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The future of the red metal—scenario analysis

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Abstract

A regional copper scenario model has been developed from the perspective of the generic Intergovernmental Panel on Climate Change framework for greenhouse gas emissions scenarios for the four world regions: OECD90, ASIA, REF, and ALM. A set of three scenarios: Tech World, Green World, and Trend World, each representing the significant driving forces influencing population and economic growth, technological change and environmental consciousness, is presented. Intensities of copper use converge in the long-term in the Tech and Green World as GDP per capita level approaches $100,000. Global copper use, currently 15 Tg Cu/yr, is expected to rise to 30–130 Tg Cu/yr by the year 2100. The rate of copper use in the ASIA and ALM regions exceeds the copper use in the OECD90 and REF regions beyond 2020. A Green World corresponds to per capita global copper use of 4 kg Cu/(capita-yr) as compared to the contemporary global level of 2.6 and 10 kg Cu/(capita-yr) in developed regions, symbolizing the sustainability theme. For the OECD90 region, the results are more sensitive to the copper intensity of use variable whereas for ASIA and ALM regions, variations in GDP per capita can influence copper use.

1. Introduction

The techniques of scenario analysis have evolved over the last several decades and are now extensively used by strategic planners and policy makers to study how the future might unfold [19]. The process of foretelling the future presents daunting challenges to the futurist, because characterizing the interplay between the driving forces that influence future events is highly challenging [7]. Peter Schwartz, in his classical book *The Art of the Long View*, outlines the broader framework of scenario planning, as a strategy tool to

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overcome those challenges [16]. Royal Dutch Shell was the first corporate enterprise to embrace Schwartz's scenario planning framework in its day-to-day operations and is widely admired in the business community as the best-known user of scenarios [4,20]. Scenarios are scripts of the future, drawing clues from past and contemporary events. Scenarios are often misconstrued as forecasts or predictions. In the world of forecasting, it is the general tendency of the practitioners to make single point discrete forecasts. The probability of success of a single point forecast is usually not very high; an illustrative example with regards to copper is shown in Fig. 1. In the United States, the National Science Foundation commissioned a study in 1975 under the leadership of Dr Wilfred Malenbaum, Professor of Economics at the University of Pennsylvania [12]. The objective was to determine the demand for 12 raw materials for 10 global regions and/or countries in the years 1985 and 2000. The methodology adopted was to use an intensity of material use, defined as the ratio of material use to gross domestic product (GDP), model to make future forecasts. For the year 2000, the difference between actual copper use and Malenbaum's prediction for the countries China, Japan, and USA was 915, −844, and −138 Gg, respectively. As shown in Fig. 1, except for China the general trend is a decline in intensity of copper use with increasing GDP per capita. In China, opposing trends are observed between the Malenbaum prediction and actual intensity of use. Malenbaum assumed a rapid increase in intensity of copper use as compared to an increase in GDP per capita for China. For Japan, Malenbaum assumed GDP per capita would grow faster than decline in intensity of copper use.

In scenario building, a set of alternative futures is presented under different groups of assumptions (e.g. high economic growth or low economic growth) rather than singular forecasts such as by Malenbaum, each with its own unique script (the 'storyline'). Scientists develop scenarios to study how the future might unfold under a particular set of

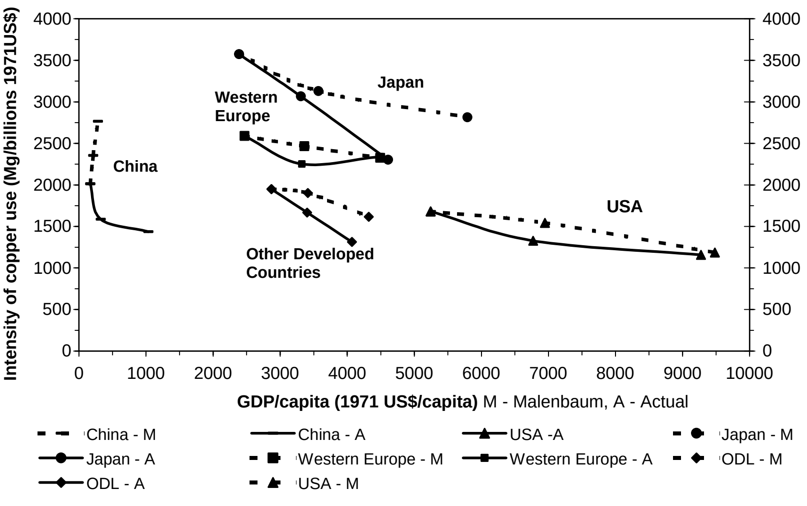


Fig. 1. Comparison of Malenbaum's intensity of copper use predictions for different countries with actual observed values. (The first point for each country is 1975, the middle point is 1985 and the end point is the year 2000.)

assumptions and actions. The results allow policy makers to decide whether to move ahead in a desired direction or to plan for alternative approaches. The development of material flow scenarios is critical from a resource and environmental policy point of view, as both resource availability constraints and environmental pressures would determine the future rate of use of materials and would accordingly drive the technological change for either more efficient production or enhanced recovery and reuse/recycle of secondary materials. Material flow scenarios can also compare alternative substitutions among materials that could, for example, achieve greater input efficiency (lower resource use per unit economic output) or greater output efficiency (lower emissions per unit of economic output) [22].

In this paper, the methodology and results of three scenarios—Tech World, Trend World, and Green World—for copper use in the 21st century are presented. The assessment of resource availability, environmental, and material substitution concerns of the three scenarios and the corresponding implications for policy are presented in follow up papers [10,11].

The name of each scenario refers to the dominant driving force influencing the future. The ‘Trend World’ scenario is a ‘business-as-usual’ scenario, in which the system in the future represents a picture of things continuing to happen in the same way that they are happening now. The ‘Tech World’ scenario assumes that rapid technological change and high economic growth determine the future material flows. The basis for the Green World scenario is a vision of a world that is increasingly environmentally sensitive.

2. Methodology

A scenario building is a creative art that involves generating innovative ideas about the future, ideas well supported by the contemporary state of scientific knowledge. The futurist usually first portrays the storyline for the future, and thereafter, wherever possible, makes an attempt to quantify the scenario’s driving forces and the plausibility of the end result. In certain cases, the futurist builds scenarios by drawing upon intellectual knowledge base of subject experts or individuals who have a well-informed opinion of the system(s) under consideration. In developing the future scenarios for copper use for this study, the following methodology was adopted:

- Use of the Intergovernmental Panel on Climate Change (IPCC) emission scenarios for greenhouse gases (GHG) as the background framework;
- Selection of spatial units of analysis and temporal scale;
- Formulation of scenario storylines for future material intensity and copper use;
- Statistical analysis of historical data;
- Assessment of expert opinion through a questionnaire survey;
- Quantification of the scenario.

2.1. IPCC scenarios framework

The Intergovernmental Panel on Climate Change in its Special Report on Emission Scenarios (SRES) has developed a widely known and respected family of four scenarios—A1, A2, B1, B2—that describe future worlds that are generally more affluent than those of the present [9]. All the scenarios assume continuous economic growth for different regions of the world, although rates of growth differ among regions and over time. The A1 scenario represents a technological world with extremely high economic growth, where global GDP will be $550 trillion by 2100, an 18-fold increase from the present level [9]. The income levels between developed and developing countries will converge, but gaps will persist. The B1 scenario represents a world where environmental issues are a priority along with high economic growth, where global GDP will be $350 trillion by 2100, lower than A1 scenario [9]. The theme of both the A1 and B1 scenarios is that of global linkages and cooperation. In both scenarios world's population peaks to approximately 8.7 billion by middle of the century and declines thereafter to 7 billion by 2100 [9]. The A2 scenario represents a fragmented world where there are trade barriers and the theme is reliance on regional or local resources only to achieve economic growth. The B2 scenario is similar to the A2 scenarios except for that the B2 scenario focuses more on the environment. In both the B2 and A2 scenarios, global population continues to increase, and by the year 2100 is expected to reach 10 and 15 billion, respectively [9]. The extent of economic growth and technological change in the A2 and B2 scenarios is lower than in the A1 and B1 scenarios.

The scenarios are shown conceptually as branches of a two-dimensional tree in Fig. 2. Each of the scenarios is defined by global–regional and development–environmental themes, respectively. The roots of the tree represent the critical drivers for each of the scenarios. They range from very rapid economic growth and technological change to high levels of environmental protection, from low to high global populations, and from high to low GHG emissions. In the SRES report IPCC states: "It is recommended that a range

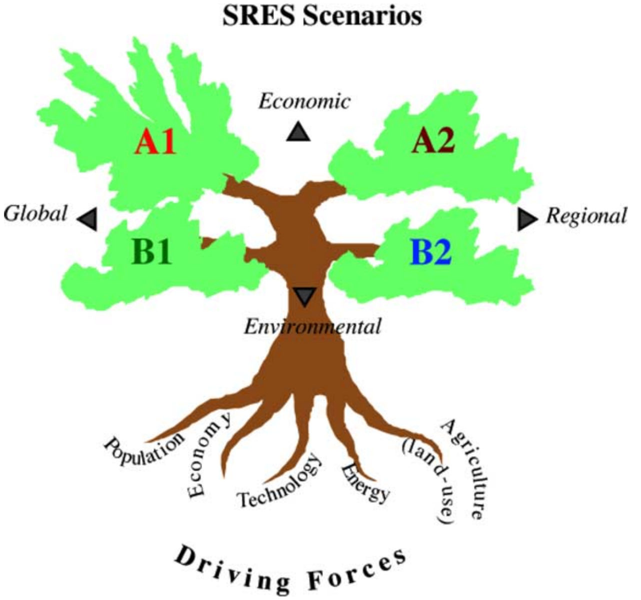


Fig. 2. Schematic illustration of SRES scenarios [11].

of SRES scenarios with a variety of assumptions regarding driving forces be used in any analysis" [9]. Taking inspiration from this statement, the present study utilizes the SRES scenarios as the basis for the development of scenarios for material use. The interrelationship between the SRES scenarios and the present study is the set of common scenario driving forces, i.e. demographics and economics. This set of driving forces and associated data variables is an essential component of any scenario-building exercise. IPCC's SRES report has done a very comprehensive review of the literature and of available knowledge concerning how these variables are likely to interact and behave in the future, and has built on this information to correspondingly develop quantitative projections up to year 2100. The present study draws upon the qualitative description of the SRES scenarios and utilizes the quantitative projections for GDP and population in developing scenarios for future rates of use of copper.

Three copper scenarios are developed, termed Tech World, Green World, and Trend World. Their baseline data and theme of the scenario storyline are similar to IPCC's A1, B1, and B2 scenarios, respectively. (A 'copper A2' is thought to be less likely and hence has not been developed.) As per the IPCC data, all GDP per capita values are in constant 1990 US dollars, based upon the market exchange rate. GDP per capita values expressed in purchasing power parity terms (PPP) were not utilized in this study, as historical time series data on PPP estimates for GDP per capita are not available. Also most of the countries in developing regions import large quantities of copper as compared to their domestic production, therefore the use of market exchange rate based GDP per capita was considered more appropriate for this study. The dependent parameter added in this work, the intensity of copper use, was based upon apparent refined copper use, for which a country or a region is defined as the sum of refined copper from domestic production, plus imports, minus exports, and change in stocks. The term 'use' here refers to the copper that enters the fabrication and manufacturing system of a country's economy. The historical data for apparent refined copper use was collected from various editions of metal statistics bulletins and yearbooks published by the World Bureau of Metal Statistics (WBMS), the International Copper Study Group (ICSG), and the United States Geological Survey (USGS). The data sources were inconsistent in reporting whether apparent refined copper use data included both primary and secondary copper production.

2.2. Spatial units of analysis and temporal scale

The spatial units of analysis selected for this study were the four-macro world regions given as follows:

- OECD90: This group includes all the countries belonging to the Organization for Economic Cooperation and Development (OECD) as of 1990;
- ASIA: All developing countries in Asia;
- REF: All countries undergoing economic reform, grouping together the East European countries and the Newly Independent states of the former Soviet Union;
- ALM: The rest of the world including all developing countries in Africa, Latin America, and the Middle East.

Table 1
List of countries for each region included in the scenario analysis

Region	Countries
OECD90	Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Japan, Italy, Ireland, Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States of America
ASIA	China, Hong Kong, India, Indonesia, Malaysia, North Korea, Philippines, Singapore, South Korea, Thailand, Taiwan, Vietnam
REF[a]	Albania, Bulgaria, Former Czechoslovakia, Czech Republic, Hungry, Kazakhstan, Poland, Romania, Russia, Slovakia, Ukraine, Uzbekistan, Former Yugoslavia
ALM[a]	Argentina, Brazil, Chile, Cuba, Egypt, Peru, South Africa, Venezuela, Zambia, Zaire, Zimbabwe

[a] For other countries in these regions, apparent copper use data was reported under the ‘Other’ category. Specific names of those other countries included in the data are not available.

The list of countries included in the scenario analysis for each region is given in Table 1. The time scale chosen for the scenario analysis is the period 2000–2100. The four world regions and temporal scale were chosen as per the IPCC’s framework.

2.3. Scenario storylines

The core themes for each of the scenario storylines have been drawn from the IPCC’s SRES storylines. The SRES storylines provide the basic structure of the scenarios in terms of describing what will be the factors that will influence growth of population, gross domestic product, and new technologies. Although the SRES scenarios do not prescribe any climate-oriented policies, but broadly describe the level of importance given to environmental concerns. As part of this study, the SRES storylines have been interpreted in greater depth from the point of view of intensity of material and copper use.

2.3.1. Tech World storyline

The Tech World scenario describes a future world of “very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence of income levels among regions; capacity building of less technologically advanced countries, and increased cultural and social interactions, with substantial reduction in regional differences in per capita income” [9].

Affluence and technological change are the two main driving forces in the Tech World scenario. A richer and technically superior world symbolizes the arrival of new goods on a more frequent basis. The material desires of global citizens are unlimited. Communication and transport technologies drive the direction of this scenario towards a more comfortable and productive mobility in urban areas. Diffusion of technologies is very rapid across regions. Although technology is the major driving force, the developing countries of the South ‘catch up’ with the North by virtue of the wealth created from human capital and through free trade across regions with no barriers. The per capita income level converges and the distinction between poor and rich nations disappears, although the convergence is over the long term and is not rapid during the next 20–30 years.

Material resources are not a limiting constraint in this scenario. Technology enhances per-unit resource use productivity and recovery of marginally economic reserves. However, as a society we remain inefficient in terms of how we utilize the materials to produce goods and the rate at which we use them and later discard them into the environment. Technological optimism overshadows resource depletion concerns. The decline in the intensity of material use is inhibited in developed countries and attains stabilization at high-income levels. In developing economies, intensities of material use continue to rise and technological leapfrogging to a less material intensive economy does not occur in the short to medium term. Environmental protection is not considered a high priority, although future laws and regulations do become more stringent with time. The rates of recovery and recycling of secondary resources improve on an incremental basis. The global society continues to create more ‘technomass’ and subsequently generates more post-consumer discards as the ‘in-use’ technomass exits the economy at the end of its lifetime. The lifetimes of new goods tend to become shorter with time. Lack of market-based instruments and policies do not promote technological development in waste management systems. The world is more technologically superior with high material use, but does not embrace a ‘design for environment’ philosophy.

In terms of implications for copper, in developed countries the intensity of copper use continues to decline as economies shift more towards the service sector and the demand for development of new infrastructure is relatively low. The increased demand for electronic goods, automobiles, and other advanced new technological artifacts that continue to penetrate the consumer markets drive copper use. Homeland security concerns would drive the use of more automated electrical systems and electronic devices for surveillance in industrial, commercial, and residential sectors. In developing countries, high economic growth would result in more demand for energy, infrastructure, and basic services which will lead to a higher intensity of copper use (End use applications of copper like plumbing and wiring would dominate). However, in certain sectors, such as electronics, telecommunications, and transport, copper use per unit of sectoral output will decline on account of their faster learning rate and rapid advances in technical knowledge. After intensity of copper use peaks in developing countries, it converges to developed region levels. The developed world will lead in technical innovation and change, through the investments in research and development efforts to develop substitutes for copper in certain end use applications, and also reduce copper use in the manufacture of finished products (e.g. use of copper alloys with less copper). The large amount of copper stock accumulated in technological societies would offer enormous potential for recovery and reuse of copper.

2.3.2. Green World storyline

The Green World scenario describes a “convergent world with low population growth. There are rapid changes in economic structures towards a services and information economy, with reductions in material intensity, and with the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity” [9].

The Green World scenario reflects an idealistic world moving towards the path of sustainability. In this scenario, sustainability is perceived to be a state of minimal use of natural resources, and of recognition of wastes as beneficial nutrients by closing the loop through reuse and recycling. Social concerns of equity and equitable use of resources are put into practice through effective governance and formalized institutional frameworks at all levels. The system introduces market based instruments and policies to promote environmental management and pollution prevention. Such win–win strategies encourage innovation and, thereafter, large-scale diffusion of clean and Green technologies across different economies. Economic growth is achieved through enhanced productivity in resource use, environmental protection, and uniform distribution of income. The world is affluent, highly globalized, and technologically driven to support a high quality of life, and the convergence of economies is rapid, with inherent disparities in per capita income levels diminishing. In this scenario, intensities of material use of different economies converge to low levels. Potential 'dematerialization' of the global economy occurs by virtue of technological change, economic incentives, and proactive environmental policies. 'Smart' materials, mainly complex bio-engineered molecules derived mainly from renewable sources, are designed with the ability to reincarnate themselves into the product life cycle infinitely, with minimal loss to the environment. The stock of traditional materials from the contemporary era slowly diminishes and the materials exiting the economy are utilized to the best extent possible with the available technologies. There is an appreciable decline in virgin extraction and production of resources. Product stewardship is more service oriented. The transformation of goods into services guarantees adequate insurance against environmental damages throughout the life cycle, especially during the use and end of life phases. Material intensity of use declines further on account of changes in material use patterns. The internalization of environmental externalities in the form of taxes or the elimination of subsidies influences behavioral attitudes of consumers towards profligate use of materials.

The decline in intensity of copper use is achieved through material substitution and technical advances in the capture and utilization of secondary copper. Copper substitutes penetrate the telecommunications, electronics/electrical, and building construction sectors. The telecommunications sector is characterized by high bandwidth wireless, satellite, and optic fiber systems. Superconducting materials are feasible for large-scale commercial use, although copper use might still prevail in local power distribution loops and electric motors.

2.3.3. Trend World storyline

The Trend World scenario describes a "world where the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than Tech World and Green World scenarios" [9].

A Trend World scenario is a world where the global economy is decentralized, non-converging, and less homogenous as compared to the Tech and Green World scenarios. The world's wealth remains concentrated in only a handful of nations. Contemporary trends in economic growth and technological change prevail. Innovations in technology are largely regionally oriented. Therefore, diffusion of technologies across regions is slow. International cooperation and agreements to address global environmental concerns remain a challenge, as the question of sharing the burden on a developed–developing country basis remains unresolved. In contrast, environmental governance at the grassroots is achieved by setting up appropriate institutions that are very effective in providing desired policy responses and mitigation measures to localized environmental concerns.

The intensity of material use continues to grow in developing regions, attains peak intensity of use in the medium term, and thereafter, decline slowly. In developed regions, the rate of decline of intensity of material use is slower as compared to the Tech and Green World scenarios. In this scenario, copper use continues to grow in its conventional end uses. Substitution of copper through technological leapfrogging to a less copper intensive system is primarily limited to the telecommunications sector. In developed regions, advances in electronics, electrical, and transport sectors will drive copper use, whereas in developing regions the building and construction sector would be the primary driver.

2.4. Statistical analysis

The long-term historical time series data for copper use over the last century is available only for OECD countries such as the United States and Japan. In Fig. 3, the intensity of copper use for United States and Japan for the last 100 years is plotted against GDP per capita, expressed in constant 1990 US$. Although one can observe huge variations in intensity of copper use over a small range of GDP per capita values, but a distinct inverted-U pattern is visible in the raw data. Non-linear regression analysis mathematically corroborates the inverted-U relationship between the intensity of copper use and GDP per capita. The data fluctuations could be due to significant changes in either copper use or GDP or population during the periods of instability such as wars (e.g. World Wars I and II), economic depression (e.g. The Great Depression in the 1930s, Oil crisis in the 1970s), etc. Without a detailed investigation, it is difficult to accurately pinpoint the causal factor for each extreme intensity of copper use value, but it is evident that as

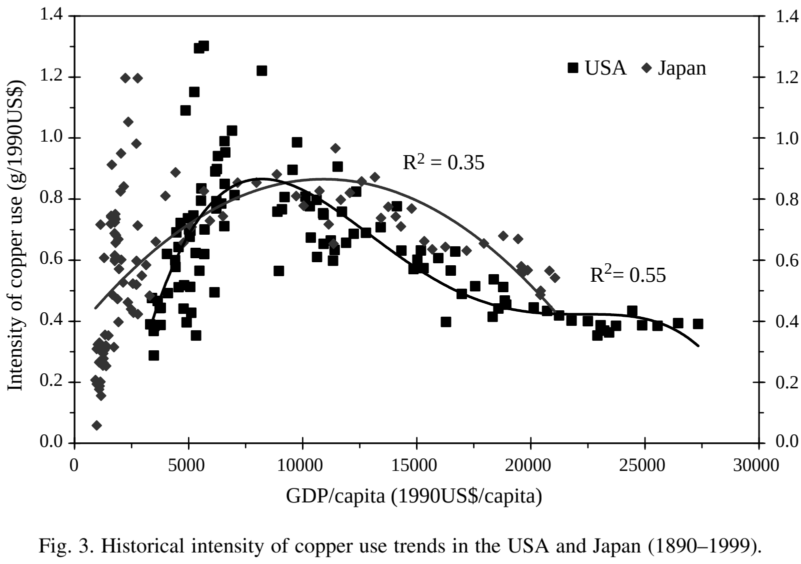


Fig. 3. Historical intensity of copper use trends in the USA and Japan (1890–1999).

the economies of United States and Japan progressed during periods of stability and instability in the 20th century, the intensity of copper use increased for the first 50–60 years and thereafter, it has been declining over the last 30–40 years. A similar trend was observed for other OECD90 countries as well such as United Kingdom, France, South Korea, etc. (The inverted-U shaped relationship between the level of environmental degradation and per capita income is also referred to in the literature as the Environmental Kuznets Curve (EKC) [8,17].) The inverted-U trend can be explained in terms of the changes in the product composition of income and material composition of products [14]. The product composition of income refers to the structural changes in the economy, as one moves from a low, resource intensive, agricultural base to a high, resource intensive, manufacturing base, leading to a peak in intensity of resource use and thereafter to a decline as the economy base shifts to the service sector which is also low resource intensive. The material composition of products refers to the changes in intensity of use due to material substitution and technological change. The intensity of resource use is considered an important indicator to develop scenarios for resource use as it captures the changes in patterns of overall resource use in relation to a country's economic growth. Technological innovations in resource production and use are also indirectly reflected in the intensity of use curve. A physical indicator such as resource use per capita could also be potentially used to make scenarios for resource use. The per capita copper use trends for the OECD90 region for the last 100 years are shown in Fig. 4. The per capita copper use trends in the OECD90 region indicate a uniform increasing trend different from the intensity of copper use curve where one can observe a declining trend. Therefore, the physical indicator does not signify the changes in product composition of income and material composition of products. The United Nations has included the intensity of material use indicator in its list of plausible indicators of sustainable development [1,6].

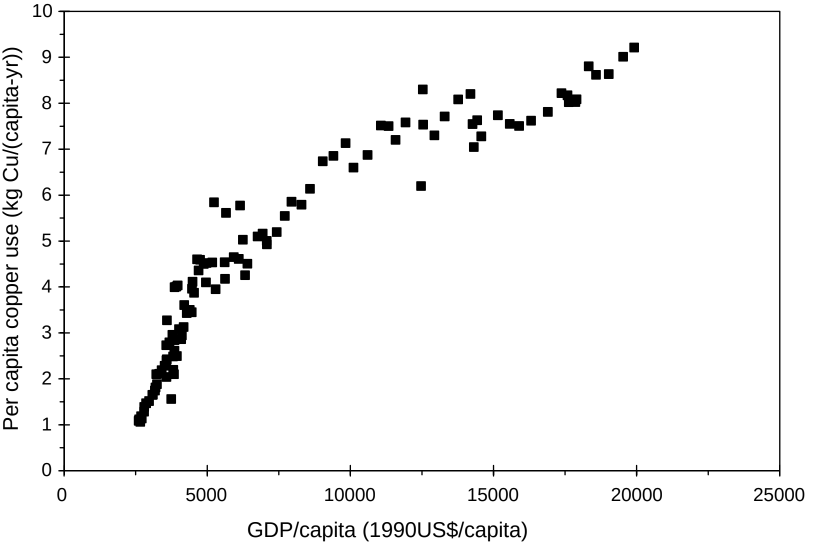


Fig. 4. Per capita copper use trends in the OECD90 region (1890–1999).

Therefore, for this study on scenario analysis for alternative copper futures the inverted-U hypothesis was assumed to hold for regions other than OECD90. However, the developing regions may not observe peak intensity of use values at similar income level as the OECD90 region and their rate of decline of intensity of use might be greater or lower than the OECD90 region. This will depend upon how fast there are growing and how rapid is the diffusion of technological change from developed to developing regions in different scenarios.

2.5. Scenario quantification

The objective of the scenario quantification process is to project the most plausible trajectory for intensity of copper use as a function of GDP per capita for a given region within the theme of the scenario storylines. Based upon the estimated intensity of copper use, the rate of copper use for a given region in a particular scenario can determined by the following equation

$$\text{Cu use}_{r,t,s} = (P_{r,t,s}) \times ((\text{GDP/capita})_{r,t,s}) \times (I_{r,t,s}) \quad (1)$$

where P is the population, I is the intensity of copper use, s is the scenario, r is the region, and t is the time.

Therefore, to make different scenarios for copper use, we need different scenarios for population, GDP per capita, and the corresponding values of estimated intensity of copper use. The future projections for population and GDP/capita in Eq. (1) over the time period 2000–2100 for each of the world regions under different scenarios have been provided by IPCC [9]. In order to project the intensity of copper use, the inverted-U curve can be conceptually broken down into three stages: the incline phase, the decline phase, and the stabilization phase (as illustrated in Fig. 5). In the incline phase, the intensity of copper use increases until it reaches the peak or the turning point, beyond which the intensity of copper use starts to decline. A stabilization phase has been added to the conventional

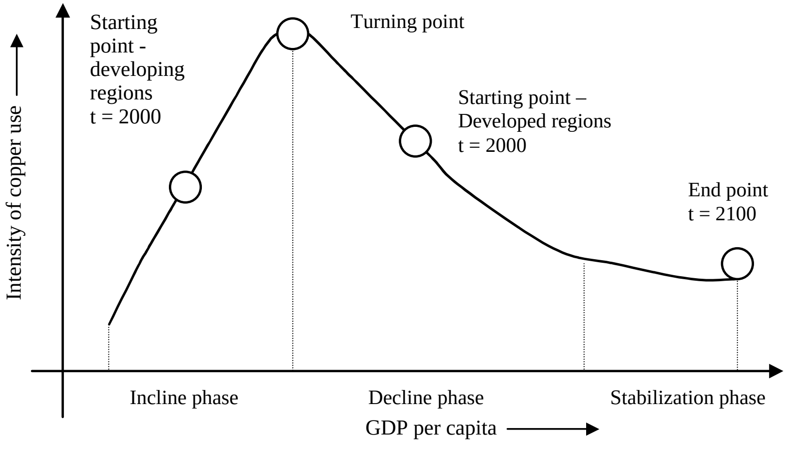


Fig. 5. Conceptual sketch of the environmental Kuznets curve (inverted-U curve).

inverted-U curve under the assumption that at extremely high GDP per capita levels in the future, the intensity of copper use will not approach non-physical limits, i.e. intensity of copper use will assume a null value. Presently, the developing regions are on the incline phase and the developed regions are in the declining phase. For developing regions, beginning from the start point at time, $t=2000$, the quantification process involves the determination of the turning point, the trajectories for the decline and stabilization phases, and the end point of the stabilization phase at time, $t=2100$. In developed regions, the quantification task is to determine the stabilization end point at time, $t=2100$, and extend the declining phase of the curve into stabilization phase until the end point.

Using the above conceptual description for scenario quantification, the actual procedure involves the following steps:

- Determination of the mathematical form of the proposed scenario model within the system's boundary conditions;
- Determination of the turning and/or end points for different regions;
- Iterative curve extrapolation until consistency between scenario storylines and quantification results is achieved.

The inverted-U relationship can be mathematically expressed either as a second-order (quadratic) or as a third-order (cubic) polynomial [3]. The generic governing equations are as follows

$$y = a_1x^3 + b_1x^2 + c_1x^1 + d_1 \tag{2}$$

$$y = a_2x^2 + b_2x + c_2 \tag{3}$$

where y is the intensity of copper use expressed in grams per 1990 US\$, x is the GDP per capita expressed in 1990 US\$, and a_1, a_2, b_1, b_2, c_1, c_2, and d_1 are constants.

The quadratic function was preferred over the cubic polynomial for the scenario model, as the cubic function in certain cases assumes a N-shaped curve, where after the second inflection point, the dependent variable starts to increase again with an increase in the independent variable [1]. The scenario model was subjected to the following boundary condition:

$$\lim_{t\to 2100} y \neq 0 \tag{4}$$

where t is time variable expressed in years.

This boundary condition was imposed upon the model under the assumption that there will be still certain end-use applications where copper will be still used over the next hundred years in all the regions across the three scenarios. Although time is not an independent variable for the scenario model, the corresponding GDP per capita projections for the different time periods were utilized in the analysis. The second order polynomial was extrapolated using declining exponential or logarithmic curves to bridge the transition between the declining phase and the stabilization phase such to provide an asymptotic characteristic to the intensity of copper use curve at high-income levels.

The generic governing equations for the exponential and logarithmic curves are as follows

$$y = a_3\, e_3^{-bx} + c_3 \tag{5}$$

$$y = -a_4 \ln(x) + b_4 \tag{6}$$

where y is the intensity of copper use expressed in grams per 1990 US\$, x is the GDP per capita expressed in 1990 US\$, and a_3, a_4, b_3, b_4, and c_3 are constants.

The determination of the plausible turning point for regions such as ASIA and ALM, where peak intensity of copper use has not yet been observed, was done after the analysis of the present rates of growth of intensities of copper use and GDP per capita in different countries vis-à-vis the overall region (e.g. China, India, South Korea, Taiwan, etc. in ASIA; Brazil, Argentina, South Africa, etc.). Also the historical evidence from the other two regions, where the intensity of copper use curve has experienced the turning point in the income level range of $6000–10,000 [23,18] served as a benchmark to determine the turning points for ASIA and ALM. The plausible range of peak intensity of copper use values determined for different regions across all the three scenarios are given in Table 2. The estimation of the end point of the stabilization phase is not as straightforward as the determination of the turning point. The end point can be determined mathematically using regression analysis techniques, or the futurist, using his or her subjective judgment, could fix the end point at a discrete value. The plausible range of end points for different regions across all the three scenarios are also given in Table 2. The peak intensity of copper use and end points for each region are discussed in more detail in Section 3.

Given the three points—the start point at $t=2000$, the turning point, and the end point at $t=2100$, the next step in scenario quantification is to extrapolate the historical

Table 2
Plausible range of peak intensity of copper use values across the three scenarios

Region	Range of peak intensity of copper use (g/$)	End point intensity of copper use (g/$)	Remarks
OECD90	0.9	0.05–0.4	Historically peak intensity of copper use observed at approximately $6000 income level
ASIA	1.3–1.8	0.1–0.6	This region is expected to grow faster than rest of the other regions for next few decades. The peak intensity of copper use will be achieved in the income level range of $1500–$4000, faster than the OECD90 region
REF	0.8–1.0	0.07–0.4	As this region returns to stable economic growth, its intensity of copper use will start to increase again and peak in the income level range of $5500–$6500, similar to the OECD90 trajectory
ALM	0.4–1.0	0.12–0.3	This region is expected to achieve peak intensity of copper use lower than the ASIA region in the income level range of $3000–$7000. This region has the potential to gain maximum benefit from technological leapfrogging opportunities, as most of the economies in this region are Agrarian based whereas in ASIA they are dominated by both manufacturing and service sectors

trends to provide a best fit intensity of use curve through the three points. This process could be iterative to ensure consistency with the theme of the scenario storyline. Another criterion to be met is that the change in slope of the intensity of use curve should be minimal at the point where the second-order polynomial and the asymptotic exponential or logarithmic curves intersect, so as to avoid a sharp change in curvature of the curve.

Based upon the above considerations, the scenarios for copper use for different regions were quantified and the details for each scenario are provided in the following sections.

3. Scenario development

3.1. Tech World

The end point for intensity of copper use for the year 2100 for the Tech World was determined statistically. The historical time series data of intensity of copper use and of the GDP per capita for the OECD90 region was subjected to double logarithmic regression ($R^2=0.87$). Based upon regression coefficients, the intensity of copper use approached 0.2 g/$ as GDP per capita levels approached $100,000. Two sub-scenarios, ASIA-High, and ASIA-Low, were constructed for ASIA, as the region is growing very rapidly and there is a high uncertainty as to when ASIA would attain peak intensity of copper use. The range (1.6–1.8 g/$) of peak values of intensity of copper use was determined by comparing ASIA's rates of growth with those of the OECD90 and REF regions. The upper bound of peak intensity of copper use was fixed at 1.8 g/$, as this is the historically highest peak observed in the REF region in the early 1980s. It is anticipated that countries in ASIA will be resource intensive in the short-term, but not resource inefficient, unlike the REF region in the 1980s [15]. The peak intensity of copper use in ASIA will occur at a lower GDP per capita (<$5000) as compared to OECD90. ASIA's trajectory will converge to the OECD90 path as GDP per capita approaches $30,000. Given the REF's region proximity to Western Europe, its potential for technological leapfrogging is high; therefore, the REF region would peak relatively quickly once their economies come out of transition and thereafter would converge to the OECD90 trajectory earlier than ASIA. REF would peak at GDP per capita levels similar to OECD90. ALM would be the last region to peak and consequently, would converge to the OECD90 path slowly.

3.2. Green World

The Green World scenario storyline outlines the scenario as the one where the material intensity of use approaches extremely low levels. It is very difficult to estimate a minimum level of intensity of material use that can sustain the needs of an economy. As a result, the Green World scenario was constructed on a normative or descriptive basis by assuming the long-term asymptote of intensity of copper use to be 0.05 g/$ as the GDP per capita levels approach $100,000. Therefore, the end point for Green World is a factor four lower than the Tech World. The regions ASIA, REF, and ALM converge onto the OECD90 trajectory as the GDP per capita levels approach $25,000, although the convergence is much faster for ALM and ASIA than for REF. ALM converges faster than ASIA, as its peak intensity of copper use is lower than that of ASIA. REF converges slowly, as it is perceived that adoption and implementation of ‘Green policies’ would depend heavily on how institutions in these countries will move from a command and control regime to a more open and market-based systems.

3.3. Trend World

In addition to utilizing the IPCC’s framework for constructing the scenarios, an expert opinion study was carried out as part of this research. The use of expert judgment in future systems planning is indispensable. Experts, or ‘well-informed’ individuals, by virtue of their extensive experience and expertise possess factual knowledge and analytical diagnostic capabilities. They can understand the structure of the present problems relatively better than non-experts and can devise plausible strategies to direct efforts towards a desirable future. The use of expert opinion, popularly known as Delphi Analysis, was originally developed in the 1950s by Olaf Helmer and Norman Dalkey, both scientists at the Rand Corporation, as an iterative, consensus building process for analyzing different futures. Delphi operates on the principle that several heads are better than one in making subjective conjectures about the future, and that experts will make conjectures based upon rational judgment rather than merely by guessing [21].

In this study, the expert opinion approach was carried out in two rounds. The experts who agreed to participate were primarily from academic institutions and industry organizations. The response rates in the first and second rounds were 41 and 75%, respectively. In the first round, each expert was requested to extrapolate the trends for apparent use of refined copper and intensity of copper use for different regions for all three scenarios, and also provide his or her subjective opinion on anticipated technological change in copper uses in the future. In the second round, each expert was provided with the analysis of the results of the first round and was asked if he or she would like to revise the estimates from the first round, the objective being to seek consensus or convergence among the experts.

The expert opinion study provided the following insights:

- The experts were either inconclusive or skeptical about their ability to comment on the rate and direction of technological change for copper in the next 50 years;
- The variations among the three median values (one for each scenario) of extrapolated intensity of copper use trends for each region were within $\pm 10\%$.

It was determined that the conventional wisdom of experts selected for this study was aligned in one direction, with no major deviations observed from ‘business-as-usual’ results, even if the experts were presented with alternative futures. Therefore, on account of consensus among experts on a ‘business-as-usual’ scenario for copper, the results from the expert opinion study were utilized to quantify the Trend World scenario.

4. Results

4.1. Intensity of copper use trends

The intensity of copper use trends for Tech World and Green World for the regions OECD90, ASIA, REF, and ALM, are shown in Fig. 6(a)–(d), respectively. Also shown in these figures are historical trends for intensity of copper use until the year 2000. The intensity of copper use trends for the Trend World scenario is shown in Fig. 6(e) for all

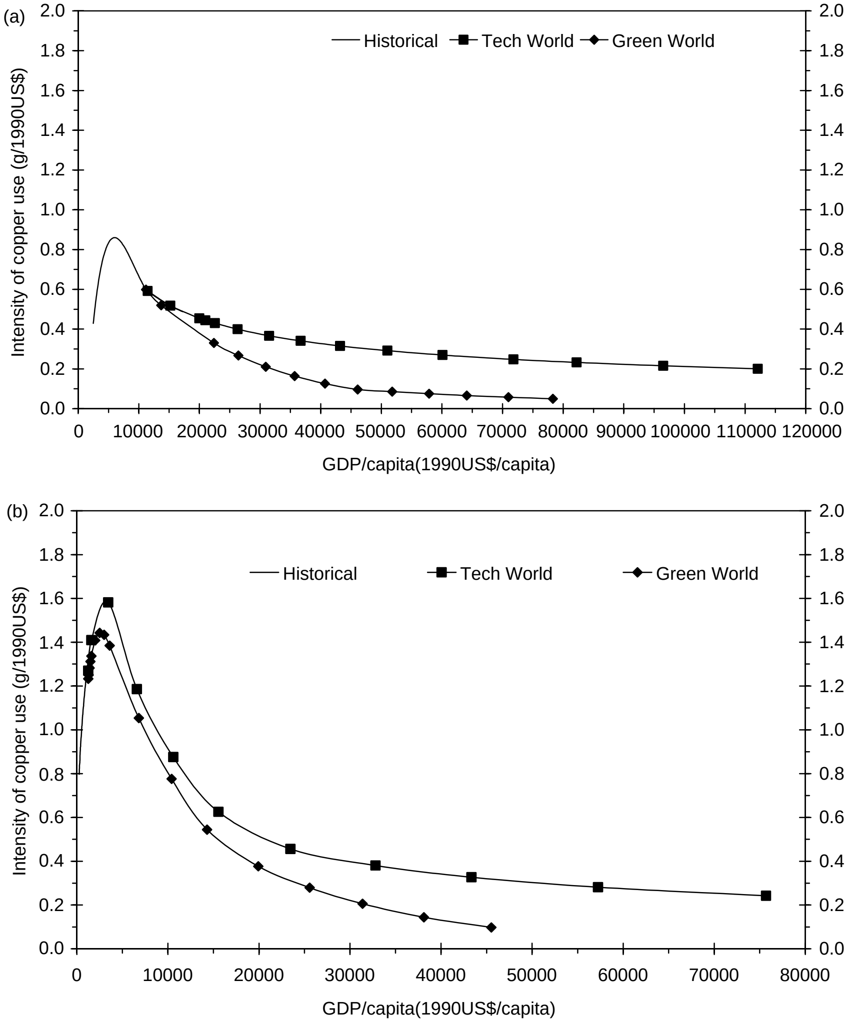
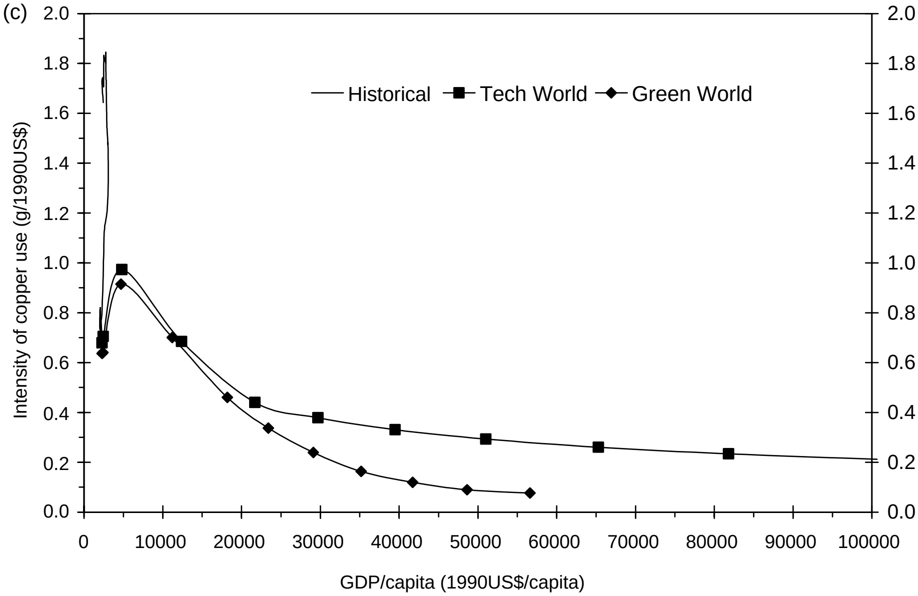


Fig. 6. Intensity of copper use trends (a) in the OECD90 region (Tech and Green World scenario); (b) in the ASIA region (Tech and Green World scenario); (c) in the REF region (Tech and Green World scenario); (d) in the ALM region (Tech and Green World scenario); (e) in the Trend World scenario.



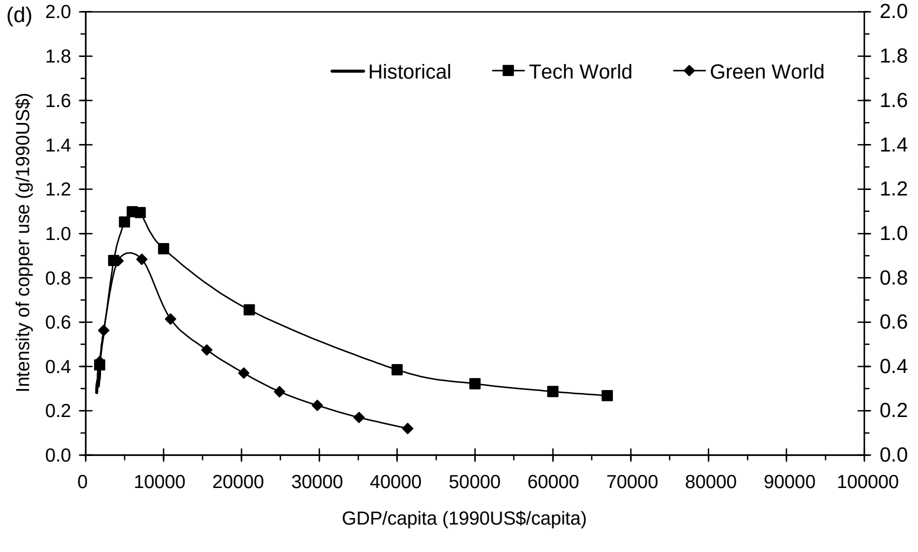


Fig. 6 (*continued*)

regions. The intensity of copper use and GDP per capita values corresponding to the years 2000, 2020, 2050, and 2100 are illustrated in Table 3 for all four regions. The Tech World and Green World are converging scenarios, whereas in Trend World no such pattern is observed. In all three scenarios, ASIA, REF, and ALM show an increasing trend in intensity of copper use in the short-term, whereas for OECD90 intensity of use is either stabilizing or slowly declining. ASIA achieves the highest peak intensity of copper use in all scenarios.

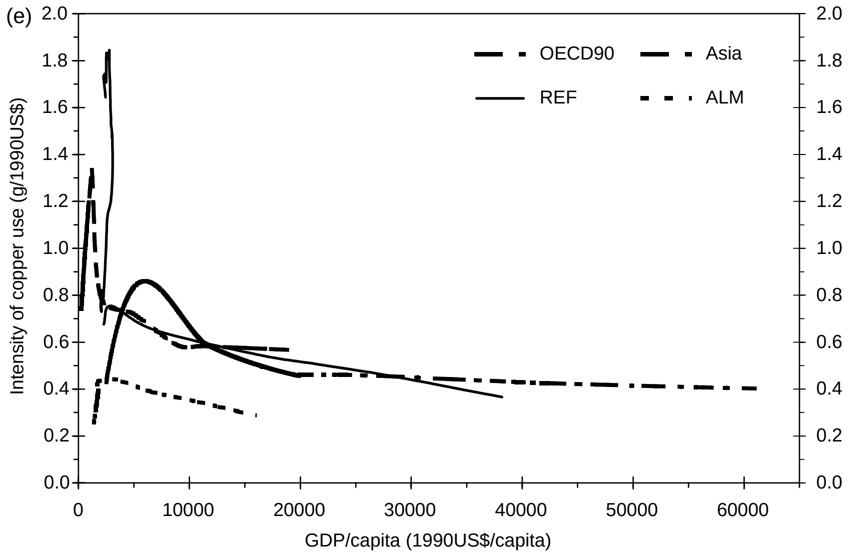


Fig. 6 (*continued*)

ALM achieves the lowest peak intensity of copper use of 0.4 g/$ in the Trend World scenario. The OECD90 region emerges as the leader, both in terms of achieving the highest GDP per capita and the lowest intensity of copper use by the year 2100. Similarly, the intensity of copper use for ASIA, REF and ALM never falls below the value for OECD90,

Table 3
GDP per capita and intensity of copper use trends (2000–2100)

	Year			
	2000	2020	2050	2100
Scenario: Tech World				
OECD90	(22,390, 0.43)	(31,500, 0.37)	(51,000, 0.29)	(112,100, 0.20)
ASIA[a]	(1207, 1.3)	(3450, 1.8)	(15,500, 0.74)	(75,700, 0.24)
REF	(2281, 0.68)	(4800, 0.97)	(29,700, 0.38)	(101,600, 0.21)
ALM	(1764, 0.39)	(4400, 1.0)	(17,950, 0.71)	(63,500, 0.27)
Scenario: Green World				
OECD90	(22,390, 0.43)	(30,925, 0.21)	(46,081, 0.10)	(78,299, 0.05)
ASIA	(1207, 1.3)	(3600, 1.38)	(14,300, 0.54)	(45,512, 0.10)
REF	(2281, 0.68)	(4700, 0.91)	(23,400, 0.34)	(56,193, 0.08)
ALM	(1764, 0.39)	(4150, 0.88)	(15,550, 0.47)	(41,350, 0.12)
Scenario: Trend World				
OECD90	(22,390, 0.43)	(30,418, 0.48)	(39,202, 0.47)	(60,971, 0.43)
ASIA	(1207, 1.3)	(3126, 0.76)	(8901, 0.53)	(19,535, 0.57)
REF	(2281, 0.68)	(4466, 0.7)	(16,148, 0.55)	(38,170, 0.37)
ALM	(1764, 0.39)	(2438, 0.43)	(6611, 0.39)	(15,899, 0.29)

The first value in each pair is GDP per capita expressed in 1990 US$ and the second value is the intensity of copper use expressed in g/$.
[a] Values only for the Asia—high scenario are provided.

except for REF intensity of copper use that marginally dips below OECD90 at the $30,000 level in the Trend World scenario. The developing economies in ASIA, such as China and India, have been growing very rapidly in the last decade and the same trend is expected to continue for the next 15–20 years. Therefore, ASIA will achieve peak intensity of copper use during this period, irrespective of the scenario. However, the rate of decline of intensity of copper use for ASIA is different on account of inherent different rates of technological change. The regions REF and ALM are expected to achieve a much lower intensity of copper use peak as compared to that of ASIA. The countries in REF prior to the break up of

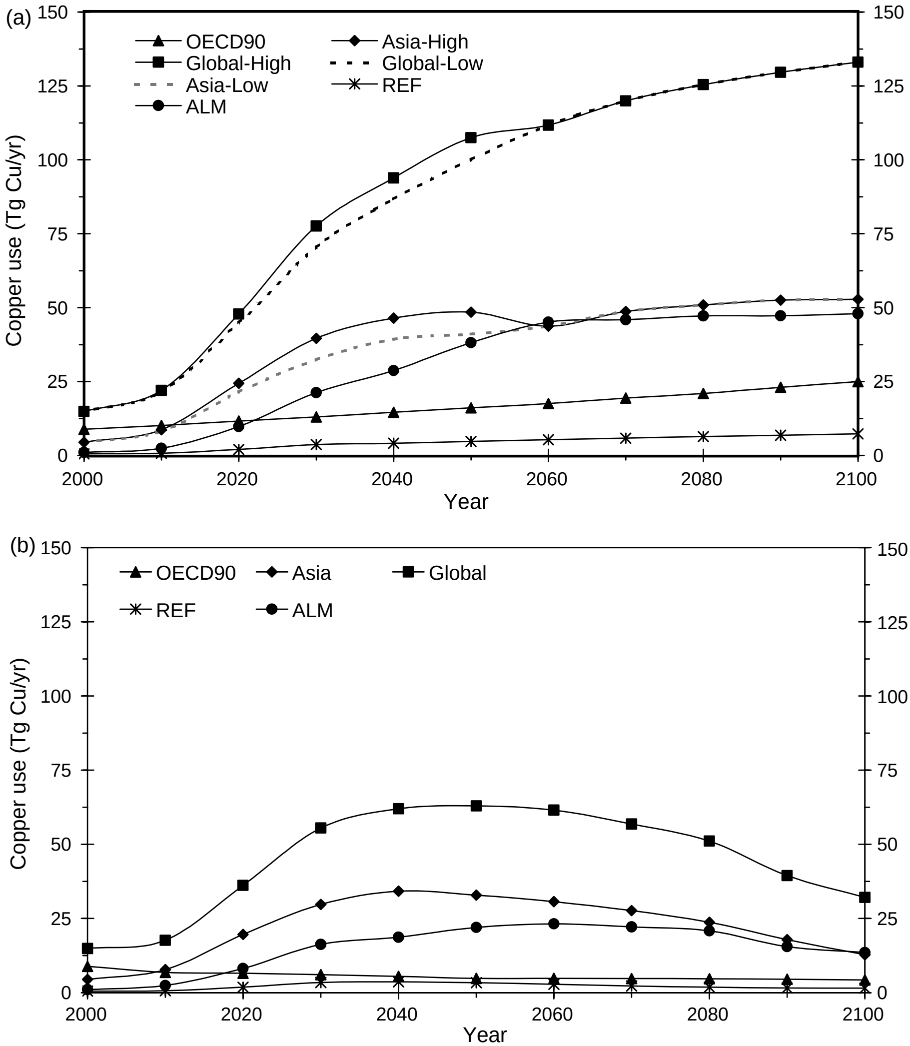


Fig. 7. Copper use trends (a) in the Tech World scenario; (b) in the Green World scenario; (c) in the Trend World scenario.

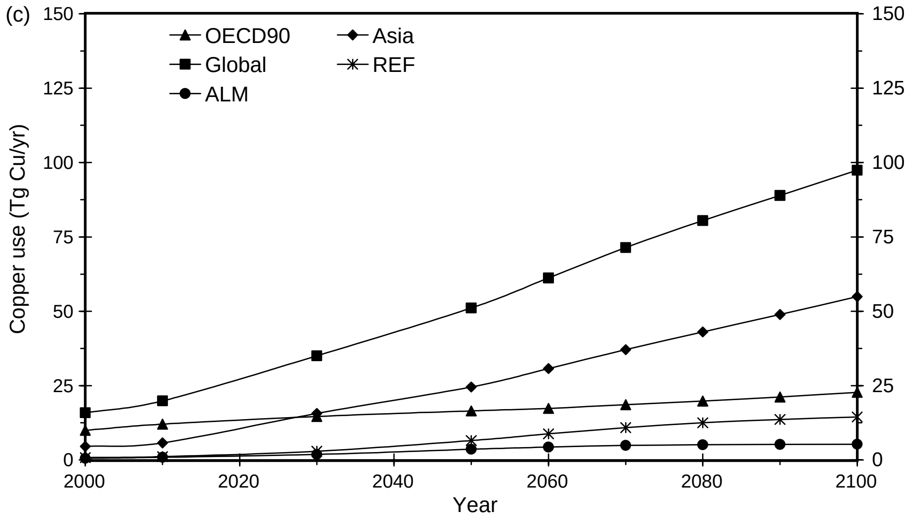


Fig. 7 (*continued*)

the Former Soviet Union had achieved a intensity of copper use peak of 1.8 g/$ in the early 1980s (based upon historical analysis of REF region). During the decade of the 1990s, not only was there a decline in the GDP per capita levels in the REF region, but copper use had also declined appreciably. Therefore, it is assumed that as countries in the REF region return back onto the path of economic growth, they will not now attain a peak similar to that of historical levels, as much of the demand for copper for infrastructure and building and construction has already been met.

4.2. Copper use trends

The copper use trends (as opposed to intensity of use trends) are shown in Fig. 7(a)–(c), respectively, for the three scenarios. Their values for the years 2000, 2020, 2050, and 2100, are illustrated in Table 4. In the year 2000, copper use globally was 15 Tg Cu/yr. By the year 2100, global copper use could range between 30 and 135 Tg Cu/yr. The Tech World and Trend World both depict a continuously increasing trend in rate of copper use. However, in a Green World, copper use will rise to 60 Tg Cu/yr by the year 2050, and thereafter decline to 30 Tg Cu/yr by the year 2100. Irrespective of the scenario, ASIA and ALM are expected to overtake OECD90 in terms of copper use during the time period 2010–2025. Thereafter, both regions will continue to maintain a significant share in terms of total global copper use. In comparison, copper use in the OECD90 and REF regions either declines or remains flat, and there is not much difference in copper use for these two regions in the Tech World and Trend World scenarios.

The long-term copper use trends developed by Ayres et al. [2] for B1 and B2 scenarios are given in Table 5. Globally, the difference in copper use is 5–10 Tg Cu/yr for the year 2050 between the estimates of the present scenario model and that of Ayres et al. [2] for

Table 4
Copper use trends (2000–2100)

	Year			
	2000	2020	2050	2100
Scenario: Tech World				
OECD90	9	12	16	25
ASIA	5	24	48	53
REF	0.5	2	5	7
ALM	1	10	38	48
Scenario: Green World				
OECD90	9	7	5	4
ASIA	5	20	33	13
REF	0.5	2	3	2
ALM	1	8	22	14
Scenario: Trend World				
OECD90	9	13	16	23
ASIA	5	9	25	55
REF	0.5	1	4	5
ALM	1	2	7	14

All values are expressed in Tg Cu/yr.

the two scenarios. However, the differences are substantial for the year 2100, especially for the B1 scenario, where the estimates of Ayres et al. [2] are approximately three times higher than the scenario model. This difference is due to the fact that Ayres et al. [2] assumed that per capita copper use in regions other than OECD90 would approach 10 kg Cu/(capita-yr) for the two scenarios.

4.3. Per capita copper use trends

The per capita copper use trends are shown in Fig. 8(a)–(c), respectively, for the three scenarios. Their values for the years 2000, 2020, 2050, and 2100 are illustrated in Table 6.

Table 5
Copper use trends: Ayres et al. [15]

	Year		
	2025	2050	2100
Scenario: B1 (Green World)			
OECD90	8.9	8.7	8.1
ASIA	17.1	29.4	38.9
REF	2.4	3.2	3.3
ALM	5.4	15.1	30
Scenario: B2 (Trend World)			
OECD90	9.3	9.8	9.7
ASIA	12.8	27.1	24.5
REF	2.4	3.2	2.9
ALM	10.7	22.3	23.6

All values are in Tg Cu/yr.

The global per capita use in the year 2000 was 2.6 kg Cu/(capita-yr). Presently, there is approximately a factor four difference between present levels of per capita copper use in OECD90 and the other three regions. The difference between the convergence theme of Tech World and Green World is demonstrated in the per capita copper use results. Based upon the sustainability theme of the Green World scenario, there is a real convergence of per capita copper use levels across regions to a range 4–5 kg Cu/(capita-yr) by the year

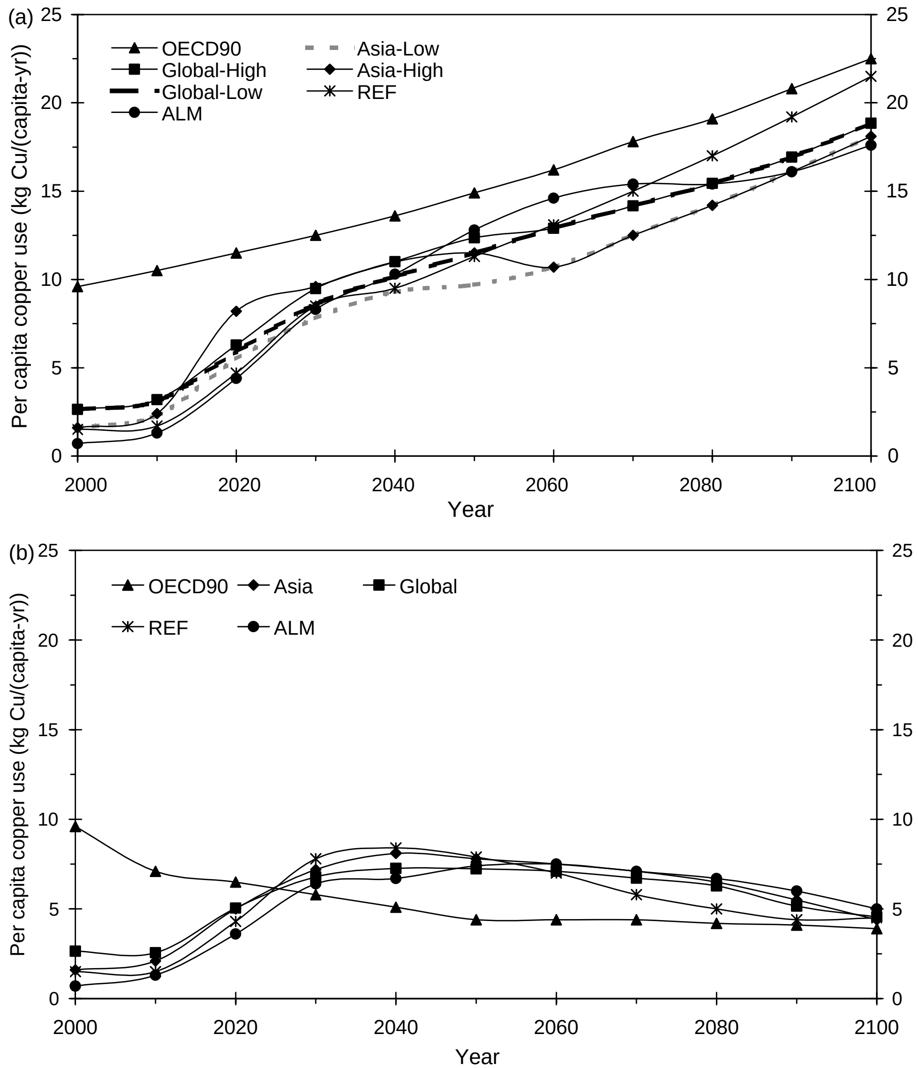


Fig. 8. Per capita copper use trends (a) in the Tech World scenario; (b) in the Green World scenario; (c) in the Trend World scenario.

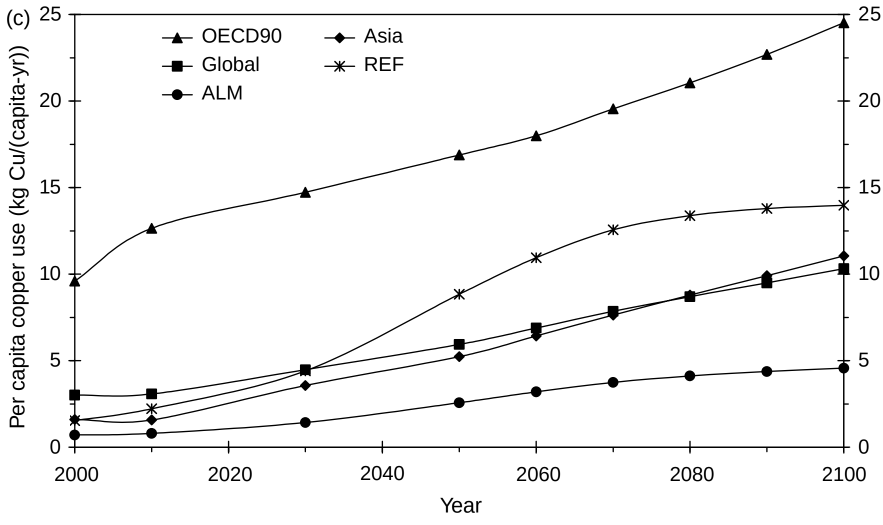


Fig. 8 (*continued*)

2100. In the Tech World scenario, a convergence in per capita copper use is also observed, but the gap in per capita levels between the two extremes (OECD90 and ALM regions) is larger, approximately 5 kg Cu/(capita-yr). The decline in per capita copper use is most significant for the OECD90 region in the Green World. In the other two scenarios, the OECD90 per capita copper use continues to remain above the global average and than

Table 6
Per capita copper use trends (2000–2100)

	Year			
	2000	2020	2050	2100
Scenario: Tech World				
OECD90	9.7	11.5	14.9	22.5
ASIA	1.6	6.2	11.5	18.3
REF	1.5	4.7	11.3	21.5
ALM	0.7	4.4	12.8	17.6
Scenario: Green World				
OECD90	9.7	6.5	4.4	3.9
ASIA	1.6	5.0	7.8	4.4
REF	1.5	4.3	7.9	4.5
ALM	0.7	3.6	7.4	5.0
Scenario: Trend World				
OECD90	9.7	14.6	18.6	26.0
ASIA	1.6	2.4	5.2	11.1
REF	1.5	3.3	8.8	14.0
ALM	0.7	1.1	2.6	4.6

All values are expressed in kg Cu/(capita-yr).

that the other regions. In both Tech and Green World scenarios, the per capita copper use in ASIA, and ALM is expected to be 8–10 kg Cu/(capita-yr) by 2040–2050, whereas in Trend World it is significantly less, as population for these two regions in this scenario is expected to be 500–800 million more by 2050.

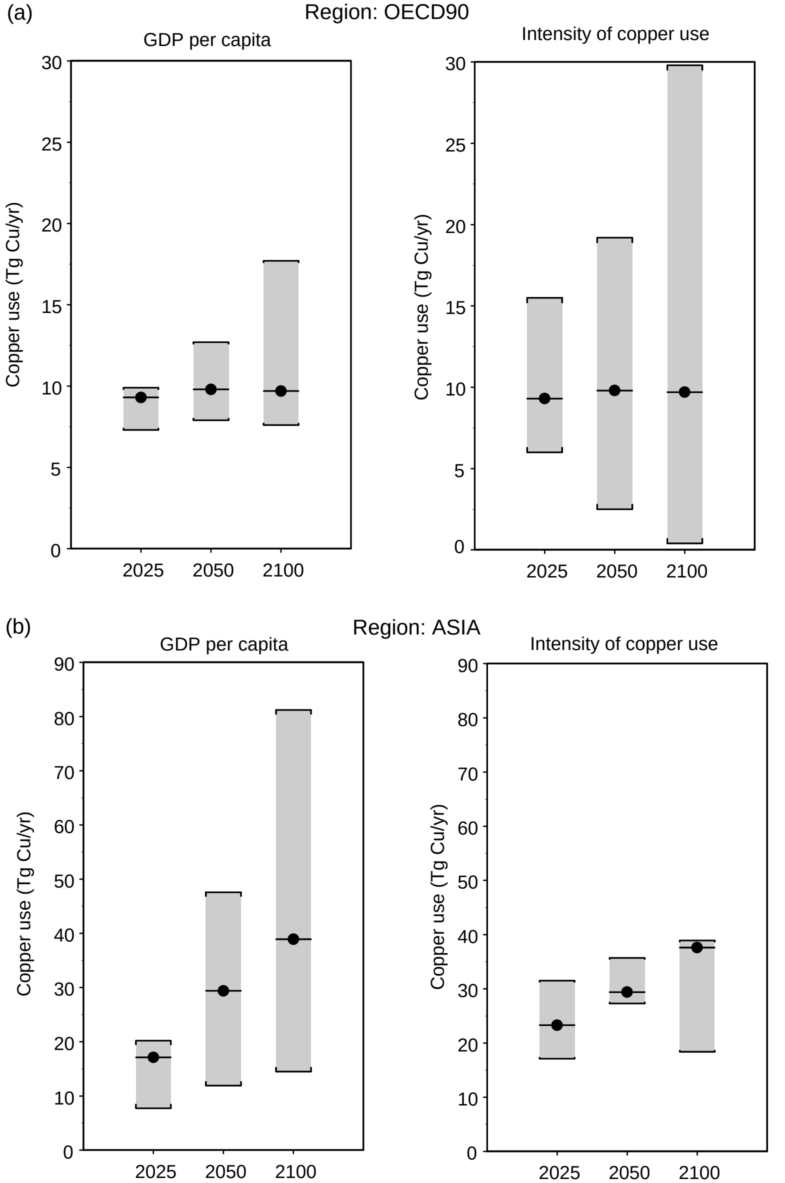


Fig. 9. Boxplots illustrating the influence of GDP per capita and intensity of copper use variables on copper use (a) for the region OECD90; (b) for the region ASIA; (c) for the region REF; (d) for the region ALM.

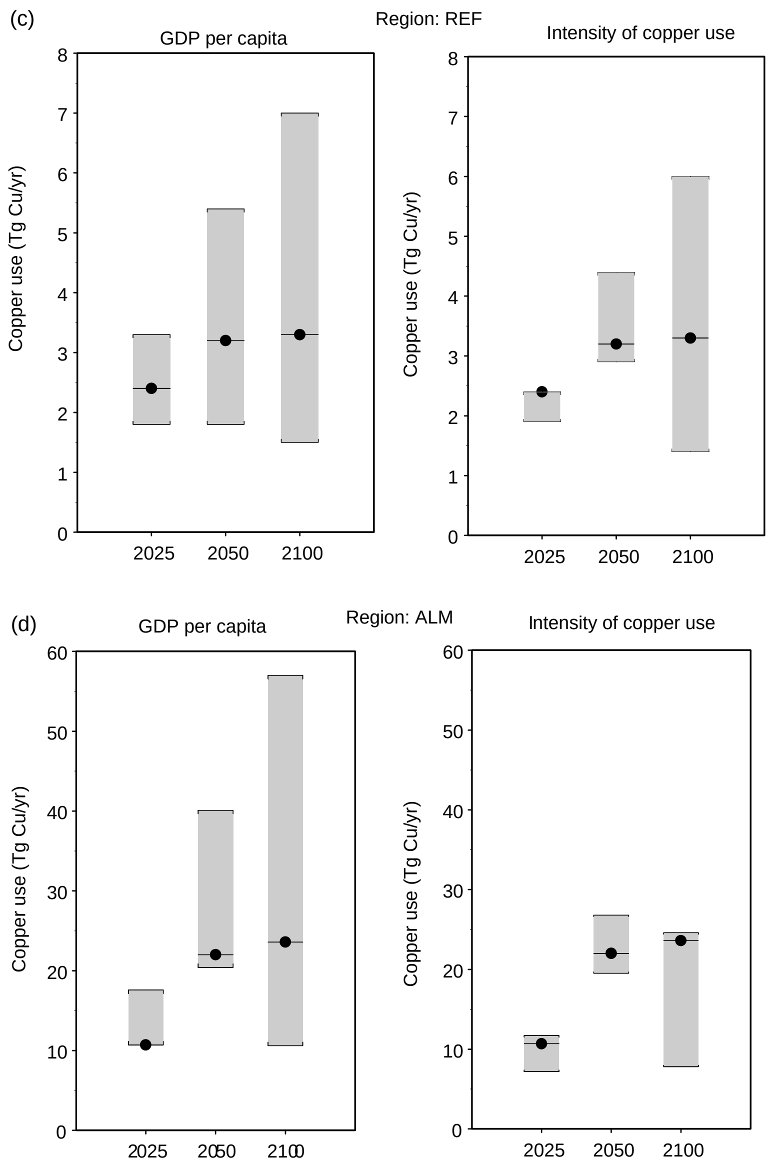


Fig. 9 (*continued*)

5. Sensitivity analysis

Potential uncertainties are important to consider in scenario analysis, especially as projections have been estimated for copper use for the next 100 years. The relative impact of three variables—GDP per capita, intensity of copper use, and population—was investigated to test the sensitivity of our estimates. The change in copper use on account of plausible variations in the three variables can be represented as follows:

$$\Delta\text{Cu use} = (\Delta P \times \text{GDP/capita} \times I) + (P \times \Delta\text{GDP/capita} \times I) + (P \times \text{GDP/capita} \times \Delta I) \tag{7}$$

In sensitivity analysis, usually a baseline reference is selected with respect to which the influence of different variables is estimated. To do so, a hypothetical median scenario was constructed using the three scenarios from this study and other scenario projections from literature [2,13,5]. The maximum and minimum values for each variable were also estimated. The change in copper use, as a result of range of values (the range of maximum and minimum value of each variable) each variable can assume, estimated relative to the hypothetical median scenario values. The analysis was carried out at three time reference points—2025, 2050, and 2100 for all the four regions. The results illustrated as boxplots are shown in Fig. 9(a)–(d), respectively. The population variable was observed to have an insignificant influence on copper ($< \pm 0.05$ Tg/yr). Comparatively, the influence of the other two variables on copper was orders of magnitude higher than population. Therefore, sensitivity of the population variable is not shown in results.

As a general trend, the spread of the variations (difference between the maximum and minimum values) in copper use relative to the median increases with time for all the regions. The projections of copper use for the REF region are observed to have minimal variations in copper use compared to the other regions. For the OECD90 region, the intensity of copper use variable is the critical parameter that influences copper use, whereas for the ASIA and ALM regions it is the GDP per capita variable. From this observation, the following inferences can be drawn:

- Increased affluence would not drive copper use in the OECD90 region. Rather, technological change and material substitution would tend to keep the rate of copper use relatively flat;
- The rate of economic growth in the ASIA and ALM regions will be the major driving force to influence copper use, more significantly beyond 2050.

6. Conclusions

Three scenarios for copper use—Tech World, Green World, and Trend World—for the next 100 years have been presented for the four world regions: OECD90, ASIA, REF, and ALM. Statistical analysis of the historical time series data of GDP per capita and intensity of copper use for the OECD90 region demonstrates an inverted-U relationship between the two parameters. The scenario model for the other three regions was based upon this inverted-U hypothesis. In Tech World, all regions converge to a intensity of copper use of 0.2 g/\$ as GDP per capita approaches the \$100,000 level, whereas in the Green World it approaches to 0.05 g/\$ at a similar income level. The Trend World scenario was quantified using the results of an expert opinion study that provided evidence that the subjective opinion of experts is usually oriented towards conventional wisdom. By 2100, the global copper use could be between 30 and 130 Tg Cu/yr, representing a twofold to ninefold increase from the present level. Beyond 2020, ASIA and ALM will overtake OECD90 in terms of copper use and will continue to dominate. In the Green World scenario, the per capita copper use levels converge in the range of 4–5 kg Cu/(capita-yr) across regions, symbolizing the sustainability theme of the Green World scenario, whereas in the other two scenarios the global average is almost twice as high. For the OECD90 region, uncertainty due to copper intensity of use is significant, whereas for ASIA and ALM regions, the GDP per capita variable is more sensitive.

The results of this study provide the basis for further studies in estimating and analyzing the implications that might rise from different scenarios. The potential implications could be environmental, resource availability, energy and water use requirements, and material substitution, discussed subsequently in the follow-up papers [10,11].

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