Despite centuries of production, there is still good potential to find more. Current mining operations in Europe yield significant amounts of base and precious metals, and regions such as Fennoscandia, Spain, Ireland and even the UK have yielded new discoveries and the re-evaluation of known prospects with a view to mining[12]. Innovative biology-based technologies developed in Europe have unlocked low-grade, previously uneconomic ore[13]. These initiatives have opened the possibility of a new generation of sustainable mining in our own back-yard — which could address concerns about ethical sourcing, and shift control of energy and water use as well as environmental stewardship to the regional scale.

Existing European operations could also be modified to recover many metals essential for new technologies. With the latest technologies, nickel extraction operations in Greece and the Balkans could recover up to 30% of Europe's demand for cobalt from material currently discarded as processing waste[14]. In another case, phosphate wastes from the iron ore mines in Sweden could be reprocessed for rare Earth elements[15], whose shortage caused such a stir in 2010.

Urban mining — the retrieval of raw materials from household waste — is also a potential source of technology metals. Discarded electronic equipment could be recycled locally, instead of being shipped to Asia for processing[16]. To achieve this, the European Union and a number of other countries have banned the export of computer waste. Better component labelling and less inbuilt obsolescence could prevent valuable components from being lost in the mountains of waste.

## A role for geoscientists

The discovery and exploration of these non-renewable mineral resources, as well as their environmentally safe handling, are key tasks for geoscientists. Reliable assessments are needed of the global distribution of resources, of the potential for supply disruption, and of the environmental consequences of their use. With both the world's population and its standard of living on the rise, demand for minerals is bound to soar.

We must acknowledge and control the complexity of giant mining projects with their demands on infrastructure and the environment. We need to work hard to understand any ethical issues with the provenance of new resources. Better ways of recycling valuable metals from discarded electronic equipment are required. And geoscientists need to undertake a thorough audit of the natural occurrences of mineral deposits that will feed our economies. There may well be high future demand for elements that many people have never even heard of. ❐

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# Metals for a low-carbon society

Olivier Vidal, Bruno Goffé and Nicholas Arndt

**Renewable energy requires infrastructures built with metals whose extraction requires more and more energy. More mining is unavoidable, but increased recycling, substitution and careful design of new high-tech devices will help meet the growing demand.**

Renewable energy forms the basis for a low-carbon society. Numerous wind turbines, solar power stations and other facilities will need to be constructed if a significant proportion of global electricity is to be produced sustainably. Building these facilities will require vast amounts of metals and other raw materials, which will then be sequestered for several decades and cannot immediately be recycled. Easily mined ore deposits are quickly declining and although new resources will be found in the deep subsurface or in remote locations, mining these deposits will consume large amounts of energy. Humankind faces a vicious circle: a shift to renewable energy will replace one non-renewable resource (fossil fuel) with another (metals and minerals).

Potential future scarcity is not limited to the scarce high-tech metals that have received much attention. The demand for base metals such as iron, copper and aluminium, as well as industrial minerals, is also set to soar. Here we argue that energy production and the recovery of metals and minerals are inseparable issues that need to be addressed in one comprehensive framework.

## A low-carbon future

Dependence on fossil fuels, such as oil, gas and coal, has caused pollution and environmental damage. We now look forward to a low-carbon society where renewable resources of energy replace fossil fuels. Renewable power resources coming from the sun (175,000 TW), geothermal flux (40–50 TW) and gravity (for example, tidal energy, 3–4 TW)[1] could supply a thousand times our current and future (2050) global energy needs, estimated at $140 \times 10^3$ TWh (16 TW) (ref. 2) and $280 \times 10^3$ TWh (32 TW) (ref. 3), respectively. However, most renewable energy sources are diffuse and intermittent. Harnessing this energy requires complex infrastructure distributed over large areas, both on land and at sea.

The construction and operation of technologies that harness renewable sources of energy will consume large quantities of raw materials. The growing demand for rare metals, including selenium and neodymium in photovoltaic panels and wind turbines, risks derailing the shift to renewable energy[4]. However, wind turbines (Fig. 1) and photovoltaic panels also require enormous amounts of common metals such as iron, copper and aluminium, as well as sand and industrial minerals to make concrete and glass, and hydrocarbon derivatives to create resins and plastics.

The beginning of the twenty-first century was marked by an explosion in demand for metals. This demand was driven by rapid development in large and highly populated countries, notably China, which currently consumes 50% of global iron production, 30% of global copper and aluminium, and similar proportions of many other metals[5,6]. The introduction of new technologies, such as cell phones or hybrid vehicles, requires a diverse set of previously little-used metals. The demand for base metals is currently increasing by 5% annually, and if this trend continues, the quantity of metal production for the next 15 years will need to match that from the start of humanity to 2013. Even though, in the past, such demand for metals have been met thanks to improvements in technology and the discovery of new resources, as mines become more remote and metal grades decline, the increasing cost of mining, and, above all, increasing energy demands, will limit further expansion and may slow the transition to a low-carbon society.

## The metal–energy dependence

Initially, the energy needed for metal extraction will come from fossil fuels. Eventually, renewable energy is likely to come to the fore, with benefits in terms of reduced greenhouse gas emissions and radioactive waste production. However, this transition will also cause much additional global demand for raw materials: for an equivalent installed capacity, solar and wind facilities require up to 15 times more concrete, 90 times more aluminium, and 50 times more iron, copper and glass than fossil fuels or nuclear energy (Supplementary Fig. 1). Yet, current production of wind and solar energy meets only about 1% of global demand, and hydroelectricity meets about 7% (ref. 2).

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**Figure 1 |** A row of wind turbines.

If the contribution from wind turbines and solar energy to global energy production is to rise from the current 400 TWh (ref. 2) to 12,000 TWh in 2035 and 25,000 TWh in 2050, as projected by the World Wide Fund for Nature (WWF)[7], about 3,200 million tonnes of steel, 310 million tonnes of aluminium and 40 million tonnes of copper will be required to build the latest generations of wind and solar facilities (Fig. 2). This corresponds to a 5 to 18% annual increase in the global production of these metals for the next 40 years. This rise in production will be added to the accelerating global demand for ferrous, base and minor metals, from both developing and developed countries, which inflates currently by about 5% per year[5,6].

> A shift to renewable energy will replace one non-renewable resource (fossil fuel) with another (metals and minerals).

Currently, 10% of world energy consumption is used for extraction and processing of mineral resources[8]. Without extraordinary advances in mining and refining technology, this fraction is set to rise as poorer and more remote deposits are tapped. Moreover, some of the commonly used metals and minerals are rare, at least at the level of purity that is required for efficient production of energy. For example, the silica used in the protective glass of photovoltaic panels must contain less than 90 ppm of iron, to ensure high transmission of light.

## Criticality

In many ways, mineral resources carry the same geopolitical and environmental issues as fossil fuels. Soaring prices of all metals, and supply problems for some, have led to the notion of critical metals — those that are essential for modern industry but whose future supply may be interrupted. Metals are usually deemed critical when they are considered to be vital by industry, sourced from a restricted number of regions that are potentially unstable, and cannot be substituted by other metals[9]. Many of the metals used in the high-technology industry, including those that generate renewable energy, have high levels of criticality.

Minor metals, such as the rare earth elements (REE) or cobalt and tantalum, have been classed as critical because they come from a limited number of politically sensitive regions. They have received particular attention because of their use in cell phones, computers and other modern electronic devices. However, we argue that much of the current focus on minor metals is misplaced, because they have a high potential for substitution. For example, the latest generations of wind turbines contain large amounts of REE, but it is possible to build less-efficient wind turbines without REE, or solar panels free of indium, galium

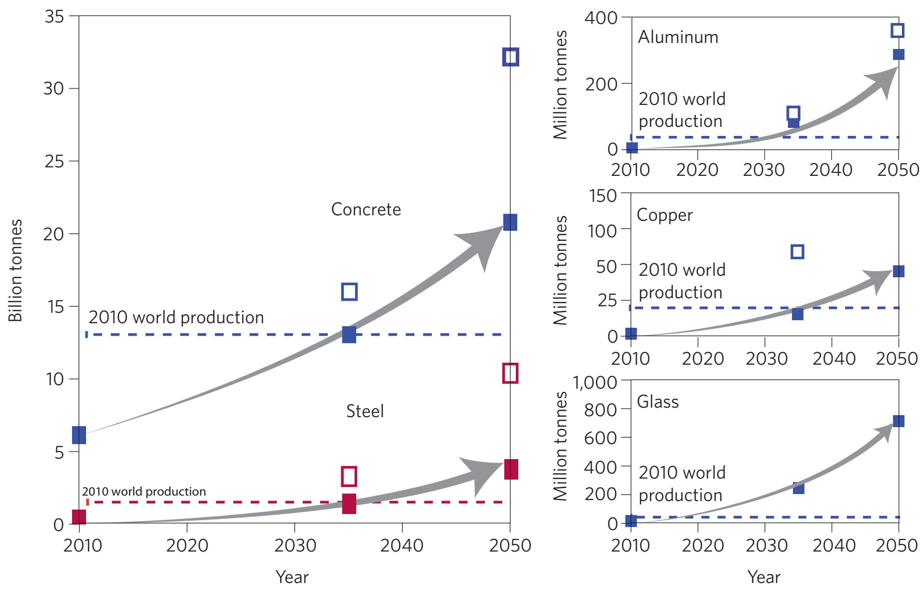


**Figure 2 |** Increasing global consumption of raw materials. The World Wide Fund for Nature (WWF) predicts that the contribution from wind and solar energy to global energy production will rise to 25,000 TWh in 2050[7]. To meet this demand, the global production of raw materials such as concrete, steel, aluminium, copper and glass will need to significantly increase. Open and filled symbols correspond to different volumes of raw material required to construct different types of photovoltaic panels (PV1 and PV2, respectively, in Supplementary Table 1).

and selenium. Moreover, when China — the main supplier of REE globally — began to drastically restrict export of REE between 2009 and 2012, industry was able to react quickly, to assure new supplies in the USA, Australia and South Africa, and find substitutes.

In contrast, most of the base metals and other raw materials needed for the transition to low-carbon energy, with the exception of copper, have low levels of criticality. This is because they are relatively abundant, their supply is assured because they are mined in many relatively stable regions, and they are technically recyclable. However, base metals cannot be substituted, and the generation of infrastructure for renewable energy will sequester huge amounts of steel, aluminium and copper over its 20–30-year lifespan, during which recycling will not be possible.

Dependence on the foreign import of metals should also be considered when assessing the criticality of a resource. For example, mineral supply to Europe and many other developed nations comes mainly from foreign sources. European industries consume more than 20% of the metals that are mined globally, yet European mines produce only 1.5% of iron and aluminium, and 6% of copper[10]. This situation is highly unsatisfactory for security, economic and ethical reasons, and makes European industry vulnerable to short- or long-term supply restrictions. Finally, estimates of criticality should acknowledge that the energy needed for extraction may become a limiting factor.

## Mine locally

Humanity faces a tremendous challenge to make more rational use of the Earth's non-renewable raw materials. The energy transition to renewables can only work if all resources are managed simultaneously, as part of a global, integral whole. Designs of new products need to take into account the realities of mineral supply, with recycling of raw materials integrated at both the creation stage and at the end of a product's life cycle. Research is crucially needed to anticipate the total material requirements and environmental impacts of any new technologies.

A case can be made for more metal production near centres of demand, similarly to the locavore movement that proposes looking closer to home for our food. It seems unreasonable to shun green beans grown in Kenya while using copper from the Congo. Green technologies should incorporate domestic mining, which reduces the financial and environmental costs of transporting metals from far-flung sources and decreases the carbon footprint, while providing jobs and wealth to the local community. Currently, much of the pollution associated with mining is outsourced to regions where the environmental impact is often uncontrolled.

In Europe, things can be done better. For example, while adhering to the stringent environmental and societal norms outlined in the Green Mining program of Finland[11], Boliden's Aitik mine, located in the harsh climate of northern Sweden, profitably exploits ore containing less than 0.3% copper[12], far lower than the global average of about 0.6% (ref. 13), thanks to efficient modern technology and highly mechanized mining. Such projects require a coordinated effort involving scientists from various academic disciplines and industries, as well as decision makers. Programmes such as ERA-MIN (Network on the Industrial Handling of Raw Materials for European Industries)[14] provide scientists with the opportunity to contribute to the huge challenges involved with raw materials, including resource management and preservation.

Earth's resources are rich and manifold, but they are finite. As the demand grows, we must fully acknowledge the inherent trade-off between the production of metals and energy, and optimize procedures and technologies to use both as efficiently as possible. Europe is a good place to start on this project. ❐

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