The weight of mineral resources in energy systems

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Humanity is using mineral resources at an unprecedented rate, and demand will continue to grow over the coming decades, fuelled by the energy and digital transitions and the economic development of highly populated countries. But the nature and quantities of mineral resources needed are highly dependent on the types of use envisaged, which vary according to the organisation and level of development of societies.

The demand for raw materials must therefore be estimated using a dynamic and regionalised approach, taking into account the different development scenarios, particularly as regards the deployment of renewable or decarbonised energy resources.

This article summarises the main analyses of previously published articles by Olivier Vidal *et al.* [1-4].

The consumption of raw materials and mineral resources (gravel and sand, cement, ores, industrial minerals) used to build the urban infrastructures, energy, transport and consumer goods of modern societies has increased over the last century at an average rate of 2 to 5% per year. Humanity is now using mineral resources at an unprecedented rate, with 70 billion tonnes of material extracted from the ground every year. Repeated predictions of the short-term exhaustion of fossil fuels have so far not been confirmed by the appearance of real shortages. The apparent increase in reserves, despite strong growth in consumption, can be explained by technological progress, which makes it possible to exploit new fossil resources of lesser quality at the same cost. As the quantity of low-grade deposits is much greater than that of concentrated deposits, reserves have increased with technological improvements.

This trend gives the misleading impression that perpetual growth is possible in a finite world, the Earth.

How can we assess future demand and availability of mineral resources?

The future availability of mineral resources depends on production capacity, which in turn depends on production technologies, the type and quality of ore deposits controlling production costs, and the proportion of products recycled at the end of their life. It also depends on demand, which is itself linked to population and standard of living, economic and geopolitical cycles, and the technological development

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Aerial view of the Beauvoir quarry in Echassières (Allier), where Imerys plans to develop lithium hydroxide production for use in electric car batteries.

“The apparent increase in reserves, despite strong growth in consumption, is explained by technological progress, which makes it possible to exploit new fossil resources of lesser quality at the same cost.”

associated with the energy and digital transitions. All these parameters define the conditions for economically viable production. They vary over time, are interlinked and should not be analysed separately.

Over the last few decades, the demand for non-energy materials has been intensively studied by means of material flow analyses. These models (see Vidal [1]) are valuable and powerful tools for discussing the issue of global resources in relation to socio-economic changes. However, they are sometimes based on questionable empirical assumptions, such as the linear dependence of total demand for metals on changes in Gross Domestic Product (GDP). This assumption, based on an empirical adjustment to global historical data covering too short a period, is at odds with recent trends in developed countries. In addition, it assumes that future demand for metal per unit of GDP will be the same as in the past, while new technologies that did not exist two decades ago are developing rapidly in the energy, transport, information technology and communications sectors.

When estimating global demand, it is essential to take into account the existence of three successive phases in the development of societies, which generate different material requirements: (i) creation of infrastructures, urbanisation and construction of buildings; (ii) development of new technologies; (iii) transition to a low-carbon economy.

This estimation requires a bottom-up approach by technology, because society's needs in materials and energy, their intensities of use and their yields evolve at different rates according to time and place. Model forecasts are based on scenarios

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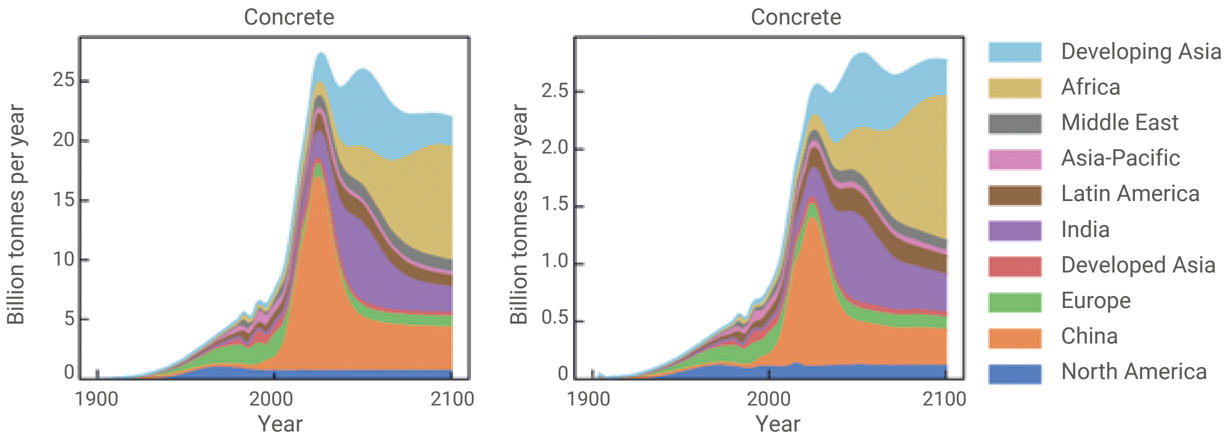

1. Cumulative trend in annual concrete and steel consumption by geographical area, based on logistic laws of GDP and population growth. (Source: figure 2 in Vidal *et al* [1]).

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whose assumptions can lead to major variations in the quantity and type of materials consumed. This is particularly the case for the consumption of materials in the energy system itself. In turn, the extraction and shaping of the mineral resources used have an impact on final energy demand.

We will first look at the methodological approach to the general evolution of demand for materials, before focusing more specifically on the demand associated with different energy scenarios.

Modelling changes in demand for mineral resources

In a finite world, it is of course impossible to draw infinitely on a limited stock of resources. A global model of mineral resource extraction using the logistic[a] equation, already presented in the analysis of fossil fuel resources (see the article by J. Treiner in this issue, p. 9), leads to a trend in the annual quantities extracted, with rapid growth at the start, a production peak, followed by a decline corresponding to the depletion of the resource. This model obviously needs to be adapted to take account of geographical variations and the fact that material requirements, both in terms of quantity and type, change as human societies develop. Empirically, there is an initial phase of construction of infrastructures that require large quantities of raw materials, for heavy industry, housing, transport, communications and energy. This phase is controlled by growth in GDP per capita, with a saturation effect systematically observed when this reaches around US$20,000 per capita. In a later phase, demand for materials is controlled by demographic and technological developments.

The evolution of the number of technological units per capita, as a function of GDP per capita, thus follows a logistic function sigmoid whose parameters are adjusted to the observations for different countries, which makes it possible to predict subsequent evolution. In this way, it is possible to model global trends in the annual consumption of materials for all infrastructures (fig. 1) by first adding up the requirements for each technology for each region, and then summing the regional trends. Annual consumption figures are obtained by taking into account annual primary, recycled and lost flows (fig. 2). This totally bottom-up approach, based on local GDP and demographic trends, makes it possible to link global materials consumption to local economic, demographic and technological developments. It reproduces (fig. 2) the trends observed since the Second World War.

After this initial phase of building their basic infrastructure, or even before its completion, countries economies move towards advanced technologies. These make use of the many properties linked to the electronic structure, the catalytic, quantum or semi-conducting properties of almost all the elements in the periodic table. Rapid changes in the use of metals have been seen in recent decades in the information and communication technology (ICT) sector. While the consumption of base metals has increased by 2-5% per year since 1990, the annual growth in the production of certain rare metals used in high technology is currently around 10% per year. It is difficult to assess future demand for these high-tech metals, as it depends more on technological innovation than on GDP per capita.

New technologies concern also the energy sector, which is evolving to reduce our greenhouse gas emissions and comply with the Paris agreements. Unfortunately, solar and wind infrastructures require more raw materials, per installed capacity and energy supplied, than fossil fuel-based installations. Figures 1 and 2 have been calculated on the assumption that the penetration of low-carbon energy technologies will remain moderate. For the same growth in GDP and population, and therefore in construction, transport and energy infrastructures, the demand for

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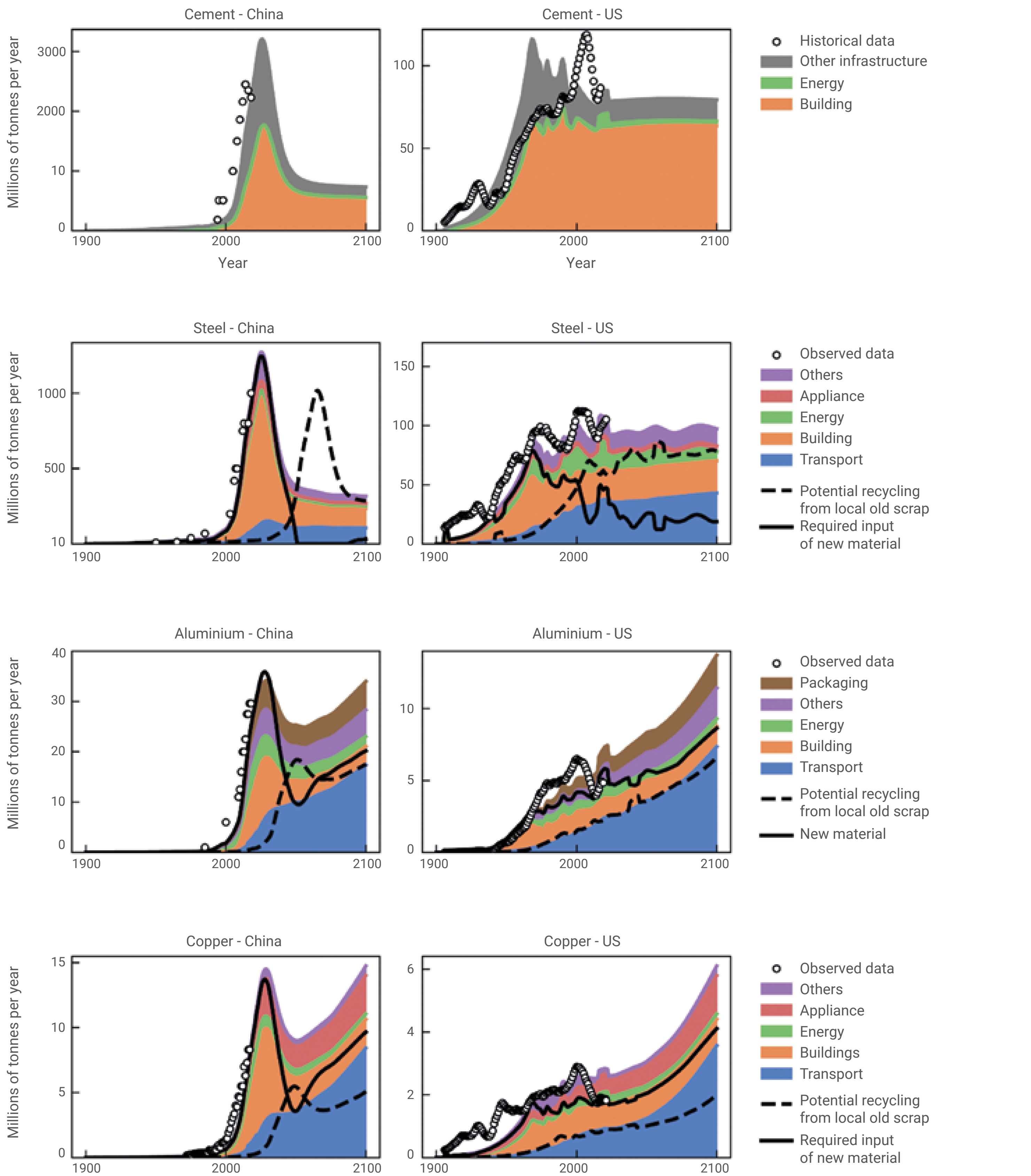

2. Demand for raw materials by economic sector (in Mt/year), calculated from infrastructure trends for China (left-hand panels) and the USA (right-hand panels). The solid and dashed black lines show the primary and theoretically recycled flows respectively. The circles show historical data (USGS). For cement in the USA, there is a discrepancy between observations and modelling due to changes in the construction sector.
(Source: figure 3 in Vidal *et al* [1]).

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metals will be different for a greater penetration of renewable energies.

Figure 3 illustrates the differences in global copper, lithium, cobalt and nickel consumption for the two contrasting energy scenarios RTS ("Reference Technology Scenario") and B2DS ("Beyond 2°C Scenario") from the IEA (2017)[(b)].

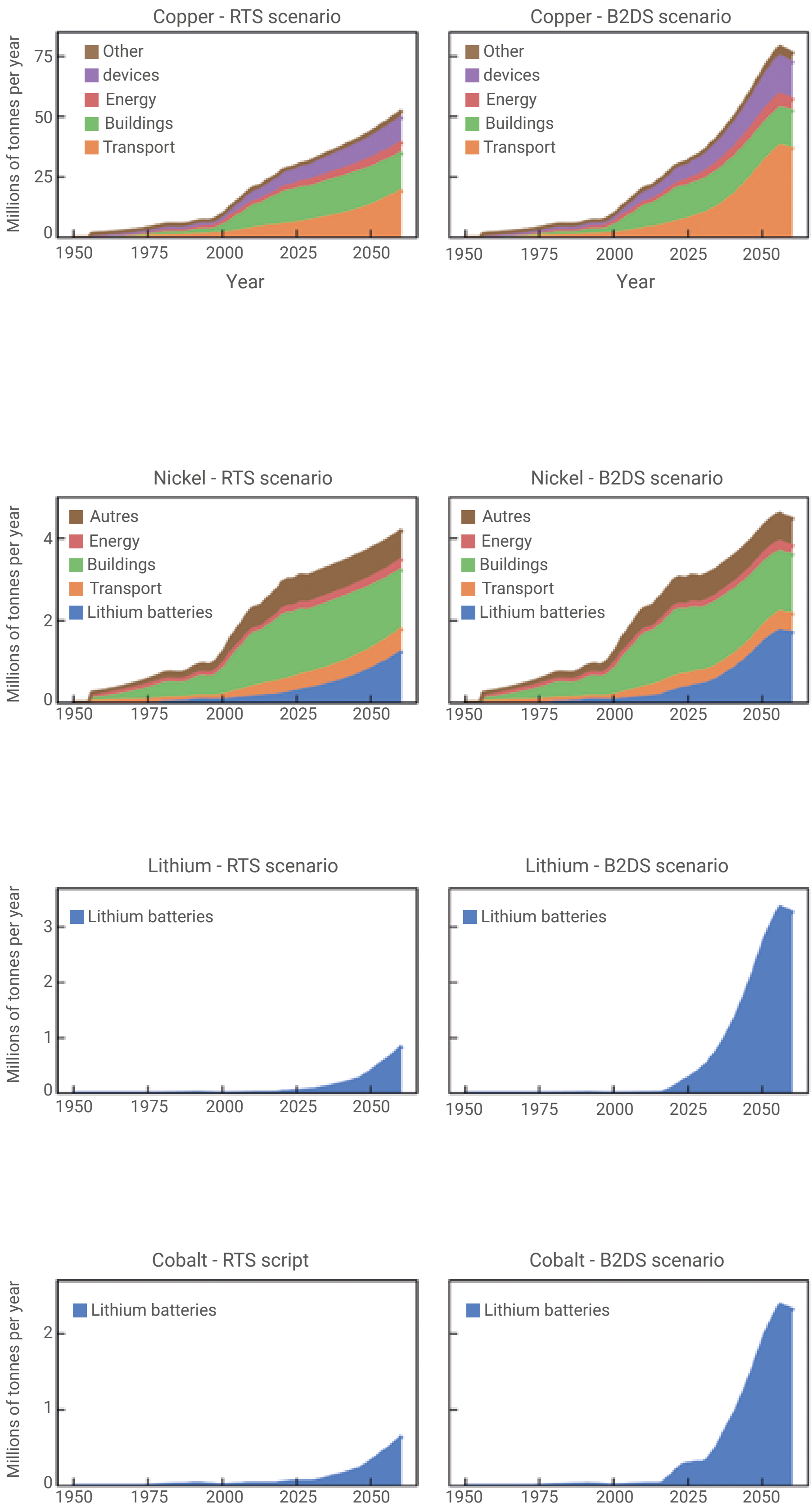
The weight of resources according to energy scenarios

This impact of the energy sector on the evolution of world demand for materials, depending on the energy scenarios and the penetration rate of renewable energies, is crucial. The evolution of demand for raw materials and mineral resources required by energy systems depends on the final consumption target, as well as the relative shares of the different energy conversion systems envisaged.

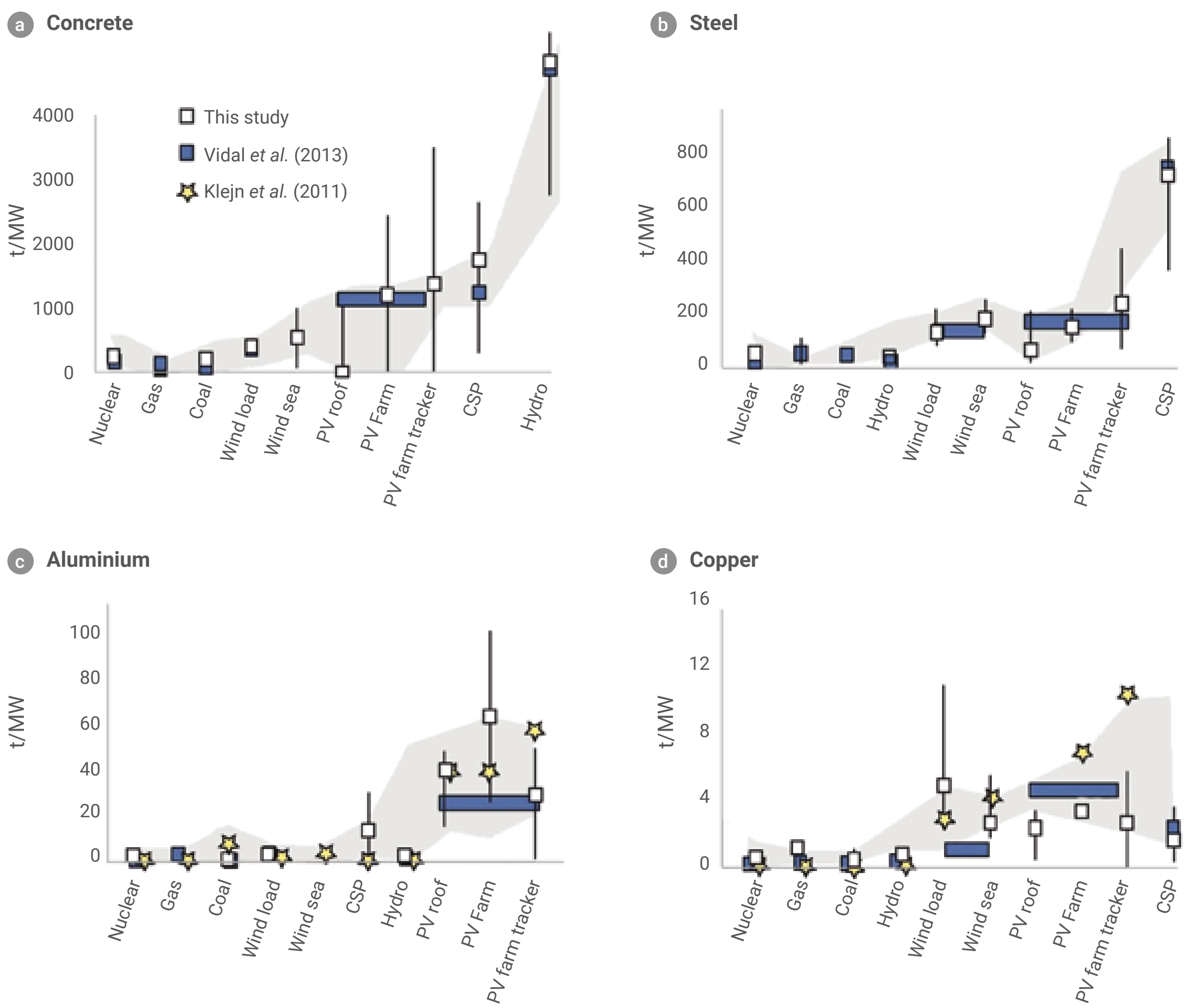
Electricity generation: how much material per megawatt of installed capacity?

The first specific feature of flow energy sources such as solar and wind power is their low density, which means that they require large-scale infrastructure spread over large areas, as well as the mobilisation of large quantities of materials. Demand concerns not only the basic materials for infrastructure (concrete, steel, aluminium and copper), but also the specific metals used in the manufacture of photovoltaic (PV) panels and wind turbine generator magnets.

Installations using stock energy (fossil fuels or nuclear) offer a higher energy density. The mobilisation of basic materials, in terms of mass per unit of installed capacity, is lower than for infrastructures using renewable energies. This is shown in Figure 4, which compares the mass required per MW of capacity for different installations, ranging from conventional thermal power stations to wind turbines and photovoltaic power stations.



3. Annual global demand for copper, nickel, lithium and cobalt, calculated for a development of infrastructures according to the reference scenario (RTS, left-hand panel) and the "below 2°C" **scenario** (B2DS, right-hand panel) of the International Energy Agency.
(Source: figure 4 from Vidal *et al.* [1]) (Cobalt oxide is widely used in the cathodes of lithium-based batteries)



4. Mass of raw material per megawatt (t/MW) required for a range of power generation facilities (nuclear, gas, coal, onshore wind, offshore wind, concentrated solar power = CSP, hydro, rooftop solar photovoltaics (PV), PV farm, solar tracker PV farm). (nuclear, gas, coal, onshore wind, offshore wind, concentrated solar power = CSP, hydro, rooftop solar photovoltaic (PV), PV farm, PV farm with solar trackers). (a) concrete, (b) steel, (c) aluminium, (d) copper. The error bars show a clear dispersion of the data between three studies, but on average the basic material requirements per MW increase significantly when moving from fossil fuel-based technologies to those using renewables. (Source: Figure 2 from Vidal *et al* [3]).

For example, for the same installed capacity, wind turbines and photovoltaic panels require between five and fifteen times more concrete, steel, copper or aluminium than conventional fossil-fired or nuclear power plants, depending on the technology. The differences are even greater if we relate the mass of materials used not to the installed capacity, but to the energy produced, because of the load factors[c] of the installations. To these needs must be added the infrastructure and storage facilities needed to integrate non-dispatchable power sources into the electricity grid.

Will supply be able to meet demand?

Depending on the scenario, global electricity consumption could rise to 35 000 TWh by 2050, with solar PV and wind power contributing up to 25 000 TWh. The IEA's NZE-2050 scenario forecasts a global installed capacity of 14 500 GWp for photovoltaic solar energy, enough to produce around 23 500 TWh of electricity per year: this corresponds to a 20-fold increase in current installed capacity.

Based on the data in Figure 4, we can make a quick estimate of the mineral resources that would need to be mobilised: 36 billion tonnes of concrete; 2.9 billion tonnes of steel, i.e. almost twice current annual consumption; 0.29 billion tonnes of aluminium, i.e. six times current global consumption; 58 million tonnes of copper, i.e. 3.5 times current cumulative global consumption[d].

For a more detailed discussion of the mineral resource requirements of different types of power generation facilities, see Vidal *et al.* [2, 3].

Conclusion

Today, around 12% of the world's total energy consumption (and 35% of industrial energy consumption)

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1• O. Vidal *et al.*, "Modelling the Demand and Access of Mineral Resources in a Changing World", *Sustainability* **14** (11) (2022). https://doi.org/10.3390/su14010011

2• O. Vidal *et al.*, "Modelling the material and energy costs of the transition to low-carbon energy", *EPJ Web of Conferences* **189** (2018) 00018. https://doi.org/10.1051/epjconf/201818900018

3• O. Vidal *et al.* "Global Trends in Metal Consumption and Supply: The Raw Material-Energy Nexus", *Elements*, **13** (2017) 319-324. DOI: 10.2138/gselements.13.5.319

4• O. Vidal *et al.* "Metals for a low-carbon society", *Nature Geoscience*, **6** (2013) 894-896. (www.nature.com/naturegeoscience).

(a) The logistic equation $dQ/dt = aQ(1-Q/Q_{max})$ was introduced by Verhulst in population dynamics. It models the temporal evolution of the cumulative withdrawal $Q(t)$ from a resource whose stock is limited to Q_{max}. For $a > 0$ and $Q(0) = Q_0 << Q_{max}$, the solution is $Q(t) = Q_{max} / [1+Q_{max} / Q_0 \exp(-at)]$. This is an S-shaped curve (sigmoid), corresponding to an initial exponential growth followed by an inflection and then gradual saturation towards Q_{max}. Annual consumption $P_A(t) = \Delta Q/\Delta t$, equated with the derivative of this S-shaped curve, therefore passes through a maximum at the inflection point of the sigmoid. This corresponds to the famous "Hubbert peak".

(b) These two scenarios, RTS and B2DS, together with the third median scenario, 2DS, make up the set of three scenarios proposed by the IEA in 2017 to meet the commitments of the Paris agreements (https://cutt.ly/iea_energy_perspectives). The RTS scenario is the least ambitious, but nevertheless takes account of all the commitments made in the Paris agreements. B2DS is the most ambitious, pushing all the possible defossilisation levers to the maximum.

(c) The load factor of an installation is the ratio of the electrical energy produced over the course of a year to the maximum energy it would have produced over the same period of time if operating constantly at its rated power (in the case of photovoltaic systems, this is referred to as peak power, Wp). It is around 0.15 for solar PV and 0.24 for onshore wind power (but up to 0.4 for offshore wind power).

(d) The numbers given here should not lead to confusion between stocks of materials immobilised in infrastructures and their annual flows. The aim is simply to provide elements of comparison for orders of magnitude.

(e) See the article by G. Bonhomme and J. Treiner on EROI in this issue (p. 24).

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is used to produce raw materials. For primary production (excluding recycling), this energy consumption breaks down into three contributions: (i) the extraction and crushing of ore, (ii) the separation and concentration of the metal-bearing phases and (iii) metallurgy. Improvements in the energy efficiency of the various processes have so far made it possible to compensate for the additional costs incurred. The improved energy efficiency of the various processes has until now made it possible to offset the extra costs incurred by the need to mine lower-grade ores when the richest deposits have been exhausted. This trend is not sustainable, however, because there is a thermodynamic limit that cannot be exceeded. This limit corresponds to the minimum energy required to break an oxide, sulphate, sulphide or silicate holding the metal into its elementary constituents. It is given by the free energy of formation of the mineral from its constituents. In the case of iron, this limit is around 10 MJ/kg. It took 50 MJ to produce one kilogram of steel in 1950; today it takes 25 MJ, and we are approaching the thermodynamic limit. The same observation applies to all metals, and it will not be possible to compensate for the decline in the quality of deposits by improving production technologies for very long. When technological improvements can no longer compensate for the decline in the quality of the deposits being mined, production costs and metal prices will rise inexorably, at a rate proportional to consumption.

The transition to low-carbon energy sources, such as solar photovoltaic and wind power, will lead to considerable additional requirements for materials, including specific metals. During the energy transition period, this will lead to excess energy consumption to produce the materials used for the energy sector itself.

To meet the objective of carbon neutrality in 2050, the transition scenarios all envisage a drastic reduction in final energy consumption. For example, the B2DS scenario envisages a 65% reduction in the share of final energy consumption accounted for by industry, compared to the RTS scenario. However, it seems difficult to hope to build a new energy production, storage and consumption infrastructure while drastically reducing final energy consumption.

The energy transition is a global issue, and all countries, rich and poor, are affected. Wealthy countries predominantly use resources imported from developing countries (Europe uses 20% of the metals produced worldwide, although it only produces 3%). The energy transition in rich countries therefore depends on the extraction of materials in poorer countries, which then bear all the associated environmental impacts. When these poor countries have the economic strength to build their own decarbonised energy infrastructure, will they have access to the quality resources they need, or will they be entirely tied up in the infrastructure built earlier in the rich countries? The poorest countries (half the world's population) will need to have access to mineral resources to build their own energy infrastructure, in areas where the use of solar and wind radiation is often optimal (abundant and of higher EROI[(e)]). To ensure that these countries are not *ultimately* deprived of their development capacity because of difficult access to mineral resources, the rich countries must agree to extract these mineral resources on their own territory.

In Europe, the extraction of available resources is increasingly coming up against fierce public opposition on environmental grounds. And yet this is an ethical issue: refusing to extract as much as we can domestically means exporting the impact of our consumption to countries where the technologies used are not the best. Not burying our heads in the sand by agreeing to manage the environmental impact of our consumption allows us to develop the best technologies to minimise it. We therefore need a global vision of the energy transition that goes well beyond technological issues. This vision must include not only future energy demand by country, but also resource requirements and their sources. ∎