

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

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Number of pages (12), Number of Figures (9) and Number of Tables (2)

Supplementary Materials

List of abbreviation

A-USC	Advanced Ultra-Supercritical Coal
CdTe	Cadmium Telluride solar cell
CIGS	Copper-Indium-Gallium Diselenide solar cell
CMF	Companion Metal Fraction
EI	Environmental Impact
GDP	Gross Domestic Product
GP	Geopolitical
GSC	Global Supply Concentration
GTCC	Gas Turbine Combined Cycle
GTE	Geological, Technological and Economic
HDI	Human Development Index
HHI	Herfindahl–Hirschman index
HREE	Heavy Rare-Earth Elements
I	Importance
IR	Import Reliance
LNG	Liquid Natural Gas
NE	National Economic Importance
PPI	Policy Perception Index
PPU	Percentage of Population Utilizing
RP	Reserve to Production ratio
RP_t	RP transformed
S	Substitutability
SA	Substitute Availability
S&R	Social & Regulatory
SP	Substitute Performance
SR	Supply Risk
SU	Susceptibility
UNDP	United Nations Development Programme
VSR	Vulnerability to Supply Restriction
WGI-PV	Worldwide Governance Indicators - Political Stability & Absence of Violence/Terrorism

List of subscript

<i>i</i>	Metal
<i>j</i>	Country
<i>k</i>	Substitute metal
<i>t</i>	Technology

Elements	Supply Risk										SR
	Geological, Technological and Economic		Social & Regulatory				Geopolitical				
	RPt	CMF	Weighted	PPI	Weighted	HDI	Weighted	WGI	Weighted	GSC	
B	53	0	Boron (all forms) Mine Production	32	Boron (all forms) Mine Production	77	Boron (all forms) Mine Production	79	Boron (all forms) Mine Production	88	55
Mg	0	5	Magnesium Primary Production	54	Magnesium Primary Production	75	Magnesium Primary Production	70	Magnesium Primary Production	94	50
Ti	0	0	Ilmenite and Rutile Mine Production	38	Ilmenite and Rutile Mine Production	73	Ilmenite and Rutile Mine Production	51	Ilmenite and Rutile Mine Production	59	37
V	0	82	Vanadium Mine Production	53	Vanadium Mine Production	73	Vanadium Mine Production	71	Vanadium Mine Production	84	60
Cr	94	0	Chromite Mine Production	41	Chromite Mine Production	70	Chromite Mine Production	67	Chromite Mine Production	76	58
Mn	83	3	Manganese Mine Production	42	Manganese Mine Production	73	Manganese Mine Production	55	Manganese Mine Production	68	54
Co	62	85	Cobalt Mine Production	51	Cobalt Refining Production	77	Cobalt Mine Production	75	Cobalt Mine Production	78	71
Ni	85	0	Nickel Mine Production	47	Nickel Mine Production	77	Nickel Mine Production	57	Nickel Mine Production	58	54
Ga	0	100	Bauxite Mine Production	40	Gallium Refining Production	75	Gallium Refining Production	69	Gallium Refining Production	88	62
Se	87	100	Copper Mine Production	29	Selenium Refining Production	82	Selenium Refining Production	45	Selenium Refining Production	70	69
Y	0	84	Yttrium Mine Production	57	Yttrium Mine Production	73	Yttrium Mine Production	71	Yttrium Mine Production	100	64
Zr	65	100	Zirconium Mine Production	37	Zirconium Mine Production	78	Zirconium Mine Production	44	Zirconium Mine Production	75	67
Nb	37	2	Niobium Mine Production	38	Niobium Mine Production	77	Niobium Mine Production	52	Niobium Mine Production	96	51
Mo	80	46	Molybdenum Mine Production	36	Molybdenum Mine Production	80	Molybdenum Mine Production	55	Molybdenum Mine Production	74	62
Ag	92	71	Silver Mine Production	36	Silver Mine Production	78	Silver Mine Production	62	Silver Mine Production	59	66
In	96	100	80% Zinc, 15% Tin, 5% Copper	42	Indium Refining Production	80	Indium Refining Production	55	Indium Refining Production	81	76
Te	0	100	Copper Mine Production	29	Tellurium Refining Production	88	Tellurium Refining Production	39	Tellurium Refining Production	73	55
Nd	0	95	Neodymium Mine Production	55	Neodymium Mine Production	74	Neodymium Mine Production	68	Neodymium Mine Production	97	65
Dy	0	94	Dysprosium Mine Production	57	Dysprosium Mine Production	73	Dysprosium Mine Production	71	Dysprosium Mine Production	100	66
Hf	0	100	Zirconium Mine Production	37	Zirconium Mine Production	78	Zirconium Mine Production	44	Zirconium Mine Production	75	56
Ta	28	50	Tantalum Mine Production	49	Tantalum Mine Production	55	Tantalum Mine Production	67	Tantalum Mine Production	79	55
W	81	5	Tungsten Mine Production	55	Tungsten Mine Production	73	Tungsten Mine Production	68	Tungsten Mine Production	93	62
Pb	94	0	Lead Mine Production	43	Lead Refining Production	79	Lead Mine Production	60	Lead Mine Production	78	59
Al	0	0	Bauxite Mine Production	40	Alumina Refining Production	78	Bauxite Mine Production	52	Bauxite Mine Production	71	40
Fe	90	0	Iron Mine Production	43	Raw steel Production	77	Iron Mine Production	56	Iron Mine Production	77	57
Cu	80	10	Copper Mine Production	29	Copper Refining Production	78	Copper Smelting Production	55	Copper Mine Production	64	53
Zn	95	0	Zinc Mine Production	41	Zinc Smelting Production	79	Zinc Mine Production	59	Zinc Smelting Production	69	57
Cd	92	100	Zinc Mine Production	41	Cadmium Refining Production	81	Cadmium Refining Production	55	Cadmium Refining Production	66	72
Sn	94	0	Tin Mine Production	56	Tin Smelting Production	74	Tin Mine Production	70	Tin Mine Production	72	61

Figure SA. The data used for evaluation Social & Regulatory and Geopolitical in Supply Risk.

Elements	Vulnerability to Supply Restriction									
	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use	NE	Primary substitute	SPi	SAi	SP	SA	IR	
B	Ceramics and glass	64%	0	Na	38	39	41	42	100	47
	Soaps, Detergents and bleaches	4%		Na	38	39				
	Agriculture	4%		None	100	100				
	other	36%								
Mg	Refractory	83%	2	None	100	100	94	97	100	66
	Environmentary	6%		lime	13	46				
	Agriculture	5%		None	100	100				
	other	6%								
Ga	Integrated circuits	62%	1	Si	38	47	38	58	44	31
	Optoelectronic devices	38%		In	38	76				
Al	Packaging	11%	39	Fe	38	57	49	56	66	53
	Consumer durables	12%		Cu	38	53				
	Machinery	2%		Fe	63	57				
	Buildings and Constractions	14%		Fe	38	57				
	Electrical	4%		Cu	13	53				
	Transportation	43%		Fe	63	57				
	other	14%								

Figure SB1. The data of light metals used for evaluating Vulnerability to Supply Restriction.

Elements	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use		Primary substitute	SPi	SAi	SP	SA	IR	
V	Ferrovanadium	98%	2	Nb	63	51	63	50	91	50
	Chemicals	2%		Pt	88	47				
Cr	Buildings and Infrastructure	25%	3	Mn	63	54	76	67	100	58
	Industrial Machinery	25%		None	100	100				
	Transportation	15%		Al	63	40				
	Household Appliances and Electronics	5%		Al	63	40				
	other	30%								
Mn	Steel Metallurgy	90%	3	None	100	100	96	97	100	66
	Non-Steel Alloys	6%		plastic ^a	63	67				
	Batteries	2%		Li	13	42				
	other	2%								
Nb	Constraction	29%	3	V	38	60	42	60	100	51
	Transportation	24%		V	38	60				
	Oil and Gas Industry	24%		V	38	60				
	Stainless steel	10%		Ta	63	55				
	Niobium Metal and Alloys	5%		Mo	63	62				
	other	8%								
Fe	Constraction	22%	100	Wood ^m	63	37	50	43	4	50
	Machinery: Industrial	5%		plastic ^a	63	67				
	Machinery: Electrical	3%		plastic ^a	63	67				
	Machinery: Appliances	1%		plastic ^a	63	67				
	Transportation: Ship	7%		Al	38	40				
	Transportation: Cars	23%		Al	38	40				
	Transportation: Trains	0%		Al	38	40				
	Transportation: others	0%		Al	38	40				
	Products	2%		Al	38	40				
	other	37%								

Figure SB2. The data of iron & its principal alloying metals used for evaluating Vulnerability to Supply Restriction.

^a plastic are based on a weighted averaged of the score of natural gas (2/3 weight) and crude oil (1/3 weight) [22].

^m Production data for roundwood are based on statistics by the Food and Agricultural Organization [76].

Elements	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use		Primary substitute	SPi	SAi	SP	SA	IR	
Ti	Pigment(paints)	53%	2	Talc	63	41	63	41	99	51
	Pigment(plastics)	19%		Talc	63	41				
	Pigment(paper)	9%		Talc	63	41				
	other	19%								
Co	Batteries	80%	1	Mn	38	54	41	54	67	39
	Cemented carbides	4%		Ni	63	54				
	Superalloys	8%		Ni	63	54				
	Magnets	1%		Nd	38	65				
	Catalysts	1%		Ni	38	54				
	other	6%								
Ni	Industrial Machinery	31%	5	steel ^b	88	58	62	59	27	31
	Household Appliances and Metal goods	28%		steel ^c	38	57				
	Buildings and Infrastructure	17%		steel ^d	38	57				
	Transportation: excluding aerospace	15%		Al	63	40				
	Transportation: aerospace	4%		None	100	100				
	Electronics	5%		None	100	100				
Mo	construction engineering steel	35%	8	steel ^c	63	53	70	62	94	56
	stainless steel	25%		steel ^e	63	57				
	tool and high speed steel	11%		steel ^f	63	58				
	cast iron	8%		Fe	63	57				
	superalloys	6%		Nb	88	51				
	molybdenum metal	6%		None	100	100				
	chemical	10%		None	100	100				
Ta	Electronic components	48%	2	Al	38	40	41	47	86	44
	Sputtering targets	11%		Zr	63	67				
	Superalloys	16%		Nb	38	51				
	Machinery	11%		Nb	38	51				
	other	14%								
W	Cemented carbides	77%	0	B	38	55	38	57	83	43
	Steel	16%		Mo	38	62				
	Mill products	4%		Mo	38	62				
	other	3%								

Figure SB3. The data of superalloy metals used for evaluating Vulnerability to Supply Restriction.

^b AISI 444 (Cr: 18%, Mo: 2%, Fe: 80%) [60].

^c AISI 430 (Cr: 17%, Fe: 83%) [60].

^d AISI 410 (Cr: 12%, Mn: 1%, Fe: 87%) [60].

^e AISI 304 (Cr: 18%, Ni: 8%, Mn: 2%, Fe: 72%) [60].

^f T1(Cr: 4, W: 18, Fe: 78) [60].

Elements	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use		NE	Primary substitute	SPi	SAi	SP		
Se	Glass manufacturing	29%	0	Ce	38	62	38	61	1	17
	Chemicals and Pigments	6%		Te	38	55				
	other	65%								
Ag	Photography	22%	14	Paper ^g	63	0	49	29	36	30
	Electrical and Electronics	9%		Cu	88	53				
	Investment	17%		Au	13	55				
	other	52%								
Te	Metallurgy	45%	0	Bi	38	77	38	61	58	36
	Solar cells	25%		Si	38	47				
	Rubber and Synthetic fiber	20%		Se	38	69				
	Electronics	10%		Se	38	69				
Cu	Telecommunications	5%	50	Si	13	47	73	47	4	38
	Electrical	28%		Al	88	40				
	Automobiles	10%		Al	88	40				
	In-plant equipments	28%		Fe	63	57				
	Business electronics	7%		Al	88	40				
	other	20%								

Figure SB4. The data of copper group metals used for evaluating Vulnerability to Supply Restriction.

^g refer to Nassar et al. [22].

Elements	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use		NE	Primary substitute	SPi	SAi	SP	SA	
In	Indium Tin Oxide thin-film coatings	86%	10	Zn	63	58	63	58	21	30
	other	14%								
Pb	Batteries	89%	13	None	100	100	100	100	10	41
	other	11%								
Zn	Galvanizing	48%	7	Si	38	47	38	45	5	18
	Galvanizing: other	16%		Si	38	47				
	Brass and Bronze	14%		Al	38	40				
	Zinc-based alloys	10%		Al	38	40				
	other	13%								
Cd	Batteriesb	99%	0	Li	13	42	13	42	3	10
	Coatings	0%		None	100	100				
	other	1%								
Sn	Solder	54%	3	Ag	38	66	36	59	88	46
	Tin plate	17%		Al	13	40				
	Chemical	13%		Pb	63	59				
	Brass and Bronze	5%		Cu	38	53				
	other	11%								

Figure SB5. The data of zinc, tin, lead group metals used for evaluating Vulnerability to Supply Restriction.

Elements	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use	NE	Primary substitute	SPi	SAi	SP	SA	IR	
Y	Phosphors	69%	1	None	100	100	97	88	100	64
	Ceramics	22%		Mg	88	50				
	other	9%								
Nd	Nd magnets	76%	9	Sm	38	64	41	62	100	53
	Metallurgy	8%		Mg	63	50				
	Battery alloys	5%		Li	38	42				
	Ceramics	4%		Ce	63	62				
	Autocatalysts	1%		Ce	38	62				
	other	6%								
Dy	Nd magnets	100%	12	Tb	38	66	38	66	100	54

Figure SB6. The data of rare earth elements used for evaluating Vulnerability to Supply Restriction.

Elements	End-use		Importance	Substitutability					Susceptibility	VSR
	Application	% of use	NE	Primary substitute	SPi	SAi	SP	SA	IR	
Zr	Refractory	36%	0	Mg	63	50	78	69	100	58
	Ceramics	15%		Al	63	40				
	Catalysts	35%		None	100	100				
	other	14%								
Hf	superalloys: aerospace	39%	0	Zr	38	67	38	67	100	51
	Nuclear energy control rod	16%		Ag-In-Cd ^h	38	68				
	superalloys: fuel reprocessing plant	13%		Zr	38	67				
	refractory	13%		Zr	38	67				
	plasma cutting tool	9%		Zr	38	67				
	other	10%								

Figure SB7. The data of nuclear energy metals used for evaluating Vulnerability to Supply Restriction.

^h Ag: 80%, In: 15%, Cd: 5% [63].

Elements	Supply Risk						SR
	GTE		S&R		GP		
	RPt	CMF	PPI	HDI	WGI-PV	GSC	
Li	0	25	26	86	34	80	42
Na	0	0	37	81	53	61	39
Ce	0	88	50	75	68	96	63
Sm	0	91	52	74	71	98	64
Tb	0	96	53	73	72	99	66
Pt	0	16	48	69	62	86	47
Au	94	12	40	76	58	50	55
Bi	83	90	53	74	70	90	77
Lime	0	0	51	76	65	85	46
talc	0	0	42	77	59	67	41
Plastic	67	100	41	83	56	55	67
wood	0	0	42	72	61	46	37

Figure SC. The Supply Risk results of substitute metals for evaluating Substitute Availability.