minerals

MDPI

Article

Evaluating Metal Criticality for Low-Carbon Power Generation Technologies in Japan

Wataru Miyamoto [1,*], Shoki Kosai [2] and Seiji Hashimoto [3]

1 Advanced Architectural, Environmental and Civil Engineering, Graduate School of Science and Engineering, Ritsumeikan University, Shiga 525-8577, Japan
2 Department of Mechanical Engineering, College of Science and Engineering, Ritsumeikan University, Shiga 525-8577, Japan; kosai0203@gmail.com
3 Department of Civil and Environmental Engineering, College of Science and Engineering, Ritsumeikan University, Shiga 525-8577, Japan; shashimo@fc.ritsumei.ac.jp
* Correspondence: rv0040if@ed.ritsumei.ac.jp; Tel.: +81-80-6135-2839

Received: 9 November 2018; Accepted: 5 February 2019; Published: 8 February 2019

check for updates

Abstract: Given a potential increase in low-carbon power generation, assessing the criticality of metals used for its technologies is of significant importance. While several studies analyzed the metal criticality of an individual technology, the national metal criticality for a wide range of low-carbon power generation technologies and the comparison of overall criticality of each technology have yet to be fully evaluated. Therefore, this study firstly evaluates the criticality of 29 metals used in facilities for renewable energy and highly efficient thermal power generation in Japan and then compares the overall criticality for each technology to identify metals that might impose limitations on these technologies and to discuss measures for removal of factors hindering the spread of low-carbon power generation technologies. It was discovered that solar power generation technology is the most critical technology from the perspective of supply risk due to the use of indium, cadmium and selenium, while wind power generation is the most critical technology from the perspective of vulnerability to supply restriction because of the use of neodymium and dysprosium. A developed approach would have a significant potential to contributing to energy-mineral nexus, which may assist in providing policy implications from the perspectives of both specific metals and technologies.

Keywords: criticality matrix; import reliance; rare earth element; by-product metals; substitute metals

1. Introduction

In the last decades, the acceleration of energy demand and excess utilization of fossil fuels have raised alarming issues of climate change and energy security. Securing a stable supply of environmentally benign energy is of utmost importance for sustaining quality of human life [1]. Currently, given the significant risk of the use of nuclear energy observed after the Fukushima nuclear accident [2], widespread acceptance of renewable energy and highly efficient thermal power generation has become necessary for realization of a low carbon society and improvement of energy security.

Globally, the importance of renewable energy and high efficiency thermal power generation has strongly increased. According to the Energy Technology Perspective 2017 (ETP2017), reported by the International Energy Agency (IEA), renewable power generation in 2015 was expanded by more than 30% compared with 2010, and it is forecasted to grow by another 30% between 2015 and 2020 [3]. In addition, according to ETP2017, a slight increase in the thermal power generation is anticipated with an improvement of overall plant efficiency.

Given the anticipated worldwide expansion of this new technology, metals required for low-carbon power generation technologies cannot be simply ignored. Renewable energy technologies require various rare metals compared with conventional generation technologies, and it is anticipated that demand for these metals will increase due to the widespread acceptance of the technologies [4–6]. Taking into account the difficulties of achieving breakthroughs on process of secondary metal recovery from electronic waste in the near future [7], it is useful to study which metals might become constraints that hinder the wider popularization of low-carbon power generation technologies.

In fact, following reports of the Department of Energy in the U.S.A. [8] and European Commission [9], interest in energy-mineral nexus has been currently growing as an interdisciplinary research topic [10] in response to resource constraints and drastic change of energy landscape [11]. Potential metal requirements and bottlenecks in the energy sector were investigated, providing various scenarios covering power mix on a basis of stringent greenhouse gas emission cuts [10] and power generation and automotive sectors [12,13].

Particularly, metal criticality assessment applied into the energy sector would have a significant potential to contributing to energy-mineral nexus. Various definitions of metal criticality have been reported [14]. Defining the universal concept of metal criticality is difficult due to its nature, namely that criticality concept context-dependent on global circumstances has over time become more complex. In addition, a multi-dimensional approach has been widely utilized to quantify the metal criticality, and the various selection of dimension appears to be dynamic and complicatedly evolves in response to the diachronic transition of material landscape. In fact, due to its arbitrary choice, some components, including economic factors and environmental impacts, have been disputed in terms of whether these should be included in metal criticality dimension [15]. Besides these, additional dimensions such as social issues [16,17] have recently been included.

Despite of the ambiguity of the concept, there seems to be an agreement that metal criticality is highly associated with both supply risk [18] and vulnerability to supply disruption [19]. The combination of supply risk and vulnerability is widely utilized in promising frameworks [20–26]. Supply risk is also formed into another promising framework with economic importance [9,27,28]. Several research works primarily focus on supply risk of metal criticality in the context of market structure [29], regulatory governance [16], external dependency [30] and geopolitical issues [31]. In addition, the aforementioned other components such as environmental, economic and social implications have been preferably regarded as a factor that brings supply restriction through tightened production regulation at the origin of metal mining [32,33]. As such, this paper focuses on these most promising components, including supply risk and vulnerability in the criticality assessment.

National critical materials have been focused on in various earlier papers [34–37], since criticality assessment is a driving force of material securement strategy. Although for energy-poor countries such as Japan renewable energy highly contributes to increase in self-sufficiency of energy generations, additional drawbacks of metal-poor situation exacerbate the reliance on resource imports [38–40]. The Japanese government sees securing rare metal resources as an important issue [41]. Given that renewable energy is expected to account for 22–24% of power supplies in Japan in 2030 [42], an evaluation of material criticality for low-carbon power generation technologies in Japan is of paramount importance.

Several research works on metal criticality assessments for the energy sectors by employing the multi-dimensional approach were published. Roelich et al. [43] assessed the neodymium criticality for wind turbine in the UK. Goe and Gaustad [44] focused on metals associated with solar photovoltaic technology including silicon-based and thin-film photovoltaic in the U.S.A. Helbig et al. assessed the supply risks associated with lithium-ion battery [45] and thin-film photovoltaics including cadmium telluride and copper-indium-gallium diselenide [46] and Habib and Wenzel analyzes wind turbines [47]. However, these papers did not consider the metal criticality for a given nation. In contrast, the national metal criticality for a wide range of low-carbon power generation technologies and the comparison of overall criticality of each technology have yet to be fully evaluated.

Therefore, the objective of this study was to evaluate the criticality of 29 metals used in low-carbon power generation technologies, including renewable energy and highly efficient thermal power generation in Japan, then to compare the overall criticality for each technology for the identification of metals that might impose limitations on these technologies and the exploration of measures for a removal of factors hindering the spread of low-carbon power generation technologies.

The paper is structured as follows: Section 2 presents objective technologies and metals, and the methodology of evaluating supply risk and vulnerability to supply restriction of each metal and technology. Section 3 illustrates the results of the criticality assessment for each metal and technology. A comparison with previous studies, the policy implication, and future work are discussed in Section 4. Finally, Section 5 presents the conclusions.

2. Methods

2.1. Objective Technologies and Metals

On the basis of Long-term Energy Supply and Demand Outlook [42], this paper selects eight types of low-carbon power generation technologies for evaluation, based on: hydro, wind, solar, geo-thermal, biomass, nuclear, liquid natural gas (LNG) and coal. In all, referring to reports of the literature [48–50], 29 kinds of metals used in these technologies were selected, namely, boron (B), magnesium (Mg), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), cobalt (Co), nickel (Ni), gallium (Ga), selenium (Se), yttrium (Y), zirconium (Zr), niobium (Nb), molybdenum (Mo), silver (Ag), indium (In), tellurium (Te), neodymium (Nd), dysprosium (Dy), hafnium (Hf), tantalum (Ta), tungsten (W), lead (Pb), aluminum (Al), iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd) and tin (Sn). For solar power generation, a copper-indium-gallium diselenide solar cell (CIGS), a cadmium telluride solar cell (CdTe), and organic system, were included. For wind power generation, electric generators using permanent magnets were included. For biomass generation, the existing facilities of coal power generation were used. For thermal power generation, a gas turbine combined cycle (GTCC) and Advanced–Ultra Supercritical Coal power plant (A-USC) were included. The summary of low-carbon power generation technology and relevant metals is presented in Table 1.

Table 1. Low-carbon power generation technology and relevant metals.

Required Metals	Hydro	Wind	Solar	Geo-Thermal	Biomass	Nuclear	LNG	Coal
Boron		✓						
Magnesium	✓							
Titanium	✓		✓	✓	✓	✓	✓	✓
Vanadium					✓	✓		
Chromium	✓	✓		✓	✓	✓	✓	✓
Manganese	✓	✓		✓	✓		✓	✓
Cobalt					✓		✓	✓
Nickel	✓	✓		✓	✓	✓	✓	✓
Gallium			✓					
Selenium			✓					
Yttrium						✓		
Zirconium	✓		✓			✓		
Niobium				✓	✓	✓		✓
Molybdenum	✓	✓		✓	✓	✓		✓
Silver			✓			✓		
Indium			✓			✓		
Tellurium			✓					
Neodymium		✓						
Dysprosium		✓						
Hafnium						✓		
Tantalum				✓	✓			✓
Tungsten					✓	✓		
Lead	✓		✓			✓		
Aluminum			✓		✓		✓	✓
Iron			✓		✓		✓	✓
Copper	✓	✓	✓	✓		✓	✓	
Zinc	✓							
Cadmium			✓			✓		
Tin	✓		✓			✓		

2.2. Evaluation of Metal Criticality Dimension

As presented in Section 1, this study evaluated metal criticality from two aspects of supply risk and vulnerability. As a promising and comprehensive framework for supply risk (SR) and vulnerability to supply restriction (VSR), indicators developed by the Yale University research group [21] were used after the four modifications to adjust the evaluation structure for each of dimension to the present case.

The first point modified for this paper was a removal of the environmental impact (EI). This was because the supply risk arising from environmental regulations was already covered in the SR. The second point modified for this paper was a simplification of depletion time. This was because the improvement of versatility was necessary for evaluating many types of metals. The concept of "depletion time" corresponds to the indicator of "RP_t", which is used for minable years. The third point modified was a removal of the rate of user population (PPU). This was because of difficulties of collecting data dedicated for utilization in Japan. The fourth point modified was a removal of global innovation index. This was because this index is dependent on the assessed demand countries and this paper focused only on Japan.

2.2.1. Supply Risk (SR)

The risk in supply countries was evaluated from the viewpoints of geological, technological and economic, social and regulatory and geopolitical.

1. Geological, technological and economic (GTE)

This aspect was evaluated based on minable years (RP_t) and companion metal fraction (CMF). RP_t indicated the minable years under the assumption that the metal production amount in 2014 remains the same in future. It was computed by using the following equation:

$$RP_{t,i} = 100 - 0.2 \times RP_i - 0.008 \times RP_i^2 \quad (1)$$

where i means metal and RP_i is obtained by dividing reserves in 2014 by production volume in 2014 [51]. For $RP_{t,i}$ to be normalized on a 0–100 scale, $RP_{t,i}$ was set to 0 when RP_i was over 100, and $RP_{t,i}$ was set to 100 when RP_i was less than 0.

In addition, CMF represents the rate of metal being produced in the form of a by-product. This evaluates the risk degree in which the production of compound metal is influenced by the demand and supply balance of host metal. One earlier study reported in the literature [52] demonstrates that the rate of production from other metals and CMF are estimated by adding these rates.

2. Social and regulatory (S&R)

This aspect was evaluated using the policy perception index (PPI) and the human development index (HDI).

PPI is an indicator developed by the Fraser Institute, in which the national policy and regulation for activities of metal production are evaluated on a basis of 15 attributes [53]. The PPI of a given metal i is expressed in the following equation:

$$PPI_i = \frac{\sum PPI_j \times R_j}{\sum R_j} \quad (2)$$

where j means a country, PPI_j means PPI in a country j and R_j means a production rate in a country j. For metals produced as a by-product, considering the production style, an estimation was made using PPI mainly of the host metal producing country. Each production style in this methodology is shown in Supplementary Figure SA.

HDI is an indicator developed by the United Nations Development Programme (UNDP), in which quality of health, education and quality of life of target countries were evaluated [54]. The HDI of a given metal *i* is expressed in the following equation:

$$HDI_i = \frac{\sum HDI_j \times R_j}{\sum R_j} \quad (3)$$

where HDI_j means HDI in a given country *j* and R_j means a share of producing countries corresponding to each production style described in Supplementary Figure SA.

3. Geopolitical (GP)

This aspect was evaluated using the worldwide governance indicator-political stability and absence of violence/terrorism (WGI-PV) and the global supply concentration (GSC).

WGI-PV is an indicator developed by the World Bank, in which the country risk of the producer country is estimated [55]. As earlier research did, this paper employed one of the dimensions in WGI-PV, namely political stability and absence of violence/terrorism. The WGI-PV of a given metal *i* is expressed in the following equation:

$$WGI\text{-}PV_i = \frac{\sum WGI\text{-}PV_j \times R_j}{\sum R_j} \quad (4)$$

where $WGI\text{-}PV_j$ means WGI-PV in a country *j* and R_j means a share of producing countries corresponding to each production style described in Supplementary Figure SA.

GSC is an indicator by using Herfindahl–Hirschman index (HHI), in which the degree of the producer country oligopoly is estimated. The GSC of a given metal *i* is expressed in the following equation:

$$GSC_i = 17.5 \times \ln\left(\sum HHI_j\right) - 61.18 \quad (5)$$

where HHI_j means Herfindahl-Hirschman Index (HHI) in a country *j*. HHI is commonly used to measure market concentration in economics [56].

2.2.2. Vulnerability to Supply Restriction (VSR)

Influences of demand side countries when the supply of the target metal is restricted were evaluated from the viewpoints of importance, substitutability and susceptibility.

1. Importance (I)

This aspect was evaluated by using the national economy (NE). The NE is defined as the market size of each metal over the GDP. The NE of a given metal *i* is expressed in the following equation:

$$NE_i = \frac{M_i \times D_i}{GDP} \times 100000 \quad (6)$$

where M means unit price of raw materials and D means domestic demand. The data in 2014 of M and D is taken from the Japan Oil, Gas and Metal National Corporation [57], Arum Publications [58] and U.S.A. Geological Survey (USGS) [59].

2. Substitutability (S)

This aspect was evaluated by substitute performance (SP) and substitute availability (SA). Given that the existence of substitute materials affected the vulnerability of the demand country, whether there were substitute metals or SA, and how adequate their performance is was or whether SP needed to be evaluated.

SP was evaluated on the basis of five ranks of adequacy as provided in earlier works [22,23,60–63]. The SP_i of a given metal *i* is expressed in the following equation:

$$SP_i = \frac{\sum SP_k \times D_k}{\sum D_k} \quad (7)$$

where k means a substitute material and SP_k means adequate performance of substitute material k.

SA was obtained by firstly computing the SR of the substitute metal and material following the method in Section 2.2.1, and then computing the obtained SR with the weighted average of D_k. The detail explanation about SP and D of each material is presented in Supplementary Figure SB. This paper estimated the SR of new metals and materials for substitution including lithium (Li), sodium (Na), cerium (Ce), samarium (Sm), terbium (Tb), platinum (Pt), gold (Au), bismuth (Bi), lime, talc, plastic and wood. The production data for roundwood was taken from the Food and Agriculture Organization [64]. The evaluated SR values of substitute materials are given in Supplementary Figure SC.

3. Susceptibility

This aspect evaluates import reliance (IR). IR represents the degree of dependence on import.

The IR_i of a given metal i is expressed in the following equation:

$$IR_i = \frac{import_i}{primary\ production_i + second\ production_i + import_i + stock_i} \quad (8)$$

The data for *primary production*$_i$, *secondary production*$_i$, *import*$_i$ and *stock*$_i$ is taken from Japan Oil, Gas and Metal National Corporation [57] and Arum Publications [58].

2.2.3. Weighting and Aggregation

The normalized indicators on 0–100 scale were integrated into a composite index to quantify supply risk and vulnerability of metal criticality dimensions. Before aggregation, the weight needed to be put on the normalized indicator. In this paper, the most common approach of equal weight was adopted [65], which has been widely utilized as a weighting scheme in various earlier research works on criticality assessment. In addition, this paper employed the additive approach for aggregation [66], where normalized indicators were first multiplied with the equal weight, and then summed to obtain the composite index. Metal criticality constituting supply risk and vulnerability were estimated using the following equations. The higher composite indexes corresponded to more critical metals. The respective composite indexes were put on a supply risk versus vulnerability graph.

$$\mathrm{SR} = \frac{\frac{(\mathrm{RP_t+CMF})}{2} + \frac{(\mathrm{PPI+HDI})}{2} + \frac{(\mathrm{WGI\text{-}PV+GSC})}{2}}{3} \quad (9)$$

$$\mathrm{VSR} = \frac{\mathrm{NE} + \frac{(\mathrm{SP+SA})}{2} + \mathrm{IR}}{3} \quad (10)$$

2.3. Overall Criticality of Low-carbon Power Generation Technologies

On the basis of the computed SR and VSR for each of assessed metals, the overall criticality of each of low-carbon power generation technologies was evaluated. The overall criticality assessment could evaluate the availability of each power generation technology in the context of specific critical metals. Although the risk of power generation has been widely addressed from the perspective of energy security [66], the approach developed in this paper would be also of a paramount importance in resource-poor countries, such as Japan.

In this paper, the SR and VSR of metals used in each of the technologies were first summed and then divided by the number of metal types to reach the SR and VSR of low-carbon power generation technologies. It was assumed that any single lack of metal leads to incompletion of the power generation technologies and the values of metals used in each power generation technology were equally weighted.

As such, the SR and the VSR of each of low-carbon power generation technologies were computed in the following equation:

$$SR_t = \frac{\sum_i^{N_t} SR_{t,i}}{N_t} \tag{11}$$

$$VSR_t = \frac{\sum_i^{N_t} VSR_{t,i}}{N_t} \tag{12}$$

where t means a low-carbon power generation technology, $SR_{t,i}$ means SR of a given metal i used in a given low-carbon power generation technology t and $VSR_{t,i}$ means VSR of a given metal i used in a given low-carbon power generation technology t. N_t means the number of metals used in a low-carbon power generation technology t.

3. Results

Metals associated with low-carbon power generation technologies were identified and the quantifying approach of evaluating their criticality was presented in Section 2. Following the developed methodology, the supply risk and vulnerability for each of the identified metals and the overall criticality of low-carbon power generation technologies in Japan will be assessed in this section.

3.1. Assessment in Supply Risk and Vulnerability to Supply Restriction of Each Metal

Each dimension and indicator of the 29 target metals is evaluated on a basis of framework. The result is shown in Figure 1.

In particular, among the 29 elements, indium, cadmium, cobalt and selenium were considered to have the highest criticality from the perspective of supply risk.

Indium, cadmium and selenium exhibited a critical score in GTE, which indicates the high possibility of depletion under the assumption of the current production rate and the severe dependence on the host metal production. Indium is a companion metal of zinc and tin, and cadmium is a companion metal of zinc, while selenium is a companion metal of copper. The productions of these metals are highly influenced by the balance between demand and supply of host metals. Additionally, there are possibilities of wasting these metals in cases where the cost for collecting them as by-products from the host metal refinery is expensive [67]. The technological innovation for improvement of exploration technology and reduction of recovery cost is required to mitigate the impact of GTE for these metals.

Cobalt exhibits a critical score in not only GTE but also GP. This results from the high geopolitical risk in the Democratic Republic of Congo, with a 50% share of the worldwide production. Political instability such as recent internal strife caused by anti-government forces in 2013 [68] may lead to sudden disruptions of cobalt supply. Besides cobalt, rare earth elements such as yttrium and neodymium exhibit a critical score in GP due to a high concentration of its production in China (nearly 90%). Improvement of technology for exploration and refining low-grade ores may contribute to the diversification of supply countries and the mitigation of risk in GP.

Among 29 elements, manganese, magnesium and yttrium are considered to exhibit the highest criticality from the perspective of vulnerability to supply restriction. This attributes to the critical score in S as shown in Figure 1.

90% of the manganese applications is steel metallurgy, as shown in Supplementary Figure SB. Steel metallurgy is used for improvement of strength and abrasion resistance by deoxidization and desulfurization in industrial appliances and building structures. 80% of the magnesium applications are refractory used in furnaces for steel, non-ferrous and cement productions. 70% of the yttrium applications are phosphors. Meanwhile, in their applications there are no substitutable metals which have a similar performance with these metals [23,62].

According to Supplementary Figure SB, the non-existence of substitutable metals is a major contributor to the increase in the score in SP and SA. Taking into consideration of change in environmental impacts [69], development of substitutable materials and reduction of consumption rates are of significant importance.

Elements	Supply Risk							Vulnerability to Supply Restriction				
	GTE		S&R		GP		SR	I	S		SU	VSR
	RPt	CMF	PPI	HDI	WGI-PV	GSC		NE	SP	SA	IR	
B	53	0	32	77	79	88	55	0	41	42	100	47
Mg	0	5	54	75	70	94	50	2	94	97	100	66
Ti	0	0	38	73	51	59	37	2	63	41	99	51
V	0	82	53	73	71	84	60	2	63	50	91	50
Cr	94	0	41	70	67	76	58	3	76	67	100	58
Mn	83	3	42	73	55	68	54	3	96	97	100	66
Co	62	85	51	77	75	78	71	1	41	54	67	39
Ni	85	0	47	77	57	58	54	5	62	59	27	31
Ga	0	100	40	75	69	88	62	1	38	58	44	31
Se	87	100	29	82	45	70	69	0	38	61	1	17
Y	0	84	57	73	71	100	64	1	97	88	100	64
Zr	65	100	37	78	44	75	67	0	78	69	100	58
Nb	37	2	38	77	52	96	51	3	42	60	100	51
Mo	80	46	36	80	55	74	62	8	70	62	94	56
Ag	92	71	36	78	62	59	66	14	49	29	36	30
In	96	100	42	80	55	81	76	10	63	58	21	30
Te	0	100	29	88	39	73	55	0	38	61	58	36
Nd	0	95	55	74	68	97	65	9	41	62	100	53
Dy	0	94	57	73	71	100	66	12	38	66	100	54
Hf	0	100	37	78	44	75	56	0	38	67	100	51
Ta	28	50	49	55	67	79	55	2	41	47	86	44
W	81	5	55	73	68	93	62	0	38	57	83	43
Pb	94	0	43	79	60	78	59	13	100	100	10	41
Al	0	0	40	78	52	71	40	39	49	56	66	53
Fe	90	0	43	77	56	77	57	100	50	43	4	50
Cu	80	10	29	78	55	64	53	50	73	47	4	38
Zn	95	0	41	79	59	72	58	7	38	45	5	18
Cd	92	100	41	81	55	66	72	0	13	42	3	10
Sn	94	0	56	74	70	72	61	3	36	59	88	46

Figure 1. Criticality assessment values for indicators and axes of target metals. Each value is presented in the range 0 to 100. The score near 100 is colored in red and the score near 0 is colored in blue. The higher score corresponds to the more critical elements.

3.2. Assessment Aggregation of Two Axes

A summary of metal criticality for 29 elements is presented in Figure 2. The horizontal axis means supply risk (SR) and the vertical axis means vulnerability to supply restriction (VSR).

This study categorizes the assessed metals into seven groups by referring to the study [22,60,61], namely, light metals (B, Mg, Ga, Al), iron and its principal alloying metals (V, Cr, Mn, Nb, Fe), superalloy metals (Ti, Co, Ni, Mo, Ta, W), copper metals and associated by-products (Se, Ag, Te, Cu), zinc, tin, lead metals and associated by-products (In, Pb, Zn, Cd, Sn), rare earth metals (Y, Nd, Dy) and nuclear energy metals (Zr, Hf).

As shown in Figure 2, to generalize, it would appear that the metals with higher SR are the ones with lower VSR. In general, the influence of host metals on a society would be greater than rare metals because of their uses for various social infrastructures. On the other hand, the SR of rare metals is greater than host metals because of their uneven distribution and scarcity. This trend is remarkable for each group, where the almost host metal of each group is located at the upper left (low SR and high VSR), and the rare metal is located at the lower right (high SR and low VSR).

The metals located at the upper left and the lower right would be critical metals containing either potential risk or influence on society. Meanwhile, the metals located at the upper right (high SR and high VSR) would be also considered more critical region for both SR and VSR. Even for metals that are hard to evaluate on a single dimension, the composition of each dimension enables to indicate the aggregated criticality of the metals. As such, to comprehensively evaluate the metal criticality, Graedel et al. [21] aggregated the two dimensions into a composite index called "criticality vector magnitude". This is obtained in the following equation:

$$criticality\ vector\ magnitude = \frac{\sqrt{SR^2 + VSR^2}}{\sqrt{2}} \quad (13)$$

Yttrium, zirconium and dysprosium potentially exhibit a high score in the composite index. These metals should be secured appropriately by reducing their risks or impacts on society, in addition to indium, cadmium, cobalt, selenium, manganese and magnesium. The aggregation approach would be useful to extract critical metals hidden behind the individual dimension assessment.

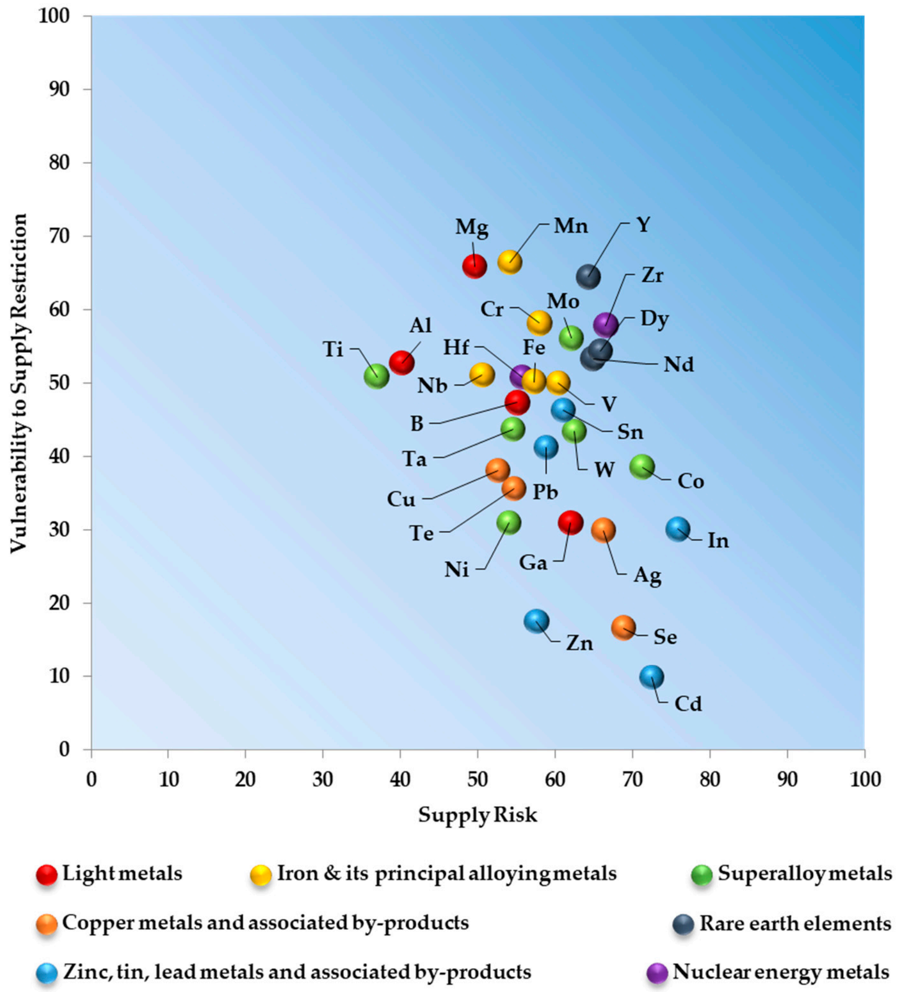

Figure 2. Location of target metals in criticality matrix.

3.3. Overall Criticality of Low-Carbon Power Generation Technologies

Following Section 2.3, the overall aggregated criticality of low-carbon power generation technologies is obtained. The result is presented in Figure 3.

Solar power generation is the most critical technology from the SR perspective. This results from the use of selenium, indium and cadmium for the CIGS system. Considering its capacity installation is expected to increase the most among renewable energy in Japan [42], ensuring the continuous supply of these metals is necessary for the solar power generation.

Wind power generation is the most critical technology from the VSR perspective. This results from the use of neodymium and dysprosium in the permanent magnet motor. These metals have high scores in S and SU, which means that there are less substitutable metals and their production is highly reliant on the other counties.

Coal, LNG, geothermal and biomass power generation also have a critical score in VSR. These technologies use the steel containing manganese, chromium, nickel and titanium to prevent oxidation and sulfurization. Among these metals manganese and chromium in particular have a critical VSR score, leading to the high VSR in these technologies.

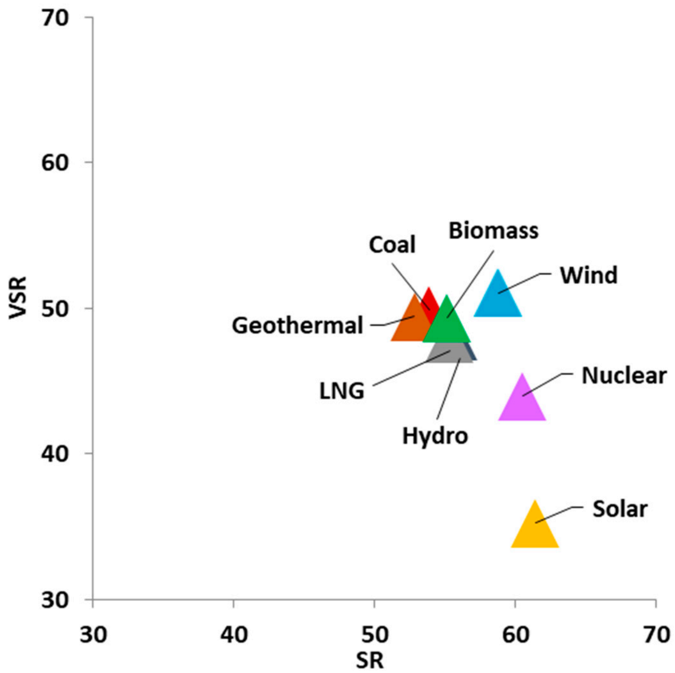

Figure 3. Overall criticality in low-carbon power generation technologies.

4. Discussions

4.1. Comparison with Previous Metal Criticality Studies in Japan

Other than this paper, there have been three research studies, reported by New Energy and Industrial Technology Development Organization (NEDO) [40], Japan Oil, Gas and Metal National Corporation (JOGMEC) [70] and Hatayama and Tahara [39] that have worked on metal criticality in Japan. Each of research works was compared to evaluate the validity of the factors used in this study, presented in Table 2. This comparison focused on the metals that were targeted in this criticality assessment.

All of the research studies, including this paper, had in common that indium, yttrium, cobalt, magnesium and dysprosium were considered critical metals in Japan regardless of differences of indicator and dimension selection.

Cadmium, selenium, manganese and zirconium, which were denoted as a critical metal in this study, were not considered critical metals in the other studies. This might be due to the inclusion of consideration of risk in production as by-products in the form of CMF in the SR and of reliance on import in the form of IR in the VSR. Taking into account the nature of rare earth elements, where its balance between demand and supply with a small market scale is highly affected by the host metals and the situation in Japan, hence depending highly on the metal import, this framework would be useful for metal-poor countries.

On the other hand, niobium, which was denoted as a critical metal in the other three studies, was not considered the critical metal in this study. This might be due to the difference of factors in SR. JOGMEC [70] took recycling rate into consideration in the SR. Since niobium has hardly ever been recycled in Japan, the evaluation highly depends on whether this factor is considered in SR or VSR. In the study of NEDO [40] and Hatayama and Tahara [39], since the SR was evaluated by only minable year and concentration, the SR of niobium was higher than this study. In addition, their studies evaluated the risk of the concentration of not only producing countries, but also countries by proven metal ores and countries by export to Japan. This may contribute to the higher SR of niobium.

Since the different selection of dimension and indicator affects the final outcome to some extent, a construction of comprehensive methodology for evaluating critical metals is required.

Table 2. Comparison with previous studies in Japan.

Study	Target Year	Dimensions	Elements	Critical Metals
This study	2014	Supply Risk/Vulnerability to Supply Restriction	29	In, Cd, Co, Se, Mn, Mg, Y, Zr, Dy
NEDO [40]	2007	Supply Risk/Price Risk/Demand Risk/Recycle/Potential Risk	36	W, Nb, In, Nd, Dy, Y
JOGMEC [70]	2012	Supply Risk/Economic importance	41	Nb, Dy(HREE[1]), W, Mg, Co, Cr
Hatayama and Tahara [39]	2012	Supply Risk/Price Risk/Demand Risk/Recycle/Potential Risk/Reserve entitlements to demand	22	Nb, In, Nd, Dy

Note: [1] HREE means heavy rare earth elements.

4.2. Policy Implications

According to the results obtained in this study, among low-carbon power generation technologies in Japan, solar power generation exhibits the highest SR, while wind power generation exhibits the highest VSR. This was attributed to the use of selenium, indium and cadmium for the solar and the use of neodymium and dysprosium for the wind.

From the perspectives of both specific metals and technologies, the strategies of mitigating the impact of SR and VSR need to be developed.

The policy implications from the perspective of specific metals are as follows. For selenium, indium and cadmium, the improvement of production and exploration technology contributes to the mitigation of CMF. The support for exploring the ore deposit where rare metals could be produced without any reliance on the host metals and the financial support such as subsidy for the metals, which requires a high recovery cost, might be useful. As for neodymium and dysprosium, the mitigation of the IR impact is required and the policy for the encouragement of stockpile for the emergent cases where the import is restricted due to the political issues and the preferential improvement of their recycling technology to increase in the secondary production would be useful.

The policy implications from the perspective of technologies are as follows. For solar power generation, the policies for confining the share of thin films such as CIGS and CdTe and organic system, which are expected to increase in its application [71] and for reducing the metal intensity, or the use of metals per technology, would be useful. As for the wind power generation, the technological road map for encouraging the non-use of rare-earth magnet for the generation motor needs to be developed.

These policy implications for the future energy use would be unique, developed on the basis of the metal criticality.

The summary of policy implications from the perspectives of both specific metals and technologies is presented in Figure 4.

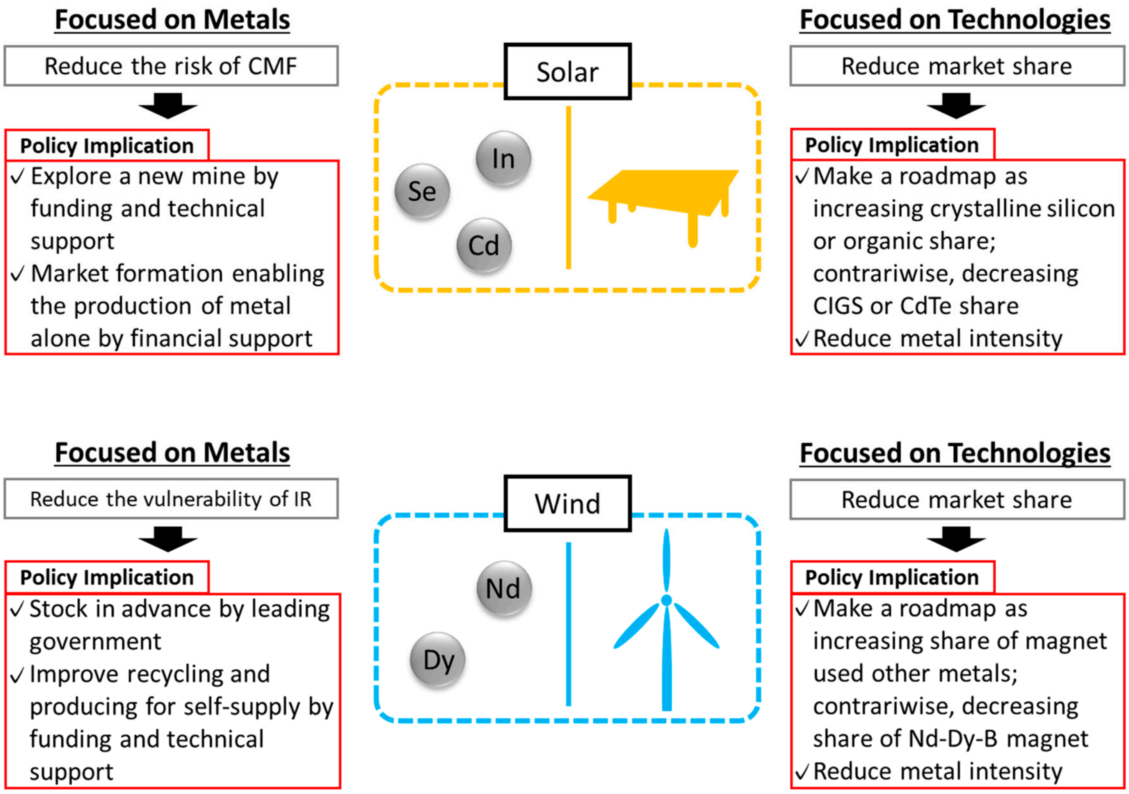

Figure 4. Concept of policy implications from the perspectives of both specific metals and technologies. The abbreviations are as follows: CMF = companion metal fraction; CIGS = copper-indium-gallium diselenide solar cell; CdTe = cadmium telluride solar cell; IR = import reliance.

Finally, the metal criticality and overall criticality for the technologies assessed in this study would be potentially integrated in the energy security. In the energy strategic plan of Japan, the security of supply of fossil fuels was evaluated [72]; the criticality of metals highly associated with the concept of energy security had never been considered in the energy policy. Moreover, it might be possible to ignore the supply risk of low-carbon power generation technology. Since the energy security is a driving force of energy policy, the metal criticality assessment would contribute to provision of insight for considering the best energy mix from the perspective of material use.

4.3. Future Work

The developed approach for evaluating the metal criticality of low-carbon power generation technologies implements the assessment of not only each metal, but also each technology. This may contribute to the development of strategies for mitigating the criticality of the target metal used in a particular technology, such as next-generation vehicles or IT devices.

Furthermore, the analysis could be improved by the inclusion of additional considerations. Firstly, although this paper employs the equal weight, the outcomes of aggregation highly depend on the weighting scheme in the multi-faceted approach, leading to the difficulties of depicting the universal conclusion [73]. Comparative analysis with changing the weighting scheme (e.g., principle component analysis (PCA), analytic hierarchy process (AHP) and data envelopment analysis (DEA) [74]) may improve the evaluation methodologies of material criticality. Secondly, the indicators selected in this paper do not fully cover the characteristics of the assessed country (e.g., Japan). The specific factors, such as sea lane risk [75], associated with the assessed country, need to be incorporated in the framework. Finally, uncertainties in quantification of qualitative components and in data assumption [76] must be assessed by conducting sensitivity assessment.

5. Conclusions

A literature review identified the significance of evaluation for the criticality of metals used in a wide range of low-carbon power generation technologies in Japan. The supply risk and vulnerability to supply restriction of 29 metals used in low-carbon power generation technologies were evaluated to identify metals that might impose limitations on low-carbon power generation technology using the metals. Finally, the overall aggregated criticality of low-carbon power generation technologies was evaluated to identify metals that might impose limitations on these technologies and discuss measures for a removal of factors hindering the spread of low-carbon power generation technologies.

In the criticality assessment for each metal, it was found that indium, cadmium, cobalt and selenium exhibit the highest criticality from the perspective of supply risk. For these metals, the technological innovation for improvement of exploration technology and reduction of recovery cost was required to mitigate the impact of GTE for these metals. Meanwhile, manganese, magnesium and yttrium indicated the highest criticality from the perspective of vulnerability to supply restriction. For these metals, the development of substitutable materials and reduction of consumption rate are of significant importance. In addition, the composite index developed by aggregating SR and VSR identified the high criticality of yttrium, zirconium and dysprosium. Furthermore, it was found that among the low-carbon power generation technologies, solar power generation was the most critical technology from an SR perspective, while wind power generation was the most critical technology from a VSR perspective. The provided policy implication might assist policymakers in designing well-grounded energy strategies taking into account the mitigation of metal criticality.

Supplementary Materials: The following are available online http://www.mdpi.com/2075-163X/9/2/95/s1. List of abbreviations, list of subscript, Figure SA: The data used for evaluation social and regulatory and geopolitical in supply risk, Figure SB1: The data of light metals used for evaluating vulnerability to supply restriction, Figure SB2: The data of iron and its principal alloying metals used for evaluating vulnerability to supply restriction, Figure SB3: The data of superalloy metals used for evaluating vulnerability to supply restriction, Figure SB4: The data of copper group metals used for evaluating vulnerability to supply restriction, Figure SB5: The data of zinc, tin, lead group metals used for evaluating vulnerability to supply restriction, Figure SB6: The data of rare earth elements used for evaluating vulnerability to supply restriction, Figure SB7: The data of nuclear energy metals used for evaluating vulnerability to supply restriction, Figure SC: The supply risk results of substitute metals for evaluating substitute availability.

Author Contributions: Conceptualization, W.M., S.K. and S.H.; Data curation, W.M.; Investigation, W.M., S.K. and S.H.; Methodology, W.M., S.K. and S.H.; Supervision, S.H.; Visualization, W.M.; Writing–original draft, W.M. and S.H.; Writing–review & editing, S.K. and S.H.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pasqualetti, M.J.; Sovacool, B.K. The importance of scale to energy security. *J. Integr. Environ. Sci.* **2012**, *9*, 167–180. [CrossRef]
2. Kosai, S.; Unesaki, H. Quantitative Analysis on the Impact of Nuclear Energy Supply Disruption on Electricity Supply Security. *Appl. Energy* **2018**, *208*, 1198–1207. [CrossRef]
3. International Energy Agency (IEA). *Energy Technology Perspective 2017: Catalysing Energy Technology Transformations*; International Energy Agency: Paris, France, 2017; ISBN 978-92-64-27597-3.
4. Kleijn, R.; Van der Voet, E.; Kramer, G.J.; Van Oers, L.; Van der Giesen, C. Metal requirements of low-carbon power generation. *Energy* **2011**, *36*, 5640–5648. [CrossRef]
5. Kleijn, R.; Van der Voet, E. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renew. Sust. Energ. Rev.* **2010**, *14*, 2784–2795. [CrossRef]

6. Elshkaki, A.; Graedel, T.E. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *J. Clean. Prod.* **2013**, *59*, 260–273. [CrossRef]
7. Sun, Z.; Cao, H.; Xiao, Y.; Sietsma, J.; Jin, W.; Agterhuis, H.; Yang, Y. Toward Sustainability for Recovery of Critical Metals from Electronic Waste: The Hydrochemistry Processes. *ACS Sustain. Chem. Eng.* **2017**, *5*, 21–40. [CrossRef]
8. U.S. Department of Energy. *Critical Materials Strategy: 2010*; U.S. Department of Energy: Washington, DC, USA, 2010.
9. European Commission. *Critical Raw Materials for the EU, Brussel*; European Commission: Brussel, Belgium, 2010.
10. Tokimatsu, K.; Wachtmeister, H.; McLellan, B.; Davidsson, S.; Murakami, S.; Hook, M.; Yasuoka, R.; Nishio, M. Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 °C target. *Appl. Energy* **2017**, *207*, 494–509. [CrossRef]
11. Giurco, D.; McLellan, B.; Franks, D.M.; Nansai, K.; Prior, T. Responsible mineral and energy futures: Views at the nexus. *J. Clean Prod.* **2014**, *84*, 322–338. [CrossRef]
12. De Koning, A.; Kleijn, R.; Huppes, G.; Sprecher, B.; Van Engelen, G.; Tukker, A. Metal supply constraints for a low-carbon economy? *Resour. Conserv. Recycl.* **2018**, *129*, 202–208. [CrossRef]
13. Kosai, S.; Nakanishi, M.; Yamasue, E. Vehicle Energy Efficiency Evaluation from Well-to Wheel Lifecycle Perspective. *Transp. Res. D-Transp. Environ.* **2018**, *65*, 355–367. [CrossRef]
14. Jin, Y.; Kim, J.; Guillaume, B. Review of critical material studies. *Resour. Conserv. Recycl.* **2016**, *113*, 77–87. [CrossRef]
15. Graedel, T.E.; Reck, B.K. Six Years of Criticality Assessments: What Have We Learned So Far? *J. Ind. Ecol.* **2015**, *20*, 692–699. [CrossRef]
16. Dewulf, J.; Blengini, G.A.; Pennington, D.; Nuss, P.; Nassar, N.T. Criticality on the international scene: Quo vadis? *Resour. Policy* **2016**, *50*, 169–176. [CrossRef]
17. Kolotzek, C.; Helbig, C.; Thorenz, A.; Reller, A.; Tuma, A. A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications. *J. Clean. Prod.* **2018**, *176*, 566–580. [CrossRef]
18. Achzet, B.; Helbig, C. How to evaluate raw material supply risk—An overview. *Resour. Policy* **2013**, *38*, 435–447. [CrossRef]
19. Helbig, C.; Wietschel, L.; Thorenz, A.; Tuma, A. How to evaluate raw material vulnerability—An overview. *Resour. Policy* **2016**, *48*, 13–24. [CrossRef]
20. Erdmann, L.; Graedel, T.E. Criticality of non-fuel minerals: a review of major approaches and analyses. *Environ. Sci. Technol.* **2011**, *45*, 7620–7630. [CrossRef] [PubMed]
21. Graedel, T.E.; Barr, R.; Chandler, C.; Chase, T.; Choi, J.; Christoffersen, L.; Friedlander, E.; Henly, C.; Jun, C.; Nassar, N.T.; et al. Methodology of metal criticality determination. *Environ. Sci. Technol.* **2012**, *46*, 1063–1070. [CrossRef]
22. Nassar, N.T.; Barr, R.; Browning, M.; Diao, Z.; Friedlander, E.; Harper, E.M.; Henly, C.; Kavlak, G.; Kwatra, S.; Jun, C.; et al. Criticality of the Geological Copper Family. *Environ. Sci. Technol.* **2012**, *46*, 1071–1078. [CrossRef] [PubMed]
23. Nassar, N.T.; Du, X.; Graedel, T.E. Criticality of the Rare Earth Elements. *J. Ind. Ecol.* **2015**, *19*, 1044–1054. [CrossRef]
24. Glöser, S.; Tercero Espinoza, L.; Grandenberger, C.; Faulstich, M. Raw material criticality in the context of classic risk assessment. *Resour. Policy* **2015**, *44*, 35–46. [CrossRef]
25. Graedel, T.E.; Nuss, P. Employing Considerations of Criticality in Product Design. *JOM* **2014**, *66*, 2360–2366. [CrossRef]
26. National Research Council (NRC). *Mineral Critical Minerals and the U.S. Economy*; Committee on Critical Mineral Impacts of the U.S. Economy: Washington, DC, USA, 2008.
27. European Commission. *Tracking the Challenges in Commodity Markets and on Raw Materials, COM*; European Commission: Brussel, Belgium, 2011.
28. Malinauskiene, M.; Kliopova, I.; Hugi, C.; Staniškis, J.K. Geostrategic Supply Risk and Economic Importance as Drivers for Implementation of Industrial Ecology Measures in a Nitrogen Fertilizer Production Company. *J. Ind. Ecol.* **2018**, *22*, 422–433. [CrossRef]

29. Rosenau-Tornow, D.; Buchholz, P.; Riemann, A.; Wagner, M. Assessing the long-term supply risks for raw materials—A combined evaluation of past and future trends. *Resour. Policy* **2009**, *34*, 161–175. [CrossRef]
30. Kosai, S.; Hashimoto, S.; Matsubae, K.; McLellan, B.; Yamasue, E. Comprehensive Analysis of External Dependency in terms of Material Criticality by Employing Total Material Requirement: Sulfuric Acid Production in Japan as a case study. *Minerals* **2018**, *8*, 114. [CrossRef]
31. Moss, R.L.; Tzimas, E.; Kara, H.; Willis, P.; Kooroshy, J. The potential risks from metals bottlenecks to the deployment of Strategic Energy Technology. *Energ. Policy* **2013**, *55*, 556–564. [CrossRef]
32. Bleischwitz, R.; Dittrich, M.; Pierducca, C. Coltan from Central Africa, international trade and implications for any certification. *Resour. Policy* **2012**, *37*, 19–29. [CrossRef]
33. Mueller, S.R.; Wager, P.A.; Turner, D.A.; Shaw, P.; Williams, I.D. A framework for evaluating the accessibility of raw materials from end-of-life products and the Earth's crust. *Waste Manag.* **2017**, *68*, 534–546. [CrossRef] [PubMed]
34. Rabe, W.; Kostka, G.; Smith Stegen, K. China's supply of critical raw materials: Risks for Europe's solar and wind industries? *Energ. Policy* **2017**, *101*, 692–699. [CrossRef]
35. Viebahn, P.; Soukup, O.; Samadi, S.; Teubler, J.; Wiesen, K.; Ritthoff, M. Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. *Renew. Sustain. Energ. Rev.* **2015**, *49*, 655–671. [CrossRef]
36. Blengini, G.A.; Nuss, P.; Dewulf, J.; Nita, V.; Peirò, L.T.; Vidal-Legaz, B.; Latunussa, C.; Mancini, L.; Blagoeva, D.; Pennington, D.; Pellegrini, M.; Van Maercke, A.; Solar, S.; Grohol, M.; Ciupagea, C. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. *Resour. Policy* **2017**, *53*, 12–19. [CrossRef]
37. Bach, V.; Finogenova, N.; Berger, M.; Winter, L.; Finkbeiner, M. Enhancing the assessment of critical resource use at the country level with the SCARCE method—Case study of Germany. *Resour. Policy* **2017**, *53*, 283–299. [CrossRef]
38. Hatayama, H.; Tahara, K. Evaluating the sufficiency of Japan's mineral resource entitlements for supply risk mitigation. *Resour. Policy* **2015**, *44*, 72–80. [CrossRef]
39. Hatayama, H.; Tahara, K. Criticality Assessment of Metals for Japan's Resource Strategy. *Mater. Trans.* **2015**, *56*, 229–235. [CrossRef]
40. New Energy and Industrial Technology Development Organization (NEDO). *Trend Report of Development in Materials for Substitution of Scarce Metals*; Report No. 08007835-0 08007838-0; Shinko Research Co. Ltd.: Tokyo, Japan, 2009.
41. Prime Minister of Japan and His Cabinet. *Resource Securement Strategy*; Prime Minister of Japan and His Cabinet: Tokyo, Japan, 2012. Available online: http://www.kantei.go.jp/jp/singi/package/dai15/sankou01.pdf (accessed on 27 April 2017).
42. Ministry of Economy, Trade and Industry (METI). *Long-Term Energy Supply Demand Outlook*; Ministry of Economy, Trade and Industry: Tokyo, Japan, 2015. Available online: http://www.meti.go.jp/press/2015/07/20150716004/20150716004_2.pdf (accessed on 10 May 2018).
43. Roelich, K.; Dawson, D.A.; Purnell, P.; Knoeri, C.; Revell, R.; Busch, J.; Steinberger, J.K. Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Appl. Energy* **2014**, *123*, 378–386. [CrossRef]
44. Goe, M.; Gaustad, G. Identifying critical materials for photovoltaics in the US: A multi-metric approach. *Appl. Energy* **2014**, *123*, 387–396. [CrossRef]
45. Helbig, C.; Bradshaw, A.M.; Wietschel, L.; Thorenz, A.; Tuma, A. Supply risks associated with lithium-ion battery materials. *J. Clean. Prod.* **2018**, *172*, 274–286. [CrossRef]
46. Helbig, C.; Bradshaw, A.M.; Kolotzek, C.; Thorenz, A.; Tuma, A. Supply risks associated with CdTe and CIGS thin-film photovoltaics. *Appl. Energy* **2016**, *178*, 422–433. [CrossRef]
47. Habib, K.; Wenzel, H. Reviewing resource criticality assessment from a dynamic and technology specific perspective - using the case of direct-drive wind turbines. *J. Clean. Prod.* **2016**, *112*, 3852–3863. [CrossRef]
48. European Commission. *Critical Metals in the Path towards the Decarbonization of the EU Energy Sector*; European Commission: Brussel, Belgium, 2013. Available online: https://setis.ec.europa.eu/sites/default/files/reports/JRC-report-Critical-Metals-Energy-Sector.pdf (accessed on 30 October 2018).

49. Joint Research Centre (JRC). *Critical Metals in Strategic Energy Technologies*; Joint Research Centre: Brussel, Belgium, 2011. Available online: https://setis.ec.europa.eu/sites/default/files/reports/CriticalMetalsinStrategicEnergyTechnologies-def.pdf (accessed on 30 October 2018).
50. Greijer, H.; Karlson, L.; Lindquist, S.; Hagfeldt, A. Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system. *Renew. Energy* **2001**, *23*, 27–39. [CrossRef]
51. U.S. Geological Survey (USGS). *Minerals Yearbook Volume 1*; U.S. Geological Survey: Washington, DC, USA, 2014. Available online: http://minerals.usgs.gov/minerals/pubs/myb.html (accessed on 10 November 2016).
52. Nassar, N.T.; Graedel, T.E.; Harper, E.M. By-product metals are technologically essential but have problematic supply. *Sci. Adv.* **2015**, *1*, e1400180. [CrossRef] [PubMed]
53. Fraser Institute. *Annual Survey of Mining Companies*; Fraser Institute: Vancouver, BC, Canada, 2015. Available online: https://www.fraserinstitute.org/studies/annual-survey-of-mining-companies-2015 (accessed on 15 November 2016).
54. United Nations Development Programme. *Human Development Data (1980-2015)*; United Nations Development Programme: New York, NY, USA, 2016. Available online: http://www.hdr.undp.org/en/data (accessed on 3 November 2016).
55. The World Bank Group. *Worldwide Governance Indicator*; World Bank Group, 2016. Available online: http://info.worldbank.org/governance/wgi/index.aspx#home (accessed on 7 November 2016).
56. United States Department of Justice and Federal Trade Commission. *Commentary on the Horizontal Merger Guidelines*; United States Department of Justice and Federal Trade Commission: Washington, DC, USA, 2006. Available online: https://www.justice.gov/atr/commentary-horizontal-merger-guidelines (accessed on 30 October 2018).
57. Japan Oil, Gas and Metal National Corporation (JOGMEC). *Mineral Resource Material Flow 2016*; Japan Oil, Gas and Metal National Corporation: Tokyo, Japan, 2017. Available online: http://mric.jogmec.go.jp/wp-content/ebook/201801/5a5c093a/material_flow2016.pdf (accessed on 24 October 2018).
58. Arum Publications. *Industrial Rare Metals 131*; Arum Publications: Tokyo, Japan, 2015; pp. 150–151.
59. U.S. Geological Survey (USGS). *Mineral Information*; U.S. Geological Survey, 2017. Available online: https://minerals.usgs.gov/minerals/pubs/historical-statistics (accessed on 10 June 2018).
60. Graedel, T.E.; Harper, E.M.; Nassar, N.T.; Nuss, P.; Reck, B.K. Criticality of metals and metalloids. *PNAS* **2015**, *112*, 4257–4262. [CrossRef]
61. Harper, E.M.; Kavlak, G.; Burmeister, L.; Eckelman, M.; Erbis, S.; Espinoza, V.S.; Nuss, P.; Graedel, T.E. Criticality of the Geological Zinc, Tin, and Lead Family. *J. Ind. Ecol.* **2015**, *19*, 4257–4262. [CrossRef]
62. Nuss, P.; Harper, E.M.; Nassar, N.T.; Reck, B.K.; Graedel, T.E. Criticality of Iron and Its Principal Alloying Elements. *Environ. Sci. Technol.* **2014**, *48*, 4171–4177. [CrossRef] [PubMed]
63. Harper, E.M.; Diao, Z.; Panousi, S.; Nuss, P.; Eckelman, M.J.; Graedel, T.E. The criticality of four nuclear energy metal. *Resour. Conserv. Recycl.* **2015**, *95*, 193–201. [CrossRef]
64. Food and Agriculture Organization of the United Nations (FAO). *FAOSTAT-Forestry*; Food and Agriculture Organization of the United Nations: Roma, Italy, 2014. Available online: http://www.fao.org/faostat/en/#data/FO (accessed on 30 October 2018).
65. Kosai, S.; Yamasue, E. Cost-Security Analysis Dedicated for the Off-grid Electricity System. *Renew. Energy* **2017**. [CrossRef]
66. Ang, B.W.; Choong, W.L.; Ng, T.S. Energy security: Definitions, dimensions and indexes. *Renew. Sustain. Energ. Rev.* **2015**, *42*, 1077–1093. [CrossRef]
67. Nose, K.; Okabe, T. Current Status and Problems of Rare Metals. *J. Surf. Finish. Soc. Jpn.* **2012**, *63*, 618–624. (In Japanese) [CrossRef]
68. Japan Oil, Gas and Metal National Corporation (JOGMEC). *Mineral Resource Information*; Japan Oil, Gas and Metal National Corporation: Tokyo, Japan, 2013. Available online: http://mric.jogmec.go.jp/news_flash/20130328/32662/ (accessed on 19 October 2018).
69. Kosai, S.; Yamasue, E. Global warming potential and total material requirement in metal production: Identification of changes in environmental impact through metal substitution. *Sci. Total Environ.* **2019**, *651*, 1764–1775. [CrossRef] [PubMed]

70. Japan Oil, Gas and Metal National Corporation (JOGMEC). *Mineral Resources Information*; Japan Oil, Gas and Metal National Corporation: Tokyo, Japan, 2015. Available online: http://mric.jogmec.go.jp/wp-content/old_uploads/reports/resources-report/2015-05/vol45_No1_01_s.pdf (accessed on 21 October 2018).
71. New Energy Externalities Developments for Sustainability (NEEDS). *Final Report on Technical Data, Costs and Life Cycle Inventories of PV Applications*; New Energy Externalities Developments for Sustainability: Schaffhausen, Switzerland, 2006. Available online: http://www.needs-project.org/RS1a/RS1a%20D11.2%20Final%20report%20on%20PV%20technology.pdf (accessed on 27 October 2018).
72. Ministry of Economy, Trade and Industry (METI). *Cabinet Decision on the New Strategic Energy Plan*; Ministry of Economy, Trade and Industry: Tokyo, Japan, 2018. Available online: http://www.meti.go.jp/english/press/2018/pdf/0703_002c.pdf (accessed on 21 October 2018).
73. Kosai, S.; Tan, C. Quantitative analysis on a zero energy building performance from energy trilemma perspective. *Sustain. Cities Soc.* **2017**, *32*, 130–141. [CrossRef]
74. Organization for Economic Co-operation and Development (OECD). *Handbook on Constructing Composite Indicators: Methodology and User Guide*; Organization for Economic Co-operation and Development: Paris, France, 2008. Available online: http://www.oecd.org/sdd/42495745.pdf (accessed on 10 August 2015).
75. Kosai, S.; Unesaki, H. Conceptualizing maritime security for energy transportation security. *J. Transp. Secur.* **2016**, *9*, 175–190. [CrossRef]
76. Kabir, G.; Ahsan Akhtar Hasin, M. Multiple criteria inventory classification using fuzzy analytic hierarchy process. *Int. J. Ind. Eng. Computations* **2012**, *3*, 123–132. [CrossRef]