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Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 °C target ☆

Koji Tokimatsu [a,b,*], Henrik Wachtmeister [c], Benjamin McLellan [d], Simon Davidsson [c], Shinsuke Murakami [e], Mikael Höök [c], Rieko Yasuoka [f], Masahiro Nishio [b]

[a] Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa 226-8503, Japan
[b] National Institute of Advanced Industrial Science and Technology, 1-2-1, Namiki, Tsukuba, Ibaraki 305-8564, Japan
[c] Global Energy Systems, Department of Earth Sciences, Uppsala University, Villavägen 16, SE-751 21 Uppsala, Sweden
[d] Graduate School of Energy Science, Kyoto University, Yoshida-Honmachi Sakyo-Ku, Kyoto 606-8501, Japan
[e] School of Engineering, The University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo 113-8656, Japan
[f] Systems Research Center, Co. Ltd, KY Bldg., 3-16-7, Toranomon, Minato, Tokyo 105-0001, Japan

HIGHLIGHTS

- Nexus approach was applied using an energy model to estimate metal requirements.
- Two original energy scenarios were developed: "Coal & Nuclear" and "Gas & Renewable".
- CCS was expanded in both scenarios, with either nuclear or PV in the two scenarios.
- The metal requirement to meet the 2 °C target in the both scenarios was estimated.
- Concerns exist that some metals might not meet requirements for PV in "Gas & Renewable".

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ABSTRACT

Stringent GHG emission cuts are required for meeting the so-called Paris Agreement. Due to higher metal intensities of renewable energy, such a transition must also include required amounts of metal. This study estimates the metal requirement for various power generation technology mix scenarios by using a cost-minimizing energy model on the global energy-mineral nexus. Two energy and climate scenarios were developed to represent primarily economic efficiency and environmental performance, respectively, under climate policies with net zero emissions satisfying the 2 °C target, and without any constraints (i.e. Business As Usual). Based on the future additions of various power generation technologies, metal requirements and cumulative production were estimated in zero-order and conservative scenarios, to compare with production levels in 2015 and reserves. The results suggest that there may be cause for concern about metal requirement and/or availability in PV, nuclear, and (Plug-in Hybrid) Electric Vehicles in 2100. For PV in the Gas & Ren scenario, most of the metal usage exceeded their production levels and the reserves. It is concluded that mineral availability and production rates should be given greater attention for planning and modeling of sustainable energy systems.

1. Introduction

1.1. Background

The Paris Agreement entered into force on 4 November 2016 by ratification of nations representing over 55% of total global greenhouse gas (GHG) emissions [1]. The Agreement aims to halt the rise in global mean temperature from global warming at well below 2 °C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 °C. However, the (Intended) Nationally

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* Corresponding author at: Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa 226-8503, Japan.
E-mail address: tokimatsu.k.ac@m.titech.ac.jp (K. Tokimatsu).

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Determined Contributions ((I)NDC) submitted by the 197 Parties to the agreement are insufficient to meet the target [2]. More stringent GHG emission cuts are required to meet the target, such as zero cumulative emissions over this century, by large-scale deployment of renewable energy, hydrogen energy, and carbon capture and storage (CCS) in all sectors of industry, as well as residential and transportation sectors [3].

In Japan specifically, since the Great East Japan Earthquake, Japanese energy policy strategies have been directed towards seeking more diversified energy options, especially fuel switching to gas, rapid introduction of renewable energy, and pushing towards a hydrogen economy [4]. Despite such stringent climate and energy policy, little consideration has been given to the mineral resources that would be used as materials for various energy technologies. Thus, while a secure supply of energy is typically argued within the context of energy resources within Japanese energy policy, there has been insufficient incorporation of minerals supply security in such policy.

The nexus approach requires understanding of not only the relationships of the resources concerned, but also the complex interactions between the natural environment and human society. It is anticipated that such an approach will lead to better understanding of the relationships between the resources by us. When analyzing one resource, some trade-offs with other resources can be revealed. Holistic understanding of these complex systems can assist in resolving such problems. The nexus between energy and mineral resources can be defined as "all the relations in supply chains between mineral resources and energy across various aspects including economy, technology, policy, society, geology, and nature" [5].

Nexus approaches have become popular recently in a variety of intersecting sectors with relations to sustainability—for example, the energy-biomass (food)-water nexus has been widely examined [6,7]. Other nexus examples can be found among the Sustainable Development Goals formulated by the UN (2015), with intersecting issues like clean and affordable energy for production, poverty alleviation and other uses in society [8]. The energy-mineral nexus has also recently gained attention, especially following the publication of reports on critical metals by the Department of Energy, United States of America (USDOE) [9], and by the European Commission Joint Research Centre (JRC) [10]. In this sense, there is a significant cross-over with the critical materials literature.

Many studies (e.g., [11–15]) have addressed scarce (or critical) metals used in particular energy technologies, such as wind power (WP), automobiles (for rare earth elements (REEs) used in magnets and generators), fuel cells (platinum group metals (PGMs)), thin-film photovoltaics (PV, using elements such as gallium, and indium), lithium ion batteries (lithium, cobalt, etc.), and other uses.

Renewable energy technologies are more metal intensive (per unit of output) than current energy sources, and decarbonization is expected to increase demand for many materials [16]. At the same time, this restructuring of the energy sector will likely imply that mining, manufacturing, and recycling industries will also become increasingly interdependent with the energy sector as the share of renewable energy increases [15,17]. In addition to academic activities, other government bodies have turned their focus to these minerals, for example, the USDOE launched the Critical Material Institute (CMI) [18], an energy innovation hub consisting of national institutes, universities, and private companies.

1.2. Research objectives and originality

The primary originality is in the application of an energy model to metal requirements in energy technologies. Studies applying such an approach through the collaboration of communities on metals and mineral resources with energy modelers are scarce, if available at all. In past studies, most have addressed specific mineral elements in technologies by borrowing energy scenarios from authorities (e.g., Strategic Energy Technologies (SET) plan, International Energy Agency (IEA) Energy Technology Perspectives (ETP), World Energy Council (WEC), or World Wildlife Fund (WWF)) [e.g., 13,19–22]. Some have applied empirical estimation models for their projections of future demand. By comparison, the present study applies models that have been developed specifically for this purpose, incorporating resources of energy (herein fuel minerals, fossil plus uranium), minerals (non-fuel minerals used for materials production), biomass, and food; to illustrate future metal requirements. This approach is a highlight of the model, in that it enables the *flexible* development of alternative energy and climate policy scenarios.

The secondary point of originality arises with the scenarios themselves (see Table 1). Two policy scenarios on energy and climate (two times two combinations) have been developed here, for which the details are described in a later section. The considered climate policies are extremely stringent regarding GHG emissions; "business as usual (BAU)" without any constraints and "net zero emission (hereafter net ZERO[1])" in which cumulative emissions are zero over the time horizon, allows positive emissions over the coming several decades that would be balanced-out by negative emissions in the latter half of the century [3]. Energy policies are "Coal & Nuclear" and "Gas & Renewable", stressing economic efficiency and environmental compatibility, respectively. These are inspired by Japanese energy policy before and after the Fukushima nuclear accident, as well as the shale revolution in the USA. These two policies are simulated only by changing the amount of resources provided in the model, keeping other settings and constraints identical. Within the authors' knowledge, no such modeling exercise has been similarly undertaken in which these two contrasting energy policy scenarios have been run simultaneously to test the effect of this specific parameter (i.e., the amount of the resource provided to the model).

1.3. Two scenarios on energy and climate

Two patterns of energy (especially power) scenarios and two climate policy scenarios were set-up. One energy scenario is dominated by gas and renewables (denoted as Gas & Ren), while in the other, coal and nuclear (Coal & Nuc) can be introduced substantially. The computation of changes in these scenarios was executed by assuming cheap gas and uranium, respectively, in each energy scenario. Common constraints on share of generation types were provided in all the four scenarios; sum of bio + oil power, sum of

Table 1
The four energy technology and climate scenarios used in this study. Metal requirements are analyzed for the two "net ZERO" scenarios.

	Climate	
Energy	BAU	Net ZERO
Coal & Nuclear	Coal & Nuclear under BAU	Coal & Nuclear under net ZERO
Gas & Renewables	Gas & Renewables under BAU	Gas & Renewables under net ZERO

Note: Common constraints on share of generation types were provided in the all scenarios; sum of bio + oil power, sum of PV + WP + ocean, coal power, and gas power (allowed as baseload operation) was less than (10, 20, 30, and 40)%, respectively.

[1] 2 °C is much easier to understand for general readers, our scenario (net ZERO) is not sole scenario to 2 °C, meaning that 2 °C may be attainable other GHG emissions paths. Our result shows 2.0 ± 0.3 °C with/without non GHG emissions.

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