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Energy modeling approach to the global energy-mineral nexus: A case of fuel cell vehicle

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Abstract

Hydrogen draw great attentions to become center of the Japanese energy policy after succeeding rapid expansion of renewable energy and dash for gas, after the Fukushima daiichi nuclear accident. This study estimates the metal requirement for hydrogen technologies by using a cost-minimizing energy model on the global energy-mineral nexus. The models are consisted from production of resources, land use and land use changes, inter-regional transportation, energy conversion (power, liquid fuels, gas), production of materials, final demand, wood products, disposal of used products, and materials recycling. Two energy and climate scenarios were developed to represent primarily economic efficiency and environmental performance, respectively, under climate policies with 2DC target, and without any constraints. Based on the future hydrogen consumption, metal requirements and cumulative production were estimated, to compare with production levels in 2015 and reserves. Candidates of hydrogen technologies are, fuel cells (for vehicle, stationary), storage tanks, and production, utilizing sectors in transport, power, and heat.

Keywords: hydrogen; energy-mineral nexus; energy model; metal requirement

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1. Introduction

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. 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" [1].

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 [2]. 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. 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) [3], and by the European Commission Joint Research Centre (JRC) [4]. In this sense, there is a significant cross-over with the critical materials literature.

Many studies 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, indium, etc.), lithium ion batteries (lithium, cobalt, etc.), and other uses. This study focuses on metal requirement in hydrogen technologies.

2. Outline of our modeling and analysis

Our global model balances demand and supply of resources for energy, mineral, biomass, and food formulated as dynamic linear programming over the time horizon in this century [5.6]. The models are consisted from production of resources, land use and land use changes, inter-regional transportation, energy conversion (power, liquid fuels, gas), production of materials (e.g, ferrous, non-ferrous (aluminum, copper, lead, zinc), and limestone), final demand, wood products, disposal of used products, and materials recycling. The models incorporate bottom-up detailed technology options close to hundred meeting the exogenously given demand scenarios to provide a consistent structure for supplying the resources.

The three models are all linked together. In addition to wood and logs as fuel for biomass energy with carbon capture and storage (BECCS), biomass residues from various biomass and food processes and products are used as potential supply of biomass resources in the energy systems model. Electricity and heat consumed in the material model are also endogenously linked to the energy systems model. Fly-ash from pulverized coal-fired power plants in the energy systems model is endogenously linked to the Portland fly-ash cement process in the material model. Zinc is also used as steel coating, which is assumed to recovered as potential zinc source. Since relations between cumulative tonnage production and ore grade for copper, lead, and zinc are given, energy consumption increase by ore degradation as well as energy penalty by mineralogical barrier are also taken into consideration.

We originally set up two patters of energy (especially power) scenarios and two climate policy scenarios. One energy scenario is dominated by gas and renewable (denoted as Gas/Ren), while another is coal and nuclear (Coal/Nuc) can be introduced substantially. The scenario changes in computation can be executed by assuming ad-hoc cheap gas and uranium respectively in each energy scenario. We give common constraints in both scenarios for share of generation types; sum of PV, WP and ocean, coal power, gas power (allowed base operation), and bio+oil power is less than 20%, 30%, 40%, and 10%, respectively. The climate policy scenarios are business as usual (BAU) with no emission control of greenhouse gases (GHGs), and zero emissions in the latter half of this century by giving cumulative emissions of WRE (Wigley Richels Edmonds) [7] 350ppm constraints over the computational time horizon (from 2010 to 2150).

In order to make rough estimation of metal requirements of hydrogen in the scenarios, we gave assumptions on market share of technologies, intensity use of the metals are to understand the requirement.

3. Results

The figure illustrates uncertainty ranges of the various (bulk, scarce) minerals in fuel cell vehicle (FCV) breakdowns under the two energy scenarios in the zero emissions scenario. Metal requirements in 2100 seem generally well exceed than 2015 production level in most of the metals, of which engines rather than tanks require. This figure changes little if steam reforming facility for producing hydrogen. We should still collect data and evaluate their levels to for comprehensive understandings of metal requirement of hydrogen production.

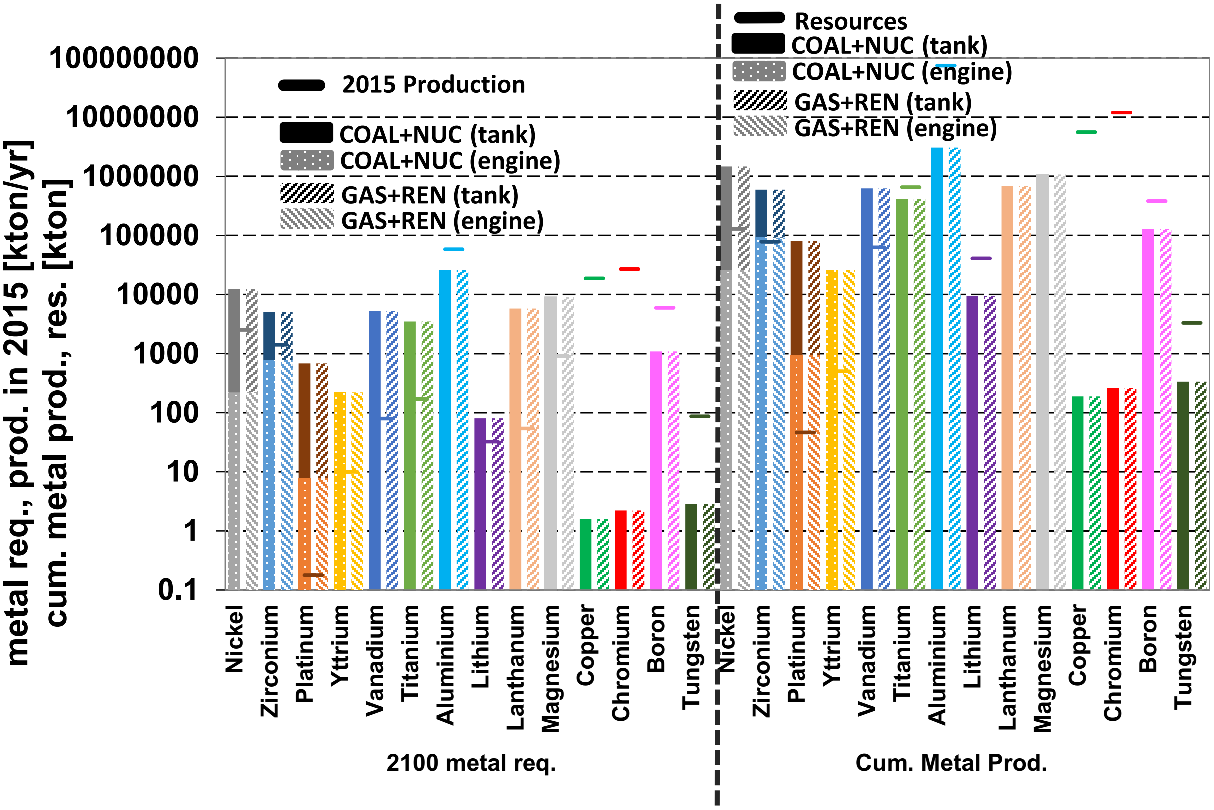

Fig. 1. Metal requirement and levels of 2015 production and resources in both energy scenarios under zero emissions scenario

4. Discussions and the way forward

The primary point of originality in this study arises from employing an energy model to approach the energy-mineral nexus. To the authors` knowledge, very few energy modelers have previously addressed this topic with the collaboration of communities in materials, metals and mineral resources. Past studies on mineral requirements were addressed by borrowing energy scenarios from authorities, while in this case original energy and climate policy scenarios were developed by addressing the 2 °C target, which is the second point of originality. Our third originality in scenario building is providing simultaneously both policy directions (i.e., coal & nuclear, gas & renewable) while existing studies in scenario building community typically treat only one direction.

As illustrated in the results, employing the energy models to metal requires enables us to estimate the requirement under scenarios developed by the modelers based on our original energy & climate policy scenarios. The collaboration of the both communities in the energy-mineral nexus bring great benefit to policy makers and research scientists for better understandings and decision makings in policy choice. Based on our first look at estimates from a conservative (or cautions) view, the metal requirement in 2100 and cumulative production in some metals in hydrogen technologies were determined to exceed the 2015 production levels and reserves under the Gas & Ren scenario while such excess was little observed under the Coal & Nuc scenario. In order to obtain more solid conclusions about metal requirements, further work is required to reduce uncertainties related to the intensity of use of metals and metal conservation (via technological progress), technology deployment, and recycling rate under more radical energy scenarios.

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