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# The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios

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ABSTRACT

In the coming decades, copper scarcity is likely to result in deteriorating ore quality, which in turn will lead to a higher GER (gross energy requirement) for copper production. In this study, this increasing GER and the effect it has on the EROI (energy return on investment) of wind turbine technologies have been analysed. The GER of copper in a 2050 100% renewable energy system will be a factor 2–7 larger than it is today, depending on technological progress, the recycling rate and the future electricity demand. Because of an increasing in-use stock of copper, recycling will play a relatively small role even when the recycling rate is high. The future EROI of wind turbines is approximately 15% less than is currently often taken into account, mainly due to network losses.

The GER of increasingly scarce materials can potentially be used as a more meaningful indicator for abiotic depletion in LCA studies than the current mineral reserve based practice.



## 1. Introduction

In the last decades, there has been an exponential growth in the demand for a large number of minerals as a result of the strong growth in emerging economies and an increasing complexity of products. In future, this trend will be increasingly reinforced by the global renewable energy transition that is at hand. Given that virtually all renewable energy is found in a far more diffuse form than fossil fuels, it requires a multitude of installations to extract it. This, in turn, means an increasing material intensity for the worldwide renewable energy supply system compared to the current system [1,2].

One effect of this growing demand in metals is a depletion of resources of higher quality and with better accessibility, which in turn may lead to increasing energy requirement for mineral production. For energy supply technologies in particular this poses a problem. The resources needed to build these technologies are extracted with the goal of ultimately producing energy. Therefore, if the extraction of materials requires too much energy the overall return on energy gets too low. This return on energy is described with the term “EROI” or ‘energy return on investment’. This concept can be defined as the energy yield divided by the energy that was originally needed to obtain it [3] or, in other words, the total energy output divided by the total energy input. In that sense, it is a useful tool that can be used to assess one single energy technology (system) or compare multiple energy technologies or systems based on their energy efficiency.[1] In line with the Life Cycle Assessment (LCA) methodology it is recommended to include all relevant processes when determining the EROI [3,6], attributing to the reliability of EROI as a feasibility indicator of energy technologies. This was also strived for in this study. According to Murphy and Hall (2010) [3] such a complete assessment can be done by looking at the so called “Extended EROI”, which includes the energy required not only to produce, but also to deliver and use the energy, including for example the infrastructure to transport it.

With this study, an attempt was made to analyse the influence of copper scarcity on various renewable energy scenarios. The central claim in various assessments of future energy scenarios is the statement that a worldwide energy supply based on 100% renewables is technically possible in a future year [7,8]. It is therefore important that the issue of material scarcity is fully addressed. Current scarcity indicators are often based on reserve estimates which do not fully grasp the process of deteriorating quality of resource deposits. With this study, an attempt is made to link the

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[1] Currently, EROI of PV (amorphous silicon) is about 6.9: 1 [4], of wind onshore (operational) 19.8: 1 [5] and of oil 11: 1 [6].

concept of material scarcity to a measurable indicator such as energy requirement in material production. Furthermore, this study aims to provide insight into the dynamics of lowering EROI values (or increasing energy payback times) as a result of copper scarcity. It can provide some methods that may be useful in follow-up studies, as well as an indication of the size of the problem. Next to that, studies such as these make it easier for energy technology producers as well as policy makers to anticipate possible complications by adjusting their long term strategies and focussing on technologies that are based on materials that will be abundant in the long term.

This study is focused on the case of copper because it is a well-studied bulk material as well as considered a scarce mineral with only 60 years of expected availability at current production levels [9]. Next to that, it can be regarded as an ECE (energy critical element) mainly because of its unique conductive characteristics, which will be essential in an economy that will rely more heavily on electric energy [10]. Furthermore, the quality of copper deposits has been shown to deteriorate [11], resulting in a higher minimum energy requirement, which makes it a suitable candidate to illustrate the relationship between energy and material scarcity. In addition, wind turbine technology is used to exemplify changing EROI values due to changing energy inputs in copper production, because wind technology relies heavily on the use of copper, in generators as well as in the electrical transmission grid. The case study is reflected in the main research question: What will be the change in the EROI value of wind turbine technology in 2050 100% renewable energy scenarios as a result of copper scarcity?

## 2. Research methods

Exploring this study's topic requires an interdisciplinary approach, combining insights from geology, economy and engineering. The methodology can roughly be divided into two phases: 1) Construction of a cumulative primary copper production/energy supply curve and 2) Modelling the effect of future renewable energy scenarios on the supply of primary and secondary copper and on the resulting changing energy requirement per kilogram copper. Especially the methodology of the first part will be addressed in detail. The methodology of the second part will be explained in less detail, but is described extensively in the Supporting Information.

### 2.1. Cumulative primary copper production/energy supply curve

The energy supply curve resulting from this analysis can illustrate how the gross energy requirement (GER)[2] of primary copper may increase in the future due to the increased use of more remote, lower grade ore deposits. Various steps were needed to construct the supply curve (see Fig. 1), which are addressed here but explained in more detail in the sections below.

First, the grade distribution that can be found in the copper deposits worldwide has been determined. A distinction was made between the undiscovered (unanalysed) deposits and the known deposits that have been analysed and partially depleted. This distribution was then linked to the expected copper availability in all the deposits worldwide. Here, the distribution functions and the total amounts of copper were subdivided into ten equal parts for both the "undiscovered" and the "partially exhausted" deposit category.

[2] GER (Gross energy requirement) can be defined as the primary energy requirement of all the (upstream) processes that are needed to make a certain product (here: copper). Another term for the similar concept used in this study is "embodied energy".

These twenty amounts of copper were calculated for 40 different depths (segments of 100 m, up to 4000 m), resulting in a matrix that represents 800 amounts of copper with different grades and depths. Next, the GER for each amount of copper was determined, taking into account the energy requirement associated with the different depths and grades. The "ore grade – copper GER relationship" was derived by combining six studies that explored this topic (see section on the ore grade–energy relation), resulting in a lower, average and upper GER value for each grade. The "deposit depth – copper GER relationship" was derived from a benchmark study of Canadian open pit mines [12]. The 800 amounts of copper were then sorted from low to high GER and multiplied with the expected yield (used here: 80.1% of copper from deposits extracted and processed, Ecoinvent pyrometallurgical route [13]) to determine the total amount of copper that can be obtained from the deposits. By plotting the GER against the cumulative total primary copper, the supply curve could be constructed.

The supply curve resulting from the procedure described above includes all the copper that is theoretically available in all the discovered and undiscovered deposits up to 4 km depth worldwide. Yet, it is very likely there are many more constraints in retrieving this copper from the ground. For instance, it could be very difficult to extract copper from areas such as nature reserves, agricultural land, mountain ranges or cities. Therefore, the same procedure was repeated for two situations where only a share of the deposits can be reached: A scenario where only the known deposits are available and a scenario where only half of the assumed undiscovered deposits can be reached. The latter is rather arbitrary, but nonetheless, it can give an idea of the implication of the availability of large amounts of undiscovered copper.

#### 2.1.1. Construction of the grade-tonnage distribution curve

In order to express the worldwide distribution of copper in terms of grade, a so called cumulative distribution function was used, which is basically a (graphical) representation of the probabilities of finding ore at different grades within a certain deposit type.

For this purpose, a methodology developed by Gerst (2008) [14] was used in this study, based on combining data on the world's copper deposits. About 93% of the copper that has been produced in the last 80 years was found in porphyry, sediment-hosted, and VMS (volcanogenic massive sulphide) deposits. Large databases of these deposits exist and were applied here: [15] (Porphyry), [16] (Sediment hosted), [17] (VMS). The deposits are often well documented in terms of ore grade and tons of ore, which makes it possible to calculate the amount of copper that is present in the various ore bodies. In total, it was possible to determine this for 1350 deposits, which could be subdivided in 422 analysed porphyry deposits (of a total of 690 identified deposits), 141 analysed sediment hosted deposits (of a total of 785 identified deposits) and 787 VMS deposits (of a total of 845 identified deposits).

From using these databases it could be derived that an estimated 4.89 Gtons of copper is available in the identified deposits worldwide of which 55% is found in porphyry, 35% in sediment hosted, 3% in VMS deposits and 7% in other deposits. These estimates are based on several assumptions. First of all, it was assumed that the deposits that have not been analysed in terms of ore grade and tonnage hold the same amount of copper and have the same ore grade as the average analysed deposit of that type. Secondly, it was assumed that the ratio of the different types of known deposits represents the actual ratio found in discovered as well as in undiscovered deposits worldwide. Although all three deposit types are an economical source of copper, it is not inconceivable that we discovered a disproportionally small or large share of one of them. Another assumption was that the 7% copper that is produced from