Copper Applications Technology Roadmap

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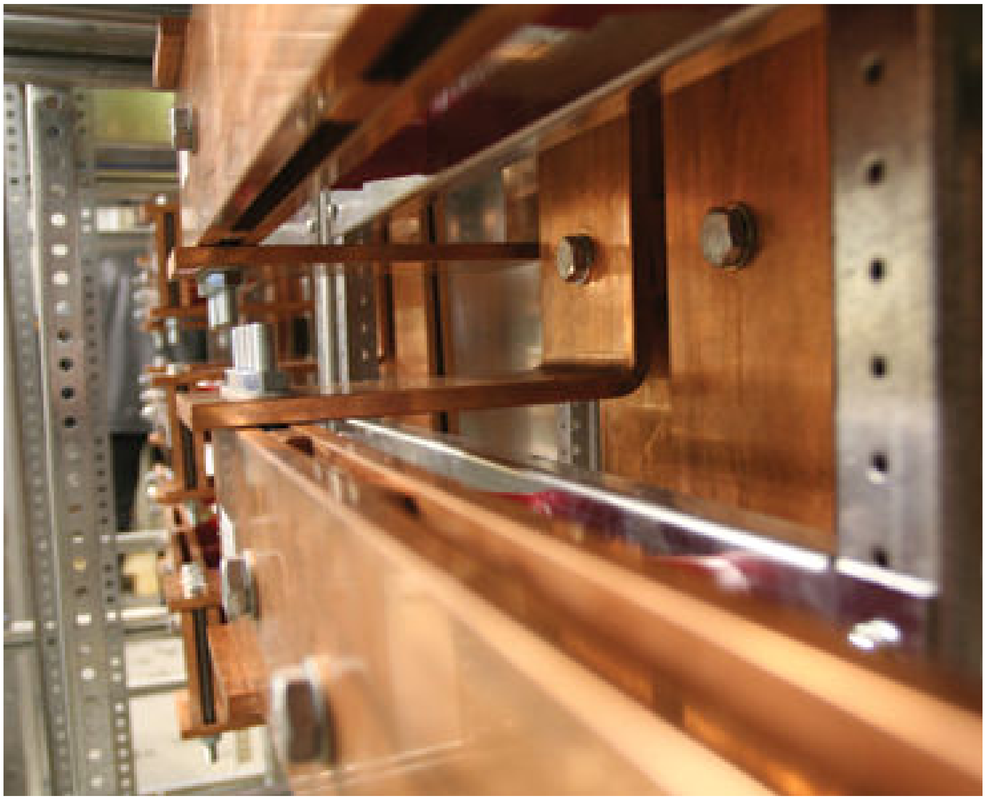
International Copper Association
Copper Alliance



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Global Outlook

Copper has a remarkable uninterrupted record as an integral part of human life and civilization.[1] It possesses a unique combination of properties that through scientific insight and creativity have been applied in some of history's greatest innovations: precision navigation instruments, electrical systems, distribution of safe drinking water, air conditioning and data communications. This Copper Application Technology Roadmap points the reader toward promising new copper developments with the potential for global application and contributions to sustainable development.

Since the International Copper Association (ICA) introduced the *Copper Applications Technology Roadmap* (the Roadmap) in 2007, it has served as a collection of knowledge and a guide for collaborative, pre-competitive research among copper producers and fabricators, copper-using industries, universities, government programs, entrepreneurs and independent technologists.

Copper and the United Nation's Sustainable Development Goals

In 2015, world leaders adopted the 2030 Agenda for Sustainable Development, which includes a set of 17 Sustainable Development Goals (SDGs). These SDGs provide a framework for addressing mankind's most critical issues over the next 15 years. (See Appendix A)

One of ICA's key missions is to rise to the challenge set by the United Nations and make a positive contribution to these goals, and this has helped guide the development of the 2017 technology roadmap. The technologies prioritized here (namely Air Conditioning, Heating and Refrigeration Systems, Aquaculture and Ultra-Conductive Copper) have the potential to deliver the most significant contribution to sustainable development.

In addition to this technology prioritization, ICA continuously seeks effective partnerships to help move forward with new initiatives. This operating model has led to several technologies being developed and readied for scale up, roll out or commercial promotion, thanks to successful collaborations with organizations looking to make a positive impact on the global sustainable development agenda.

The roadmap supports and compliments the wide-ranging initiatives already put in place by ICA and its members. An overview of these efforts can be found at sustainablecopper.org

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New Directions

ICA members have invested approximately $50 million per annum in our programs. The vast majority of these funds are directed to initiatives producing positive impacts on sustainable development. Examples of these impacts include technical advances in renewable energy systems, efficient electric motors, and antimicrobial surfaces for public health. Some of these initiatives were identified and/or described in past versions of the Roadmap and have passed the pre-competitive stage of R&D and are being deployed through global supply chains.

The diagram shown on page 7 depicts the copper industry's complete downstream activity. The first section of the Roadmap looks more closely at the outer edges of the diagram, specifically, existing/evolving applications and emerging applications. The italicized applications areas are those where significant improvements have been made in recent years. While these areas are no longer seen as R&D priorities, work continues to promote the advancement of copper technology in these applications.

Appendix A describes how copper can play a major role in helping nations to address long-term societal needs as described in the United Nation's Sustainability Development Goals. Appendix B provides a case study of how an advance in copper rotor motor technology moved through research, process development, engineering design and into commercial use. Appendices C, D and E address the center area of the diagram, describing the fundamental properties of copper, discussing the trends and changes influencing copper use and examining how these attributes can assist in society's future progress.

Roadmap Priorities

This Roadmap guides collaborative, pre-competitive R&D programs benefiting the copper industry and society. Industry favors this approach because expertise is available to project teams and costs are distributed among parties expecting to benefit. The ICA seeks high-quality R&D proposals for all priority opportunity areas.

The following general criteria for selecting priority activities were established by copper industry associations, semi-fabricated/fabricated product producers and end-use manufacturers:

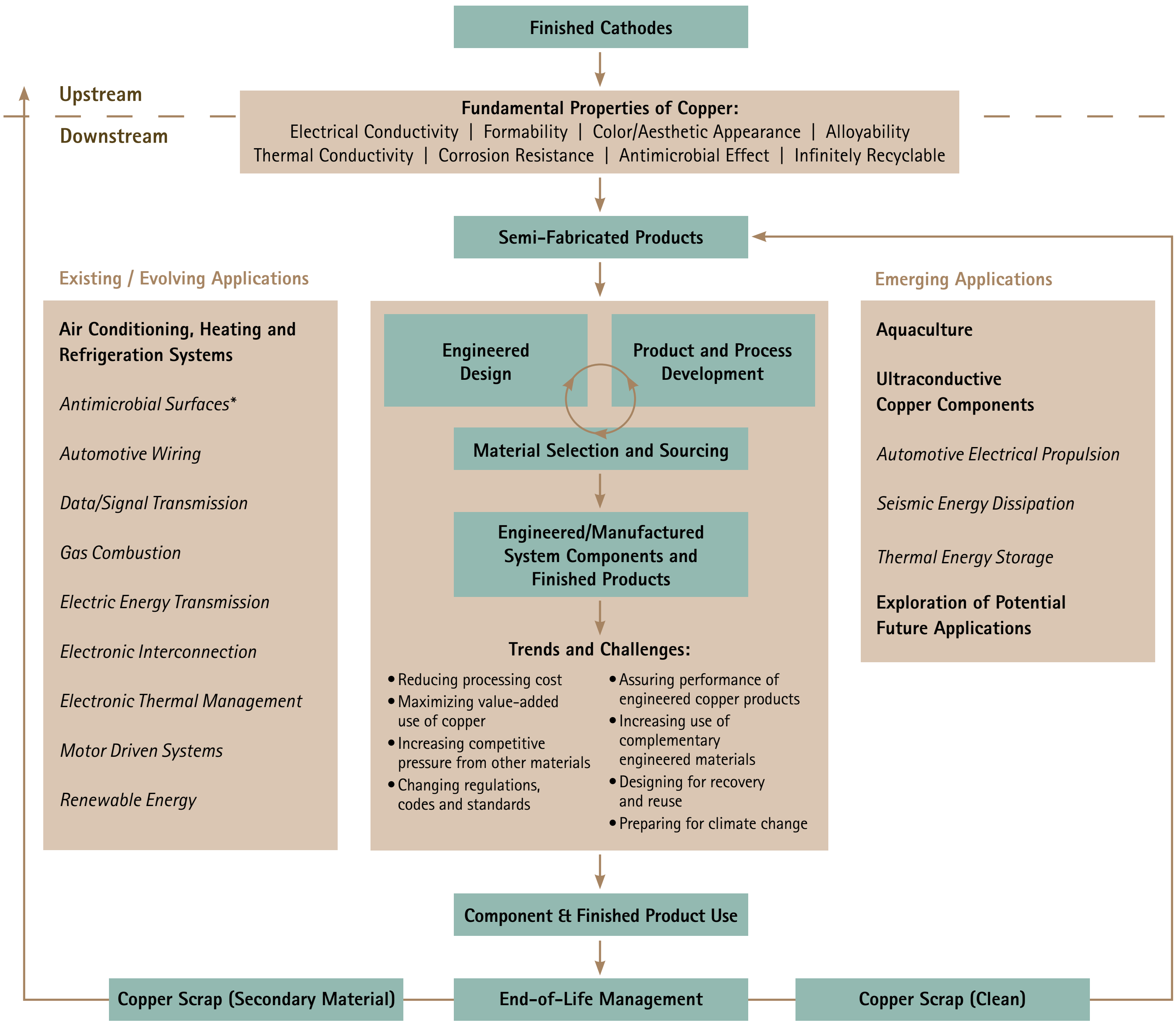
- **Contribute to sustainable development**—
  Efforts by members of the copper industry emphasize sustainable development in mining, through copper refining, use, and recycling and is a fundamental driver for investment and development.
- **Additional copper usage**—
  Address technical issues that, if resolved, should result in a significant positive impact on copper utilization in existing or new application areas.
- **Commercialization potential**—
  Have a high probability of commercial implementation due to the involvement and support of a range of industry participants, research organizations, influential policy makers, and co-funding organizations.

Classification of Prioritized Opportunities

Prioritized opportunities described in this Roadmap are grouped into two broad classifications:

- **Existing/Evolving Applications** maintain or increase current large-scale uses of copper. Typically cost pressure, inter-material competition and design constraints (e.g., miniaturization) influence copper use in these applications. The objective is to apply copper's technical properties more effectively to maintain copper's position as the material of choice.
- **Emerging Applications** open entirely new markets for copper, thereby broadening and increasing its use. The focus is on the improvement and creative application of copper's properties to solve new technology problems. The exploitation of copper's antimicrobial efficacy for touch surfaces and the commercialization of copper-based cages for fish farming are examples of this category.

R&D Priorities



Long-Term Societal Needs:
Improved Human Health | Environmental Sustainability
Increased Energy Efficiency | Higher Standards of Living

* Items in italic were in prior editions of the Roadmap and are not current R&D priorities.

Today's priority applications include:

- **Air Conditioning, Heating and Refrigeration Systems**—The trend toward sustainable, more compact energy-efficient systems and the imperative to use nonhydrofluorocarbon (HFC) environmentally friendly refrigerants presents both design implications and opportunities for copper. Since the first version of this Roadmap in 2007, a team of industry and academic researchers coordinated by ICA has reduced the copper content in some high-production-volume air conditioning heat exchangers by 40 percent through the use of smaller diameter inner-grooved copper tube. The team has also developed sophisticated heat exchanger design software capable of optimizing heat exchangers with low or zero global warming potential (GWP) refrigerants, new mechanical and pressure expansion technologies that simplify manufacturing of small-diameter copper tube heat exchangers and new low-frosting fins for heat pumps. Due to the ease of manufacturing, the results of these efforts are now being applied to millions of room air conditioners and refrigeration equipment, commercial air conditioning systems, water heating pumps and thermal energy storage devices. Copper also offers improved indoor air quality due to its proven antimicrobial effect—another unique sustainability advantage.

Emerging applications open entirely new markets for copper, broadening and increasing its use. Each area requires the development of new and improved copper-based technologies. The top emerging opportunities are:

- **Aquaculture**—Marine aquaculture nets and pens made with copper-alloy mesh are emerging as an effective solution to important problems facing the near-shore fish farming industry. The technology is also enabling the transition to open ocean aquaculture with reduced environmental impacts. Typical net pens constructed from synthetic materials with anti-fouling coatings become encrusted with marine organisms after only several months of use. Copper-alloy nets, however, remain free of fouling for years. This important benefit improves fish health, increases the rate of fish growth and eliminates the need to clean or replace cages. The mechanical strength and resilience of a copper-alloy structure also helps to prevent predator attacks and the escape of fish from aquaculture nets and pens.

- **Ultraconductive Copper Components**—Progress is being made in the methods of incorporating nanocarbon materials into copper in a way that improves the electrical conductivity and ampacity of copper at ambient temperatures. In 2016, independent testing confirmed a 17 percent increase in conductivity in a copper/nanocarbon composite. This technological breakthrough promises to deliver large efficiency improvements in electrical energy transmission and distribution networks; much more compact, low-loss electrical motors and generators; and important heat generation reductions in all types of electronic systems.

Future Application Concepts

Copper is essential for pushing the boundaries of innovation in cutting-edge fields, including nanoparticles, wearable technologies and space exploration. The copper industry, acting through ICA, funds pre-competitive research and development that may create or enable significant future market applications or enlarge existing ones. Researchers are invited to propose creative concepts derived from scientific advances, technology transfers or business/societal needs. Such proposals must identify the breakthroughs required and describe credible approaches for progress. There is preference for relatively rapid demonstrations and/or development timescales. Nonetheless, proposals regarding longer-term scientific investigations are welcome.

This Roadmap looks downstream from mines, mills, smelters and refineries to fabricators, processors and manufacturers, as well as to specific disciplines, industries and applications (see R&D Priorities diagram on Page 7.) Copper is a reliable material to apply in a wide range of existing and emerging applications because it is abundant and not at risk of scarcity. It has properties that make it immensely valuable in scientific research and technological products. Because of this, the copper industry must actively identify and evaluate new technology opportunities. This Roadmap seeks to identify those areas in which technological research and development will most likely lead to a significant impact on the value of copper in evolving and emerging applications linked to sustainable development.

The Roadmap will continue to evolve as industry reacts to societal trends, competitive pressures, related technical developments and unanticipated opportunities. While the current Roadmap does not cover all technological pathways, it focuses on the perceived highest-priority pre-competitive needs of the copper industry and its customers. Identifying and defining new research activities continues to be a challenge. To that end, the third section of this Roadmap outlines plans for an industry-managed process to create, launch and manage copper applications projects. The success of this Roadmap is measured by the number and scope of collaborative R&D projects that it inspires, and the benefits that those projects accrue.

Driving Innovation: Copper's Fundamental Properties

Copper's fundamental properties have met society's needs throughout history. In order to drive innovation, the copper industry must continue to explore copper's fundamental properties:

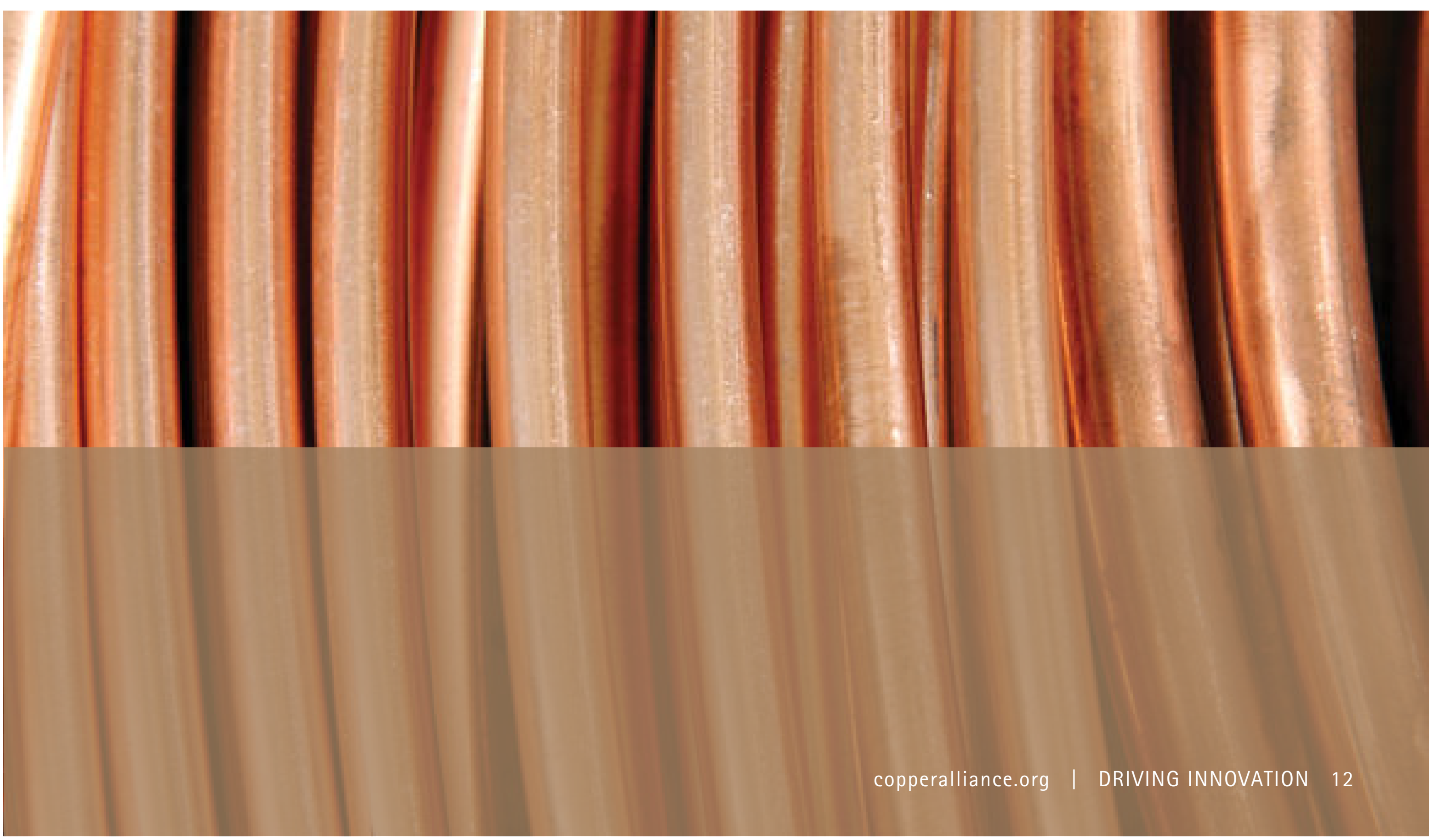
- Electrical conductivity
- Thermal conductivity
- Antimicrobial effect
- Formability
- Corrosion resistance
- Infinite recyclability
- Color/aesthetic appearance
- Ease of joining
- Alloyability

As the industry moves forward, it must collaborate with its partners to examine the ways copper's intrinsic advantage can help society apply the benefits of copper for a better, sustainable world. Success will come from:

- **Development of new materials**—The copper industry continues to explore more cost-effective ways to produce and process new copper-based alloys, composites and compositions. The electrical-connector and electronic-packaging industries are two successful examples of this approach.
- **Optimize how copper is used or fabricated**—ICA-sponsored development of cost-effective copper die casting is an example of collaborative process R&D with the copper industry (see Appendix B for details).
- **Innovation that counteracts material substitution**—Development and deployment of small-diameter inner grooved (MicroGroove™) tube in air-conditioning systems is a current example of how to take advantage of copper's unique attributes.
- **Imaginative thinking**—R&D teams need to think about how copper can be connected with new applications, and then work together to overcome technical challenges. For example, could a copper-based material conducting electricity five times better than pure copper at normal temperatures help make electric aircraft a reality?

Copper's Intrinsic Advantages

No other metal, alone or in alloy form, so effectively offers the amount and breadth of useful properties as copper. Over the coming decades, technological progress will largely depend on advanced materials such as metals, alloys, composites and other structures, many of which can potentially contain copper. In addition to high-technical performance, these materials must positively influence issues such as human health, energy efficiency, sustainability and standards of living. Copper and copper-based materials clearly meet these criteria.



From Cathodes to Finished Product: Engineering Design and Product/ Process Development

Copper cathode and recycled copper are the starting materials for downstream copper applications. Semi-fabricating companies process these materials, often with alloying elements, to produce an intermediate form with properties suitable for fabrication and final end use. These value-added copper materials are then fabricated into the precise shape of the end-use product. Materials experts in semi-fabricating companies and their customers' engineers and product specialists closely interact throughout the engineering design and development processes to ensure the composition and purity of copper alloys. This is necessary to achieve the desired functionality and performance in the final application.

The copper industry, using its own representatives and those of more than two dozen copper centers throughout the world, offers users a high level of support to assist in the selection of the most effective copper material solution. Additional details are provided on key issues, opportunities and recommended pursuits for copper that will support future technical collaboration with product and process engineers.

A Visual Transformation of Copper:


Recycled Copper


Fish Cage


Precision Rolled Copper Alloy


Connectors


Extruded Copper


Air Conditioning Tubes

Existing/Evolving Opportunity

Air Conditioning, Heating and Refrigeration (AHR) Systems

Advances in heat exchanger design engineering, two-phase heat transfer and system optimization are underway to achieve more sustainable, cost-effective air conditioning and refrigeration systems. Technological advances in small-diameter copper tube (≤ 5 mm diameter) offer significant advantages in heat exchangers and systems, including reduced size, reduced refrigerant charges, the ability to contain high pressures and mildly flammable refrigerants (such as CO_2 and hydrocarbons), lower cost and higher energy efficiencies.

The October 2016 hydrofluorocarbon (HFC) amendment to the Montreal Protocol will phase out HFCs as today's refrigerants of choice in appliance heat exchange applications. The changeover to new refrigerants presents both design implications and opportunities for copper. Systems using low global warming potential (GWP) CO_2 and flammable hydrocarbon refrigerants, such as iso-butane and propane, require proven high integrity containment characteristics that copper tube can provide. Flammable refrigerants hold great promise for reducing HFCs, thereby lowering environmental impacts from air-conditioning and refrigeration systems. ICA has updated heat exchanger and system design simulation software for small-diameter copper tube that now has the capability to facilitate air conditioning and refrigeration heat exchanger designs using the new refrigerants.

Advances since the 2012 Roadmap

Small-diameter copper tube MicroGroove™ heat exchangers are ideal for the growing use of small-charge natural refrigerants, such as R290 and CO_2. To assist original equipment manufacturers (OEMs) to transition to new refrigerants, ICA organized efforts across the supply chain to update technologies required to design and manufacture heat exchangers using MicroGroove™ tube. The following advances are noteworthy:

- **New design software maximizes benefits of using MicroGroove™ tubes**—Design software, developed with ICA assistance, enables engineers to select parameters needed to optimize a heat exchanger for a selected application. Tube diameter, various fin types (e.g., louver or slit type), tube distance and circuitry can be varied to obtain the desired performance and refrigerant charge. The software incorporates the latest research pertaining to heat transfer and pressure drop correlations for natural refrigerants.
- **Improved manufacturing processes for assembling large and small heat exchangers from small diameter tubes**—Manufacturing processes using 5mm or smaller tubes are mostly identical to the current 3/8 inch or 7mm OD copper tubes. Improvements in expanding these tubes could significantly increase productivity. Pressure expansion was found to expand tubes 5mm and below in an effective, fast and safe manner. The result is a method that reduces scrap rates substantially, reduces copper use due to zero tube length shrinkage, eliminates bell and flare rework, reduces the potential for leaks in brazing joints in an automated line, and leads to an overall increase in productivity.
- **Assisting major global OEMs in developing initial heat exchanger designs**—This initiative resulted in the production of tens of millions of energy-efficient air conditioners with reduced refrigerant charge. To continue and expand this type of assistance, ICA formed a Heat Exchange Technology Alliance (HETA) with air-conditioning manufactures to focus on overcoming technical challenges in improving the performance of air conditioning and heating systems.
- **Improved corrosion resistance**—In tightly-sealed energy-efficient buildings, organic acids released from construction materials, household chemicals and personal care products can occasionally cause pinhole refrigerant leaks in indoor heat exchangers. New copper-alloy tubes resist this type of corrosion.

Trends, Issues and Drivers

- Reduce global warming from refrigerant releases by transitioning to refrigerants that have low or zero GWP.
- Replace coal used for heating with efficient heat pump systems to reduce pollution.
- Provide affordable, efficient air-conditioning systems for developing economies.
- Replace millions of refrigeration systems in supermarkets, retail stores, vending machines and restaurants with redesigned systems and updated refrigerants.
- Manage electricity demand from air-conditioning systems to reduce demand on transmission networks and enable expanded use of renewable energy.
- Reduce refrigerant charge for natural refrigerants.
- Improve corrosion resistance in indoor coils.
- Maintain energy efficiency to standards across the system operational lifetime.

Opportunities and Recommended Pursuits

Further advances in MicroGroove™ technology development and disseminations

- Optimize small-diameter MicroGroove™ copper heat exchanger designs at 5mm and 4mm to reduce refrigerant volume, circuiting, flow distribution and pressure drop for the next generation of working fluids.
- Investigate surface tension and capillary effects on heat transfer and pressure drop of refrigerants in ≤3mm UltraMicroGroove™ small-diameter smooth and microfin copper tube.
- Continue to explore advantages of combining multiple tube diameters in copper heat exchangers.
- Optimize small refrigerant charge systems capable of using hydrocarbon refrigerants.
- Publish case studies on MicroGroove™ systems design using the newly developed software.
- Assist OEM's in the implementation of MicroGroove™ technology using the newly developed software.
- In an educational outreach effort, educate relevant university professors, students and research groups worldwide about small-diameter tube-fin heat exchanger technology and its sustainability benefits.

Heat Pump Systems

- Research new 5mm fin pattern designs for indoor and outdoor units to improve Annual Performance Factor (APF) of the system.
- Expand heat pump water heater use through improved heat exchanger designs and defrost technologies that do not use electricity.
- Further develop electric vehicle heat pumps.

Additional Heat Exchange Applications and Technologies

- Expand application of 5mm and 4mm tube systems to larger sizes, such as variable refrigerant flow and light commercial rooftop systems.
- Develop small-diameter copper tube commercial air conditioning system with R32 refrigerant (as a transition to fully HFC-free systems).
- Extend the use of small-diameter copper tube systems into phase change material cold storage systems for time-shifting electricity use.
- Develop copper heat exchangers for emerging magneto-caloric refrigeration techniques that may involve pulsating flows and low approach temperatures.

Energy Efficiency

- Apply advanced simulation software, optimization algorithms and high-performance computing to investigate larger heat exchanger and system optimization possibilities.
- Establish the long-term energy efficiency of air conditioning and refrigeration systems in real operating environments and develop and disseminate design concepts to avoid degradation of energy efficiency.

Manufacturing Processes

- Explore 3D printing of designs incorporating solid copper components and printed elements.
- Investigate 3D printing of flow intensification design concepts for making compact heat exchangers.

Emerging Opportunities

Aquaculture

Fish farming is a multi-billion dollar global industry. Depletion of wild fish stocks and the growing demand for farmed fish has increased the installation of near-shore aquaculture facilities and is simultaneously driving aquaculture expansion into the offshore marine environment. These developments, in addition to concerns regarding predator attacks, fish escape, the environmental sustainability of fish farming practices and possible threats to human health from antibiotics and vaccines fed to farmed fish have created an attractive opportunity for copper-alloy mesh in aquaculture.

Unlike other materials, copper-alloy mesh stays clean. It permits oxygen-rich water to flow through fish nets or pens, flushing out debris and fish waste. In addition, copper-alloy mesh mitigates the spread of infectious diseases by significantly reducing the accumulation of parasitic eggs, thus reducing or eliminating the need for therapeutic treatments. These unique benefits, compared to the use of other materials, help to maintain a healthier environment for fish. The mechanical strength and resilience of copper-alloy mesh resists predator attacks, storm damage and the escape of fish stock. Unlike nets made from synthetic materials, copper-alloy structures are completely recyclable at the end of their useful life.

In the 1960s – 1980s, the copper industry developed various copper-based pens for aquaculture. These pens were rigid and not easily scalable to large-volume production. Recent developments in copper alloys and pen designs have enabled the development of woven wire nets and cages formed from expanded metal mesh panels with flexible connections. These new designs have extended service life beyond six years.

New copper-alloy nets are enabling a 10 – 15 percent faster growth rate for fish, a 50 percent reduction in fish mortality due to improved fish health, more-efficient use of feed and increased profit for farm owners.

Advances since the 2012 Roadmap

- Open ocean submersible fish pens equipped with copper-alloy mesh have been deployed in Hawaii, Japan and the north of Chile. These cages demonstrated excellent performance with *Seriola rivoliana, Seriola lalandi* and *Seriola quinqueradiata*, a game fish and farmed alternative to wild tuna. The pens dramatically reduced parasites, yielded faster growth rates, improved food conversion and enhanced economic benefits to farmers.
- Salmon need water temperature below 20°C. Typhoons can destroy fish farming installations. In Korea, salmon were grown year-round in 32-meter diameter 12-meter deep submersible copper alloy mesh pens to avoid warm (29°C) surface water temperatures during the summer months and survive typhoons. This technology shows that salmon can thrive when submerged for months in copper alloy mesh enclosures, expands the areas where farming salmon is possible and is applicable to other species.
- Improved copper alloys are yielding increased service life.
- The Chinese government issued industrial standard "SC/T4030 General technical specifications for Copper-Alloy-Mesh Cages" and announced plans to deploy 10,000 offshore pens during the next five years as part of its 13th Five-Year Plan (2016 – 2020).
- Copper-alloy mesh cages and enclosure facilities have been commercialized in China to grow large yellow croaker (*Larimichthys crocea*), which is one of the main farmed fish in China.
- A Life-Cycle Assessment (LCA) study published in the peer-reviewed journal, Aquaculture, described several performance improvements achieved by farming Atlantic salmon (Salmo salar) with copper-alloy nets. These include a 10 percent reduction in feed use, 15 percent reduction in on-site energy use, 79 percent reduction in labor hours and 31 percent reduction in antibiotic application. The LCA study also identified indirect environmental benefits that were not previously quantified: life-cycle greenhouse gas emissions reduced by 16 percent, acidification reduced by 17 percent and total energy demand across the study's life-cycle model reduced by 18 percent.

Trends, Issues and Drivers

- Consumers are demanding for more sustainable seafood products.
- Global expansion of aquaculture (8 percent per year for the past 30 years) is expected to continue.[2]
- Aquaculture is moving to unprotected offshore locations. Technologies need to be improved to endure severe storms, reduce maintenance and operational costs, and achieve longer useful equipment life.
- Fish loss from predators, storms, parasites and infections need to be reduced.
- Labor and its associated costs, specifically from divers, need to be reduced.
- Continuing pressure for fish farmers to achieve certification for safety and sustainability.
- Fish farming business models, including equipment leasing, insurance and subsidy policies need to be further developed to support industry transformation and upgrading to more productive and sustainable practices.

Opportunities and Recommended Pursuits

Fish Pen

- Advance offshore submersible net-pen technology to withstand hurricanes and typhoons.
- Develop offshore feeding and monitoring systems, including robotics, for maintenance and extracting dead fish.
- Develop methods to accelerate joining copper alloy mesh net sections to reduce installation time.
- Investigate designs that include or facilitate mesh panel pre-assembly.
- Improve mesh-to-floatation system connection designs to simplify assembly.
- Develop more efficient harvesting techniques that consider the semi-rigid nature of copper alloy mesh.
- Investigate pen designs for alternative species.
- Design low cost pens for use in developing regions.

Alloy and Mesh Development

- Develop copper alloys with further improvements in resistance to mechanical wear and corrosion.
- Investigate methods to weave complex shapes and edges (selvedges) suitable for rapid joining.

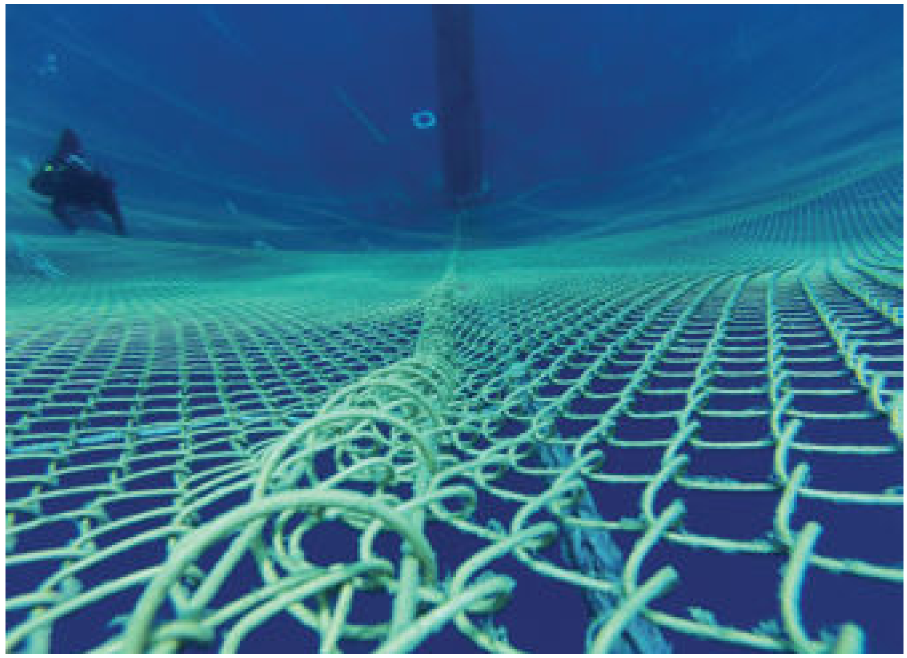


Photo courtesy of InnovaSea

Environmental and Sustainability Impact

- Perform research activities and publish results related to the positive impacts of copper-alloy mesh on fish stress, parasites, pathogens, mortality rate, growth rate and food conversion rate, as well as copper releases to the nearby marine environment.
- Perform studies further demonstrating the life-cycle value of aquaculture in copper-alloy mesh systems.
- Investigate opportunities in the marine environment where the exclusion or containment of specific species is of high value (e.g., marine mammals).
- Cooperate with organizations interested in promoting sustainable aquaculture and share best practices; e.g., standards on copper-alloy mesh performance.

Ultraconductive Copper Components

Ultraconductive copper (UC copper) has garnered much attention in the materials research world due to its promise of substantial energy-efficiency improvements in all types of electrical and electronic applications. By reducing electrical losses, UC copper promises to have a transformative effect on a broad area of technology that would strongly benefit society. Smaller, lighter and more electrically efficient equipment enabled by UC copper should prompt technological advances in electrical transmission and distribution, motor technologies for transportation systems and in other ways that are difficult to foresee.

UC copper is a nanocomposite material comprised of a copper metal matrix integrated with nanocarbon (nanotubes or graphene). Electricity conduction in these copper/nanocarbon composites augments the normal bulk conduction mechanism of pure copper by adding a new-and-efficient mechanism of conduction at the carbon/copper atomic interface. Optimizing the electron flow in a copper-carbon nanocomposite requires careful engineering on a nanoscale. Studies and trials are underway on the scale-up of production from grams to thousands of tonnes of wire. Progress has been made in methods of incorporating nanocarbon into copper in a way that improves the electrical conductivity and ampacity of copper at ambient temperatures. However, much work needs to be done over the coming decade to transform UC copper into a widely available engineering material for use in electrical components and systems.

Advances since the 2012 Roadmap

- Postage stamp-sized samples of UC copper exhibiting an electrical conductivity of 117 percent International Annealed Copper Standard (IACS) have been repeatedly produced and verified.
- Meter-length UCC wire was developed with a conductivity of 104 percent IACS.
- An atomic charge-transfer model was developed that successfully explains the increased conductivity at the carbon-copper interface. The model points to a potential increase of UCC conductivity by up to 10 times more than what has currently been achieved in the laboratory.
- Bare wire samples repeatedly exhibit 46 percent more ampacity at 60°C compared to pure copper wire with similar geometry.

- The Ultra Conductive Copper-Carbon Nanotube Wire (Ultrawire) project, part of the European Commission's 7th Framework Programme (FP7), aimed to develop a copper nanocarbon composite with significantly improved electrical, thermal and mechanical properties over bulk copper. After three years of research, the project demonstrated a significant decrease in the composite's thermal coefficient of resistivity, pointing the way to its improved high-temperature performance in motor windings where pure copper's conductivity is only 63 percent of its room temperature value. Two industrial partners are continuing with UCC development.

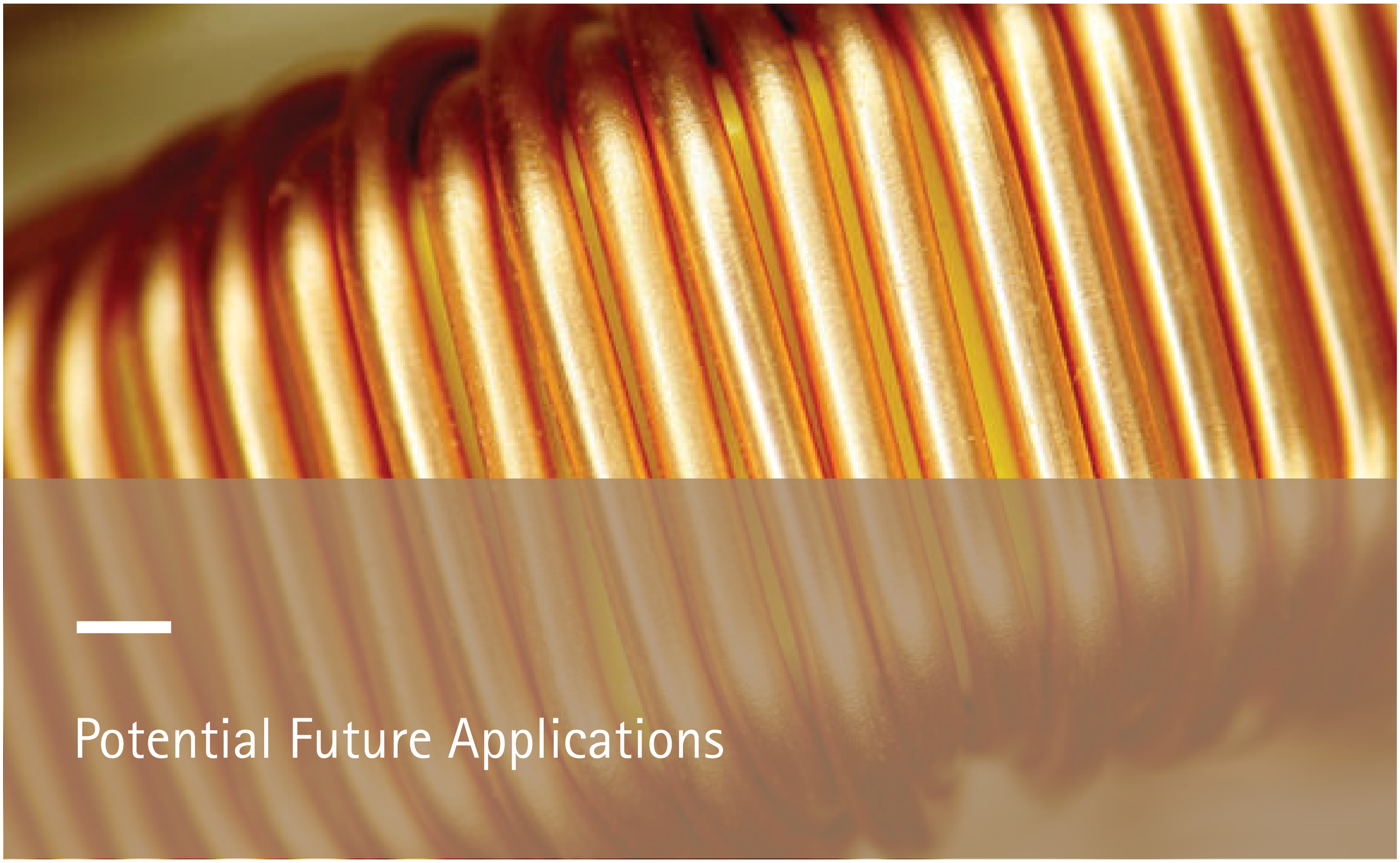
Trends, Issues and Drivers

- UCC-based products may slow or reverse the trend of OEMs specifying aluminum as an alternative to copper (due to the higher unit cost of copper).
- Investment in UCC development began in 2013. During 2012 – 2015, at least $12 million was invested in UCC development worldwide.
- Work is continuing worldwide to lower the production cost of all forms of nanocarbon.
- The push for greater vehicle fuel economy is highlighting the need for lower-weight electrical conductors.
- There is an increased global focus on energy efficiency in electrical power generation, transmission, distribution and use.
- Increasing investment in the renewable energy sector is creating a need for more compact and lighter wind turbine generator sets.
- Significant funding has started for the development of electrical/combustion hybrid propulsion systems for aircraft – with the promise of at least doubling fuel economy. Lowering the weight of high-current electrical components is central to these developments.

Opportunities and Recommended Pursuits

- Encourage more applied scientific research to achieve higher electrical energy transfers between nanocarbon and copper components.
- Develop methods for making UC copper using standard processes from today's copper supply chain.
- Develop methods for producing UC copper in different useful forms:
  - Wire (using existing wire processing lines or directly during UCC material manufacture; for motor stators, in-vehicle wiring)
  - Foil (for printed circuit boards, batteries)
  - Strip (for transmission/distribution transformers, large generators/motors)
  - Directly deposited layers (for the manufacture of integrated circuits).
- Develop methods to directly synthesize nanocarbon during UCC material manufacture (rather than combining discrete copper and nanocarbon materials).
- Collaborate with carbon nanotube production companies to optimize nanotubes appropriate for UC copper.
- Explore other properties of UC copper, including thermal conductivity, strength, modulus and ductility.
- Explore accessory processes, such as insulating, joining and terminating UCC wire.
- Form cooperative structures for long-term cross-industry development and implementation of UC copper.
- Develop and prototype high-value applications for UC wire and bus bar.

Electricity conduction in these copper/nanocarbon composites augments the normal bulk conduction mechanism of pure copper by adding a new-and-efficient mechanism of conduction at the carbon/copper atomic interface.



Potential Future Applications

Copper facilitates innovation by providing an essential material for the creation of new products and processes. In addition to the priority opportunity areas presented in this document, the copper industry seeks research ideas that promise new copper applications. Acting through ICA and its network of Copper Alliance national/regional copper promotion organizations[3], the industry funds pre-competitive research leading to the creation of significant new applications for copper. Typical applications for investment include research focused on finding new ways copper can be used to reduce energy consumption. Researchers in academia or industry, working in either basic or applied research related to copper and whose work addresses the interests of the copper industry, are encouraged to contact the ICA with proposals that identify the breakthroughs required and describe a credible technical approach to successful realization.

An ideal copper technology development proposal will:

- Require R&D effort to achieve a technical breakthrough enabling potential global application.
- Create a new market application or defend an existing copper application from alternative materials or technologies.
- Identify a reasonable path toward commercialization.
- Apply copper's superior attributes. Copper is essential to health, its use promotes energy efficiency, and its recyclability is nearly unsurpassed among all engineering materials.
- Lead to the use of at least 10,000 metric tonnes of copper annually within five years of initiation. Proposals with smaller tonnage impact but large societal benefit are also considered. Technology with a longer timeline to market requires stronger market impact and a clearer path to commercialization.

Trends, Issues and Drivers

- Increasingly rapid cross-fertilization of ideas and global collaborative creativity
- Pervasive digitization, communication and computing
- Simulation and modeling of metallurgical phenomena
- Deeper scientific understanding of living systems
- Greater concern about environmental consequences
- Global spread of venture capital investment model

Possible Areas for Exploration

- 3D printing of copper for heat exchange and electrical conductivity applications
- Copper materials as a catalyst or as a substrate for other catalysts for surface chemistry-oriented applications in the energy industry:
  - Hydrogen production
  - Oxygen transport
  - Carbon dioxide capture and transformation into useful chemicals
  - Capture of acid gases
- Copper composite materials containing various forms of fiber or particles to achieve unusual or enhanced properties
- Fundamentally new forms for heat-exchange surfaces and structures

Recommended Pursuits

- Technology scouting through participation in government and industry R&D forums and exhibitions
- Cooperative research and development of advanced materials based on copper through government/industry/academic scientific research initiatives in a number of countries

Implementation

The *Copper Applications Technology Roadmap* continues to evolve as the industry reacts to societal trends, competitive pressures, related technical developments and unanticipated opportunities. While it does not cover all technological pathways to the future, this Roadmap does focus on what its contributors believe are the highest priority pre-competitive needs of the copper industry and its customers. As such, it is intended to guide the planning and implementation of collaborative R&D programs that will involve copper producers and fabricators, copper-using industries, universities, government laboratories, entrepreneurs and independent technologists.

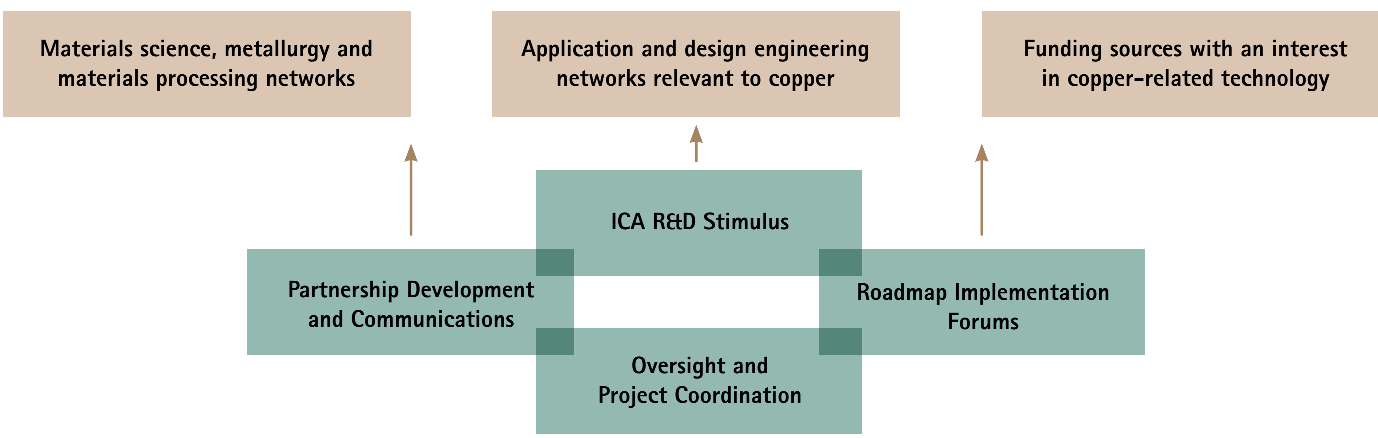
Many of the organizations participating in the creation of this Roadmap invest significant resources each year in developing innovative products, new copper alloys and advanced process technologies. Their history of technology investments is, and will continue to be, a major source of their own future market success. By working together to develop and refine this Roadmap, the industry has taken steps toward important business technology transformations.

The ICA will play three roles in implementation of the Copper Applications Technology Roadmap:

- **Outreach and Partnership Development Activities** will engage relevant individuals and organizations to inspire continued idea development regarding copper application opportunities and required R&D. (See next section for more details on Partnership Development.)
- **Roadmap Implementation Forums** will provide focused venues for brainstorming about specific opportunity areas and will disseminate findings among the networks created.
- **Roadmap Oversight and Project Coordination** involves managing interactions among the diverse organizations participating in the use of the Roadmap. ICA has historically taken a coordinating role in the development and implementation of major copper applications R&D, and ICA will continue in this role. ICA will also spearhead efforts to secure co-funding from third parties, including governments, nongovernment organizations and appropriate industry organizations.

Figure 1 outlines the main implementation steps. These steps are designed to catalyze dialog about copper, and subsequently launch and manage scientific research on copper application-development projects. Strong leadership and persistence ensures that important opportunities do not fall through the cracks. In addition, achieving early success helps maintain the momentum generated by the Roadmap and convince companies that the technology collaboration model can work.

Figure 1: Catalyzing Conversations About Copper—Connect Individuals and Networks Within Key Domains and Stimulate Thinking About Copper-Related Technology



Partnership Development and Communications

Collaborative partnerships will leverage resources and capabilities among copper semi-fabricators, component producers, system manufacturers, original equipment manufacturers (OEMs), government organizations, universities, producers and other stakeholders. Combining the expertise and perspectives of all facets of copper-related markets ensures that their needs are met and anticipated. Information and cost-sharing minimizes the duplication of technology development efforts and maximizes resources to efficiently achieve effective solutions. The roles of companies and organizations in implementing this Roadmap have not been determined. These roles will take shape as specific activities are designed and implemented.

Ongoing communications are important to keep industry groups across the globe informed and up-to-date regarding effective strategies and technologies to enhance the value of products. Online web-forums, journal articles, published reports, conference briefings and regular news updates can increase global awareness of the latest developments in copper innovation.

Roadmap Implementation Forums

A Roadmap implementation forum can solicit new ideas to accelerate progress for the most time-sensitive projects. If it is determined that a particular Roadmap opportunity is not being addressed through ongoing efforts, copper industry leaders, including ICA, will need to organize activities bringing together the range of expertise necessary to think creatively about potential responses. This effort may be directed toward applied research, commercialization of technology, product integration, field testing, training/outreach or any other means or method that advances a particular opportunity.

Prior to launching new projects, the copper industry must clearly define the desired outcomes, resources and capabilities required and how the results will contribute to achieving a particular accomplishment. Each of these factors will be integrated into requests for proposals to solicit innovative solutions and projects from universities, private companies, government laboratories, researchers or the technical community.

Roadmap Oversight and Project Coordination

This Roadmap encourages organizations and individuals to participate in ways that will best capitalize on their distinct skills, capabilities and resources for developing opportunities. This affords companies and organizations the flexibility to pursue projects corresponding with their unique interests. However, the lack of a unified structure makes it challenging to adequately identify, organize, fund and track the diverse activities and their corresponding benefits. In accordance with its mission, ICA will fulfill this role by providing the required oversight and coordination to initiate and resource projects and activities.

ICA's Mission:
ICA's mission is shared by all members of ICA and other Copper Alliance entities: ICA brings together the global copper industry to develop and defend markets for copper and to make a positive contribution to society's sustainable development goals.

See copperalliance.org for additional information.

Moving Forward

The revised Roadmap provides the copper industry with an updated set of copper application-development paths. Subsequent efforts can produce a more in-depth set of directions and an effective path toward success in specific markets. Collaborative partnerships among materials science, metallurgy and materials processing researchers, application and design engineers, manufacturers and government can generate the requisite power and momentum to drive copper and its industries along these paths.

As the industry looks to the future, the success of this Roadmap will be measured by the number and scope of R&D projects that it inspires and the benefits those projects accrue. Complementary but equally important benefits will include the enhancement of the perception of copper as a life-connecting, environmentally friendly, advanced technical material essential for sustainable development.

Appendix

Appendix A: Copper's Role in Sustainable Development

In September 2015 world leaders adopted the 2030 Agenda for Sustainable Development, which includes a set of 17 Sustainable Development Goals (SDGs). These SDGs provide a framework for addressing mankind's most critical issues over the next 15 years.

Many of the issues on the sustainable-development agenda can be addressed by copper and its unique properties: climate-change mitigation and adaptation, energy efficiency and energy security, water quality, renewable energy, energy access, public health and others. No other metal or material connects so broadly and critically with the global sustainable-development agenda.

Copper is particularly important in affordable and clean energy, industry, transport infrastructure and sustainable cities.

Copper is infinitely recyclable; it can recycled over and over again without loss of any of its inherent properties. Each year nearly one-third of copper demand is met through recycling. Of the 550 million tonnes of copper produced since 1900, it is estimated that two-thirds is still in productive use today. Copper is critical to the circular economy and contributes to stronger life-cycle analyses of end-use products containing it. Other materials are consumed or downcycled at end of life.

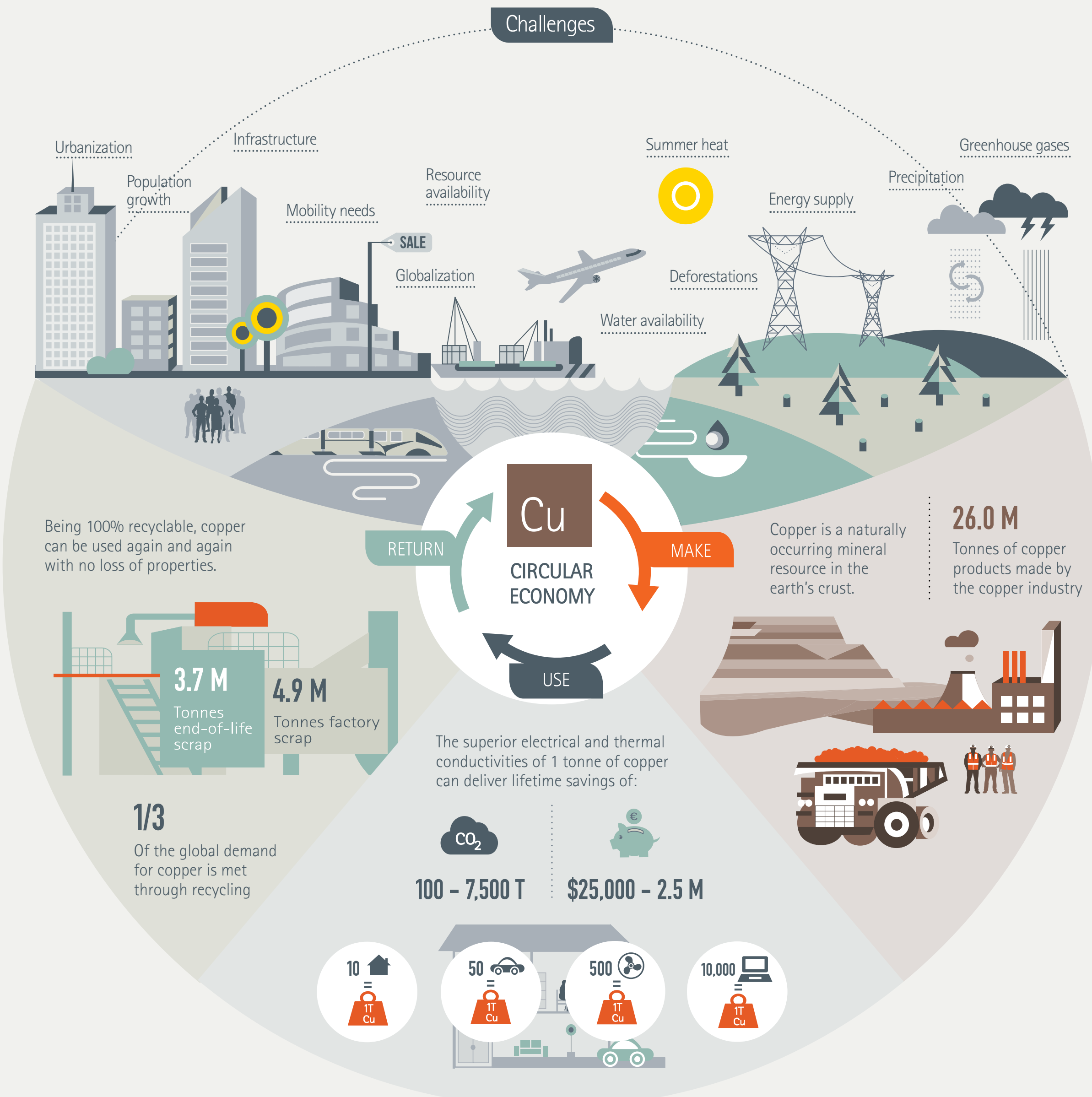
Extractive industries such as copper mining are often viewed with a narrow, negative focus. Copper mines are found in challenging geographies – deserts, mountains, deep underground. Mining for minerals is resource-intensive, requiring large amounts of energy and water. Yet, without copper, quality of like would be vastly different. Viewpoints on the production of copper need to balance the extractive nature of the industry with the important benefits it provides.

A summary of ICA's copper-based sustainability initiatives, titled, *The Copper Industry: Our Contribution to Sustainable Development (2016)*, is available at: issuu.com/copperalliance/docs/ica-sustainable-dev-goals-web

COPPER'S CONTRIBUTION TO THE CIRCULAR ECONOMY

Sustainability and climate change present growing challenges for policy makers, businesses, and society. Regulators are adopting policies intended to break the link between economic growth and the use of natural resources. Industries are making new products and systems that need fewer materials, but still satisfy customer expectations. Society, both businesses and citizens, needs to be much more aware of the importance of returning end-of-life products back into recovery and recycling.

This infographic shows how copper supports the circular economy.



Appendix B: Evolution of the Copper Rotor Induction Motor

Virtually all motors and generators above 37kW (50HP) use fabricated copper rotors to achieve high efficiency and compact size. However, small motors frequently use die cast aluminum in the rotors and cannot achieve high-efficiency standards. The copper industry invested in the potential of die cast copper rotors for motors 15 years. As in many research and development activities, the technical focus shifted over time and application opportunities changed. Solving the initial technical challenge was only the beginning; launching this new technology required persistent effort, attention to changing technology and the right market conditions.

The mid-1990s saw great interest in the development of more efficient, lighter and smaller AC induction motors for use in the industry and government sectors. Passage of the U.S. Energy Policy Act of 1992 and similar legislation in Europe reflected a growing awareness of the importance of motor efficiency in the larger arena of energy conservation. Industrial motors consume about 40 percent of global electricity production, so any improvement in efficiency is significant. Industry responded to this legislation with more efficient motors using an increased amount of copper in the stator windings, thereby reducing resistive losses.

The laborious methods used to produce large electrical machines with copper rotors were not easily applied to induction motors produced at high volume. As a consequence, a die cast copper rotor project was initiated in the mid-1990's following decades of incremental improvements in induction motor efficiency. It appeared to be a worthwhile technology to pursue. Copper in the rotor reduced rotor resistive losses by around 40 percent and had the potential to reduce overall motor losses by 10 - 20 percent compared with conventional aluminum rotor motors. It was subsequently shown that motors with copper rotors can be made smaller and lighter and can operate at lower temperatures, which decreases maintenance requirements. Despite these advantages, existing copper die casting methods were not economical for high-volume production. In addition, motor manufacturers demanded that if it were to adopt the die cast copper rotor, it needed to be manufactured in commercially available pressure die casting equipment.

Pursuing the Opportunity

In 1996 ICA initiated funding for an R&D project to create a practical copper rotor motor (also known as a copper-rotor induction-motor) suitable for mass production. Led by the U.S. Copper Development Association Inc. (CDA), a consortium of motor manufacturers, die casters and government representatives initiated (and cooperatively funded) the Die Cast Copper Rotor Motor Program.

Challenges

Researchers addressed the challenges of reducing processing costs and assuring adequate copper rotor performance. For example, during the high-pressure die casting process, conventional die steels are susceptible to surface cracking (heat checking) due to thermal stress and strain in the die as temperatures cycle from a few hundred degrees to the melting point of copper (i.e., 10850C; 19840F). The melting point of aluminum is 660oC, which is much lower than copper. Therefore, when using conventional die steels, aluminum casting produced lower thermal stress and strain in the die which led to a longer die life than when casting copper. It was also recognized that there would be benefits beyond just changing to a die casting process; the design of the rotor and motor was reimagined to apply copper more effectively.

Solutions

The CDA-led team of industry and academic researchers determined that die cracking could be reduced and die life could be extended with just two simple changes:

1. Replacing certain portions of the steel die with easily removable, ductile, heat-resistant, nickel-based super alloy components
2. Pre-heating the die to approximately 6000C (1,1000F).

These actions, and a number of related improvements, rendered the copper die casting process technically viable.

Motor design was also investigated. Since starting torque is reduced in a high-conductivity rotor conductor, the shape of the rotor bars and rotor slots had to be modified to improve the motor's operating characteristics. Accomplishing this enabled rotor designers to use the "skin effect"—the tendency of alternating current flow to crowd toward the external conductor surfaces. Also, at a given efficiency, the copper rotor used less lamination steel in the rotor and stator stacks. This benefit enabled the overall size of the motor and its material costs to be reduced.

Opportunity in Standard Industrial Motors

In 2006, Siemens, a major international motor manufacturer, embraced the new die cast copper rotor technology and brought to market a line of super-efficient industrial motors. Within just one year, the motors were commercially acceptable in the U.S. The motors were up to two percentage points more efficient than those meeting NEMA Premium™ standards and they offered substantially lower life-cycle costs. While the initial cost of purchasing a copper rotor motor may be somewhat higher than less efficient standard motors, the life-cycle costs for a standard motor far exceeds the incremental costs of a copper rotor motor. This is because the initial cost of an industrial motor represents only 2 percent of the total cost of its ownership. Energy costs, maintenance and other variables make up the other 98 percent of the lifetime cost of the motor.

Opportunity in Integral Motors

Several manufacturers making drive systems integrating a custom designed motor with gears recognized the value of using copper rotor motors. They believed the overall size of the motor could be reduced to exactly match their requirements. Rather than continue to use aluminum rotor motors exclusively, a leading manufacturer of motor-driven gear-drive systems, SEW Eurodrive, decided to use integral motors with die cast copper rotors in about a third of their product line. This allowed retrofitting existing drives with high-efficiency motors that would fit into the same package. This first large scale commercial application signaled to the motor industry that the challenges facing die casting copper rotors had been overcome. Other manufacturers followed in adopting the technology for compact, lightweight electro hydraulic systems for aircraft, refrigeration compressors and traction motors.

Opportunity in Automotive Propulsion

As global interest in electric vehicles increased, automotive engineers recognized that they required special motor designs to meet complex technical, cost and volume production requirements. Interest in using motors with die cast copper rotors increased when, in the alternative permanent magnet motor architecture, concerns arose about the availability of rare earth elements, such as dysprosium, and with magnet performance at elevated temperatures. Technical studies showed that induction motors could have similar compact, high-power density and higher system efficiency in parallel hybrid-drive systems, generating further interest in using die cast copper rotors. In 2011, with funding from the U.S. government, Baldor Reliance demonstrated a hybrid military vehicle using four fluid-cooled, very high-energy density traction motors with die cast copper rotors.

In the series hybrid traction application, the copper rotor motor offered substantial advantages:

- The ability to redistribute losses in the stator for more effective cooling, due to reduced size and weight.
- The ability to be de-excited when not producing torque, thereby eliminating no-load rotational and magnetic losses.
- Meeting efficiency requirements across a broader range of loads and speeds;
- Better mechanical properties and ruggedness than aluminum-rotor.

Around the same time, Tesla Motors launched their plug-in electric vehicle with a power train that included a motor with a copper rotor with a maximum operational speed of 13,500 RPM, a power inverter and lithium ion battery packs. The large amount of copper in the inverter, cables, batteries and motor reduced electrical losses and avoided heating under high-amperage conditions. Tesla's continued use of a copper rotor induction motor in their vehicles has confirmed the suitability of this technology for automotive propulsion. As production of electric vehicles expands, millions of new cars with copper rotor motors at their core will signal a substantial contribution to sustainable transportation, as well as a deserved technological success for the copper industry.

Continuing Research, Development and Commercialization

ICA helped to develop and transfer copper rotor motor die casting technology to manufacturing companies around the world. The capacity to produce die cast rotors now exists in Germany, France, Japan, India, Korea, China and the U.S.

Research into the vertical die casting process was conducted at the Non-Ferrous Technology Development Centre (NFTDC) in Hyderabad, India. This work was supported by ICA with co-funding from the U.N. Common Fund for Commodities and the Global Environment Fund (GEF). The technical team at NFTDC investigated cost-effective methods for die casting copper rotors and explored their use in industrial, water pumping and vehicle applications.

In 2006, with the support of ICA, Yunnan Copper Group and Nanyang Explosion Protection Group established a joint venture company (Yunnan Copper Die Casting Co. Ltd. [YCD]) to commercialize die cast copper rotor motors in China. In the last 10 years YCD matured their design and production technology making it possible to mass produce high-quality copper rotors both technically and economically. Copper rotor motors are proving a cost-effective way of meeting high-efficiency IE3 and IE4 motor standards.

ICA supported the Chinese government in developing two national standards for super-efficiency motors that use copper rotors. These are the world's first national standards for industrial motors with copper rotors.

While the initial cost of purchasing a copper rotor motor may be somewhat higher than less efficient standard motors, the life-cycle costs for a standard motor far exceeds the incremental costs of a copper rotor motor.

Collaborative Technological Projects

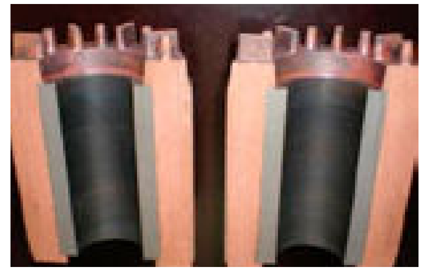
The Copper Rotor Motor program embodies the principles and objectives of the Copper Applications Technology Roadmap. As a result of well-defined technological needs, industry has organized collaborative efforts to fund and implement projects that produce innovative solutions that benefit society at large.

Facts

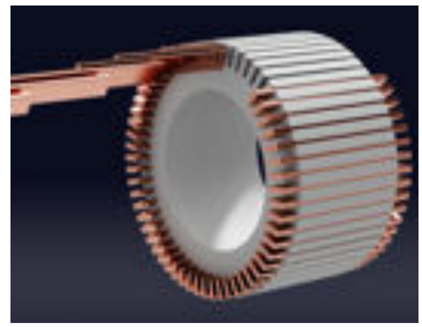
- Direct ICA funding 1996 – 2012: $2.7 million
- Co-funding from industry and governments: >$10 million
- YCD will ship about 80,000 die cast copper rotors in 2016 for use in high efficiency 0.75 – 45kW industrial motors
- Tesla Motors will ship about 80,000 cars with fabricated copper rotor induction motors in 2016
- Siemens is producing motors with die cast and fabricated copper rotors.

Key Business/Technology Learning

- The initial focus on high-efficiency, standard industrial motors, which was reasonable in 1996, is still attractive and economically viable. Regulators around the world are raising minimum efficiency standards for industrial motors and copper rotors provide a cost-effective route to achieve super-premium performance.
- Die casting of copper motor rotors is feasible and commercially viable on horizontal and vertical die casting machines. However, the economics are improved when the casting location is located close to a copper recycling facility so that excess copper from the die casting operation can by readily recycled.
- Inventive copper rotor fabrication technologies can reduce processing costs. One technology combines insertion of shaped rotor bars into the rotor stack with die casting of aluminum end rings, and another uses laser welding of end rings to inserted shaped rotor bars. These automated fabrication method allows most of the benefits of using copper in the rotor to be achieved while simplifying high volume production. They have led to an increase in the use of copper rotors in industrial and vehicle motors.
- Motor and rotor designs must be optimized to use die cast copper rotors effectively. Substituting copper in a rotor geometry designed for aluminum does not achieve maximum benefits. However, substituting a copper rotor for an aluminum rotor when refurbishing an older motor (a common practice) can improve efficiency by 2 – 3 percent, thereby upgrading an old motor from IE1 to IE3 efficiency.
- Custom motor designs can benefit from reduced material use, compact size and lighter weight that has been enabled by copper rotors.
- The copper rotor appears to be well suited to the needs of automotive propulsion systems, which was not a focus of the initial technology development effort. The automotive industry chose the permanent magnet motor architecture in the late 1990s when rare earth metal prices were substantially lower than they are today. As evidenced by the success of Tesla vehicles, the copper rotor induction motor is now proving to be an attractive and reliable replacement for that architecture.
- Industrial induction motor-driven systems using die cast copper rotors are no longer a research priority in the Copper Applications Technology Roadmap. This is because attention has shifted from research to application engineering and large-scale commercialization.
- An emerging opportunity is to create motor stator winding wires with lower resistance losses at normal motor operating temperatures. This is a focus for Ultraconductive Copper.



Cross-section Through Rotor Bars and End Ring of Die Cast Copper Rotor



Insertion of Shaped Rotor Bar into a Laminated Rotor Stack

Copper Rotor Propulsion Motor in Tesla's Powertrain

Fabricated Induction Motor Produced by Laser Welding of Rotor Bars to End Rings

Appendix C: Fundamental Properties of Copper

Pure or alloyed in literally hundreds of compositions designed to meet specific requirements, copper-based metals provide optimized properties for innumerable products.

- **Electrical conductivity**—Copper has an exceptional current-carrying capacity, better than any other non-superconducting conductor except for silver. The copper in today's building wire has a conductivity rating significantly higher than the International Annealed Copper Standard (IACS), the accepted maximum of a century ago. Copper's excellent electrical conductivity means motors with new copper rotors can be smaller and run cooler than traditional motors.
- **Thermal conductivity**—Copper conducts heat up to eight times better than other engineering metals. Combined with its inherently high-corrosion resistance and ready formability, copper's thermal conductivity makes the metal ideal for heat exchangers of all types, including heat pumps for space and water heating.
- **Antimicrobial effect**—Concerns over hospital-acquired infections and cross contamination in the food-processing industry continue to grow. The bactericidal, fungicidal and, to some extent, antiviral properties of copper, copper compounds and copper alloys have been known for centuries. Surfaces made with copper and many of its alloys are significant deterrents to the transmission of microbial-based infections in healthcare and air-handling systems.
- **Formability**—Copper's formability can cut installation time and reduce labor cost, particularly in the plumbing trades. Tubes and fittings are easily joined by soldering or brazing, and press fittings further reduce installation times. Copper and its alloys are ubiquitous in electrical and electronic components, including switches, current-carrying springs, connectors and lead frames. Hot- and cold-forged copper products are demanded when reliability and ease of machinability is a requirement. A number of cast copper alloys provide corrosion resistance as well as good thermal or electrical conductivity.
- **Corrosion resistance**—Copper metals can resist attack under a wide range of corrosive environments. This makes them ideal for applications in the offshore power, offshore oil and gas and desalination industries. In the presence of moisture and a variety of atmospheric constituents, copper in architectural products (i.e., roofing, flashing, leaders, gutters, domes and spires) eventually weathers to a protective patina that is attractive and retains its functionality for centuries.
- **Repeated recyclability**—Copper has the longest recycling history of any material. It is estimated that 80 percent of all copper ever mined (during the past 10,000 years) is still in use somewhere today. Recycling copper does not result in any reduction in quality or loss of properties; therefore, it can be repeated over and over again. Recycling saves natural resources, reduces energy consumption and avoids the loss of valuable materials.
- **Color/aesthetic appearance**—Copper is increasingly utilized for its aesthetically pleasing appearance and for the broad color palate offered by its alloys. As copper use extends to hygienic surfaces, the "look" of many copper alloys will increasingly be perceived as a "healthy" antimicrobial metal by consumers.
- **Ease of alloying**—Copper's industrial importance has grown due to the ease with which it alloys with other metals. The result is an extensive family of more than 400 alloys in use today. New copper alloys continue to be developed for existing and new applications.
- **Abundant and available**—Copper is an integral part of human life and civilization. Copper's fundamental properties have met society's needs throughout history. Fortunately, copper supplies remain abundant from mining and recycling. Copper is routinely processed by common manufacturing methods and is available in many forms and alloys that enable efficient production.

Appendix D: Trends and Challenges Influencing Copper Use

Market trends, regulations and innovations continue to influence copper use. While it is impossible to predict the future, insight into possible development pathways and priorities can be gained by considering common economic, social and technological forces that influence the global copper industries. For information on end-use markets for copper, see Appendix F.

- **Reducing processing costs**—To remain competitive, fabricators must continue to reduce their manufacturing costs while maintaining high product quality. Copper is routinely processed by common manufacturing methods and it is available in many forms and alloys that can be produced efficiently. Copper adapts to net-shape processing techniques. Some copper products can be semi-fabricated using the "upstream" electrowinning step in copper cathode production. Copper's ability to be manufactured as formed or in powder/metal (P/M)-derived products enabled significant cost reduction in a variety of electronic applications. For example, components for 150-A and 200-A fuse blowouts utilized in coal mining equipment were converted from machined copper bar stock to a near-net-shape powder/metal P/M copper part, saving approximately 25 percent in product costs.
- **Maximizing the value-added use of copper**—Manufacturers naturally seek to utilize the least amount of material consistent with optimum functionality. Improvements in engineering analysis, design methods, and process simulations allow materials to be used only where needed. In copper's existing market applications, there are opportunities to use less metal while maintaining or improving product performance. In addition, copper's value can be enhanced by a collaborative material selection process whereby copper experts, such as those at ICA and the Copper Alliance, provide a high level of technical support regarding new, emerging and established applications to all industries. For example, an increasing number of electrical applications require new alloys that combine mechanical strength and conductivity. The same concept applies to aquaculture applications where high mechanical strength is needed in combination with resistance to corrosion and growth of organic matter.

  Copper's ability to perform well even when used in reduced thicknesses and weight is a characteristic that presents added value. For example, in copper tubes used for drinking water, wall thickness can be reduced from 1.0 mm to 0.3 mm without destroying functionality. In solar thermal collectors, reducing copper sheet thickness from 0.2 mm to 0.12 mm reduces product cost. In automotive applications, copper's formability and high conductivity helps reduce the size of circuits, connectors and wiring harnesses.
- **Competitive pressure from other materials**—Many of copper's traditional markets have been challenged by metals, composites, polymers, multi-layer systems and other alternative materials. This is because end users of all materials are facing constant competitive pressures to improve performance, reduce cost, minimize material usage and demonstrate responsible stewardship. This has focused the copper industry on increasing its dedication to innovation and high-value applications. Copper often can offer systemic improvements and/or economies unachievable with other materials. While the cost of copper products may be higher than those made with other materials, copper is often the best suited and most cost effective material for specific applications in the long term. For these reasons, the copper industry continues to seek ways for copper, with its unique features, to offer system improvements unachievable with other materials. This strategy has helped to diminish the effect of cost sensitivity in purchasing decisions.
- **Changing regulations, codes, and standards**—As energy efficiency and sustainability issues remain at the forefront of business and government policy agendas, copper stands to benefit. Due to its properties, copper is increasingly perceived as an energy-efficient material, and one that is infinitely recyclable. In the motor industry, higher efficiency standards have been instituted and the market for high-, premium- and super-premium efficiency motors has increased. This bodes well for copper because energy efficient motors utilize more than 20 percent more copper in stator windings and conductor bars compared with older, "standard-efficiency" motors. Copper also benefits from energy efficiency increases in air conditioning, electrical grids and lighting products.

  Environmental regulations are prompting governments to support scientific investigations to understand the potential impacts of metals and other substances in soils, waters, wastes and sediments. The copper industry continues to be involved in these investigations.
- **Assuring performance of engineered copper products**—Computer simulation is increasingly applied to predicting and validating copper's performance in new applications. Miniaturization and material integration will prompt additional research into the mechanical properties of small systems, the behavior

of surface and sub-surface regions of copper and its alloys, phenomena that affect interfaces of copper with other materials and impacts of different materials on copper recyclability. The development and use of new alloys, combined with more stringent design constraints, requires that the properties of those alloys (and other, conventional materials) be known or predictable with high certainty. Improving the control of thermal, electrical, physical and mechanical properties will also enhance copper's performance in advanced applications.

An enormous technical literature database on copper is freely available online. It is supported by more than two dozen national and regional copper development organizations.

- **Increasing use of "complementary" engineered materials**—Additional (complementary) materials can be added to the surface of copper or embedded within it to improve its performance. Copper is frequently combined with other engineered materials to achieve a desired effect for a specific application. Complimentary materials applied to copper surfaces can produce thinner layers of electrical insulation, protection against rough handling, protection against corrosion or other desirable qualities. Demands for materials with higher strength-to-weight ratios have led to increased interest in composite materials, in which a reinforcing material is added to another material to increase strength and durability, and in some cases, reduce weight. Copper is not intrinsically a material with a high strength-to-weight ratio and it is not often used where this property is singularly specified. However, formulations such as silicon carbide fiber-reinforced copper-base composites have thermal conductivity and high strength properties at elevated temperatures.
- **Designing for recovery and re-use**—Copper is among the most efficiently recycled metals in global commerce because it is 100 percent recyclable without any loss in performance. Important too, recycling meets 34 percent of global copper demand. When total life-cycle costs are analyzed, superior energy efficiency and end-of-life recyclability make copper an attractive alternative in energy-related applications. Therefore, designs that enable recyclability will preserve copper's value while benefiting the environment. Today, copper is routinely extracted from automobiles, electronics and buildings at the end of their useful lives. It has become increasingly important for engineers to consider how products will be disassembled and the copper recovered. During manufacturing, some copper becomes waste, and this material needs to be recovered and recycled. Copper that is not contaminated with undesirable impurities facilitates reuse.

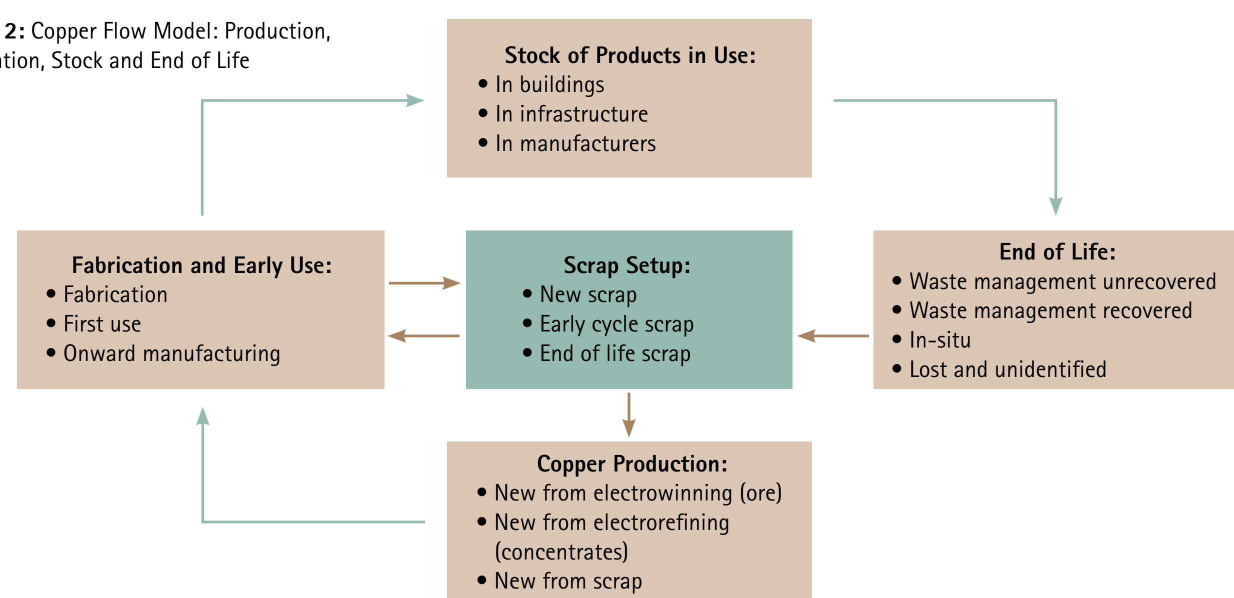
Appendix E: Copper Lifecycle

Sustainable mining practices and 100 percent recyclability add to the value and importance of copper. The broad range of properties of copper and copper alloys used in end-product applications can be obtained using newly mined or recycled copper. Copper materials can be recycled repeatedly without any loss in properties or performance. It has also been estimated that at least 80 percent of all copper ever mined is still in existence, due to copper's infinite recyclability.

- Refined copper originates through two quite distinct process chains. The smaller and simpler route is electrowinning, where refined copper is nearly always produced at the mine site by a leaching process. The more complex route incorporates electrolytic refining, where mined copper ore is processed into concentrates at the mine, processed further to make blister or anode copper at the smelter and processed again into refined copper cathode at a refinery. Scrap copper may be added at the smelter and refinery stages.
- Refined copper and high-grade scrap are combined for processing into fabricated products, primarily electrical wire, cable and mill products. Material may be used directly (as in plumbing tube), it may go through simple one-stage manufacturing (as in plumbers' fittings), or through one or more intermediate manufacturing stages (as in winding wire used in motors used in automotive). Once copper has gone through process stages to make a particular copper-based product, it begins its useful life. This is the "stock" phase of the product lifecycle. Copper products are classified by end-use markets, such as building construction, infrastructure and equipment manufacture.
- There are three options for copper scrap at the end of a product's life: it can be earmarked for materials recovery through a waste-management system, it can be disposed nonproductively or it can remain in situ where it is no longer used. Industrial engineers find that it is useful to categorize scrap as new scrap, early-cycle scrap and end-of-life scrap. The former two categories apply before copper enters its useful product life. This distinction is useful as new scrap, generated during fabrication and some first stage processing, is generally clean (free of undesirable impurities), while scrap in the latter life-cycle stages is more likely to contain impurities from other materials.

By collecting and aggregating industry and value chain life-cycle data, the ICA helps to demonstrate how copper creates an increasingly sustainable society.[4]

Figure 2: Copper Flow Model: Production, Fabrication, Stock and End of Life



Appendix F: Copper Demand in Applications Today

Copper is used in a wide range of applications and overall demand for copper continues to grow. In particular demand is buoyant among developing geographies with growing populations, increasing wealth and substantial government led investment. In these regions, copper supports important building blocks needed to raise living standards, bringing electricity, clean water and efficient transportation to support expanding economies. In geographies with established infrastructure and buildings, demand is partly underpinned by renewal and renovation. Copper is a common material in construction, energy, communications and transportation systems and products. Figure 3 illustrates global total end uses of copper, by product share, in 2015.[4] Base: 25 million tonnes copper content (estimated).

In 2015, electrical conductivity applications were 58 percent of the global copper market. Power cable was the largest material demand (15 percent), followed by building wire (13 percent) and magnet wire (12 percent). These products are used in usually larger scale applications such as power transmission, power distribution, transformers and motors. Semi-finished products were 38 percent of the copper market. These products are used by industries to make finished goods and are segmented according to physical shape: alloy plate, sheet and strip, alloy rod, bar and section, alloy tube, copper foil, copper plate, sheet and strip, copper rod, bar and section and copper tube. Copper foundry products and powder were 4 percent of the market.

The largest product demand is seen in electrical conductivity including wire, cables, bus bars and other electrical components. In 2015 demand for copper products was largest in the Asia region, in particular China.

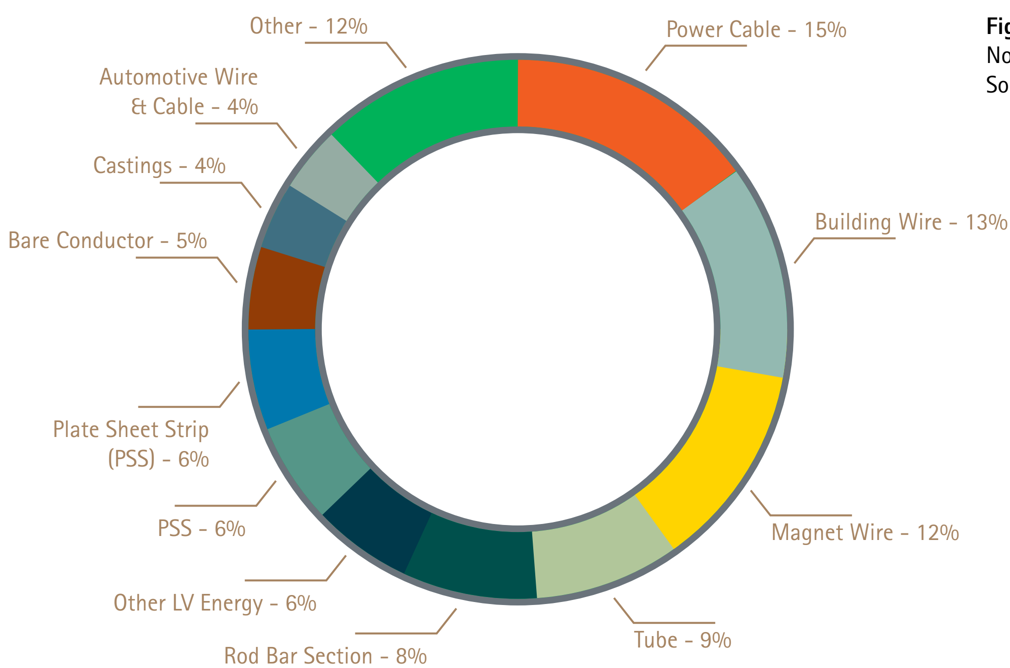


Figure 3: 2011 End-Use Markets for Copper
Note: Figures are rounded
Source: ICA Global End Use Data Set

Appendix G: References

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[4] Copper Alliance website copperalliance.org/core-initiatives/development/

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