including copper, when buildings reach the end of their life.

## Circular Business Models

Innovative business models are emerging that support circular use of copper in construction. These include:

1. Leasing models for copper-intensive building systems, such as HVAC equipment, where the manufacturer retains ownership and responsibility for maintenance and end-of-life recovery.

2. Take-back programs for copper roofing and cladding materials, where manufacturers agree to recover and recycle their products at the end of their useful life.

3. Material exchanges that facilitate the reuse of salvaged copper components from demolished buildings in new construction projects.

## Challenges and Opportunities

Despite the high potential for copper recycling in the construction sector, several challenges are widely recognized:

1. Contamination: Copper recovered from buildings may be contaminated with other materials, such as paint or insulation, which can complicate recycling processes.

2. Changing Building Practices: The trend towards more integrated and composite building materials can make material separation more difficult.

3. Lack of Information: Older buildings often lack detailed information about the materials used in their construction, making it challenging to plan effective recycling strategies.

4. Economic Factors: The economic viability of copper recycling from buildings is influenced by factors such as copper prices, labor costs, and the availability of recycling infrastructure.

However, these challenges also present opportunities for innovation. For example, the development of new recycling technologies specifically tailored to recover copper from complex building waste could significantly improve recycling efficiency. Similarly, the integration of material tracking technologies into building management systems could provide valuable data for future recycling efforts.

The construction sector offers substantial potential for implementing circular economy principles in copper use. By combining strategies such as design for disassembly, urban mining, and innovative business models, it’s possible to significantly increase the proportion of copper demand met through recycling and reuse in this sector. This not only conserves valuable resources but also reduces the environmental impact of both copper production and building construction.

## General Approaches

One of the key advantages of recycled copper is its lower environmental footprint compared to primary production. Recycling copper requires up to 85% less energy than primary production from ore. This energy saving translates into reduced greenhouse gas emissions, making recycling a crucial strategy for both resource conservation and climate change mitigation.

The effectiveness of copper recycling varies across different end-use sectors. In the construction sector, for instance, the recovery rate for copper at the end of a building's life can be as high as 95%. This high recovery rate is due to the relatively large quantities of copper used in buildings and the ease of separating it during demolition.

In contrast, recycling rates for copper in consumer electronics are generally lower, often around 40-50%. This is partly due to the challenges in collecting and processing small electronic devices, as well as the complex nature of electronic waste, which often contains copper in small quantities mixed with other materials.

To improve recycling rates, several strategies are being pursued and are briefly described below:

1. Enhanced Collection Systems: Implementing more efficient and widespread collection systems for end-of-life products containing copper is crucial. This includes improving e-waste collection infrastructure and incentivizing consumers to return old electronic devices.

2. Advanced Sorting Technologies: Developments in automated sorting technologies, such as those using artificial intelligence and machine learning, are improving the efficiency of separating copper from mixed waste streams.

3. Urban Mining: The concept of urban mining, which involves recovering valuable materials from urban waste streams, is gaining traction. Cities are increasingly being viewed as “mines” of the future, with significant potential for recovery from infrastructure, buildings, and consumer goods.

4. Design for Recyclability: Encouraging manufacturers to design products with end-of-life recycling in mind can greatly facilitate copper recovery. This includes designing products for easy disassembly and using standardized components.

5. Chemical Recycling: Advancements in hydrometallurgical and biometallurgical processes are enabling more efficient recovery of copper from complex waste streams, including low-grade electronic waste.

The circular economy concept goes beyond simple recycling to encompass broader strategies for keeping materials in use for as long as possible. For copper, this includes:

1. Product Life Extension: Designing products for durability and repairability can extend their useful life, reducing the need for new copper production.

2. Remanufacturing: Refurbishing and remanufacturing copper-containing products, such as electrical equipment, can give them a second life while conserving resources.

3. Sharing Economy Models: Promoting sharing and leasing models for copper-intensive products, such as certain types of industrial equipment, can reduce overall copper demand by increasing utilization rates.

4. Industrial Symbiosis: Encouraging the exchange of copper-containing by-products and waste streams between industries can create closed-loop systems that minimize waste.

Policy measures play a crucial role in promoting recycling and circular economy approaches. Extended Producer Responsibility (EPR) schemes, which make manufacturers responsible for the entire lifecycle of their products, including end-of-life disposal, have been effective in increasing recycling rates in many countries. Landfill bans on recyclable materials, including copper-containing waste, also drive recycling efforts.

## Chapter Summary

The strategies for managing copper demand through efficiency, substitution, recycling, and circular economy approaches offer promising pathways for balancing the growing need for copper with sustainability imperatives. These approaches are not mutually exclusive but rather complementary, and their effective implementation will require coordinated efforts across industries, governments, and communities.

Efficiency and substitution strategies can help reduce the copper intensity of various applications, from electrical systems to construction materials. However, it's crucial to carefully consider the trade-offs involved in substitution, ensuring that alternative materials do not compromise performance, safety, or long-term sustainability.

Recycling and circular economy approaches hold particular promise for copper, given its infinite recyclability. Increasing recycling rates, especially in sectors like construction and electronics, can significantly reduce the need for primary copper production. The development of urban mining and the implementation of circular business models offer innovative ways to keep copper in use for longer periods.

The construction sector, as a major consumer of copper, presents both significant challenges and opportunities for demand management. The long lifespan of buildings means that strategies implemented today will have impacts decades into the future. Approaches such as design for disassembly, material passports, and innovative recycling technologies can help maximize the recovery and reuse of copper from the built environment.

As we move forward, it's clear that no single strategy will be sufficient to manage copper demand sustainably. Instead, a holistic approach that combines efficiency improvements, strategic substitution, enhanced recycling, and circular economy principles will be necessary. This will require ongoing innovation, supportive policy frameworks, and a shift in mindset towards viewing copper not as a consumable resource, but as a valuable asset to be managed and recirculated through our economic systems.

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