

NIMS-EMC Materials Data for the Environment, No. 18

Overview of Total Material Requirement



Strategic Use of Elements
Interdisciplinary Cluster
National Institute for Materials Science

NIMS-EMC Materials Data for the Environment, No. 18

Overview of Total Material Requirement

March, 2009

Authors

Nozomu Katagiri

Kenichi Nakajima

Kohmei Halada

Strategic Use of Elements
Interdisciplinary Cluster
National Institute for Materials Science



Nozomu Katagiri

Basic Research Group
Innovative Materials Engineering Laboratory
National Institute for Materials Science

Kenichi Nakajima

Research Center for Material Cycles and Waste Management
National Institute for Environmental Studies

Kohmei Halada

Strategic Use of Elements Interdisciplinary Cluster
National Institute for Materials Science

**Strategic Use of Elements Interdisciplinary Cluster
National Institute for Materials Science**

1-2-1 Sengen, Tsukuba, Ibaraki, 3050047 Japan
Tel: +81-29-859-2668
Fax: +81-29-859-2601
e-mail: emc@wotome.nims.go.jp
home page: <http://www.nims.go.jp/>

Preface

The 21st century, which is being hailed as the "environment century," is becoming an age where the global environment is being considered from every possible aspect, such as daily and economic activities. Against this backdrop, raw and processed materials are being used to make all types of products. As resources, these materials are being extracted from the earth's environmental sphere, and returned to this sphere as waste, so they are very closely tied with the global environment. Therefore, not only the producers of materials, but also all the people who produce, use, and dispose of the products, have a vested interest in learning about the environmental load and recyclability of these materials to improve productivity and make the right choices for creating a sustainable society for the future.

Unfortunately, there is still relatively little processed information available regarding the environmental load and recyclability of these materials. Sometimes, information that has been "fleshed out" can be found here and there, but it is still often not sufficient to make informed decisions.

To address these issues, the EcoMaterials Center, as a core organization for the acquisition and processing of reliable information on substances and materials, is working hard to issue NIMS-EMC Data as a series. NIMS, it should be noted, is the acronym for the National Institute for Materials Science, and EMC refers to the EcoMaterials Center. While there may be slight differences in procedures for collecting data and creating databases, we would like to use detailed surveys by experts and other vehicles to provide essential material data which can be used to create product materials which cannot be derived from statistical data, and which includes data on such considerations as recyclability and LAC, or Life Cycle Assessment.

March 2006



Dr. Kohmei Halada
Director of the EcoMaterials Center
National Institute for Materials Science

In 2003, the abovementioned Materials Data for the Environment were first publicly released. After that, the EcoMaterials Center underwent restructuring, but it has continued to release Materials Data for the Environment in the same format.

March 2009



Dr. Kohmei Halada
Managing Director
Strategic Use of Elements Interdisciplinary Cluster
National Institute for Materials Science

Contents

1. Introduction

2. Background to the Idea of “Resource-end Weight”

3. Definition of Resource-end Weight (TMR)

4. TMR Coefficient and its Derivation

4.1 TMR coefficients of metallic ores

4.1.1 Estimates based on actual operating data

4.1.2 Estimating TMR based on crude ore content

4.1.3 Estimating TMR by crustal abundance

4.1.4 Interpretation and discussion of the TMR coefficients of metal ores

4.1.5 Conclusions of section 4

4.2 TMR coefficients for energy resources

4.2.1 TMR coefficients of petroleum resources and thermal (oil-based) power generation

4.2.2 TMR coefficients of coal and coal-powered power generation

4.2.3 TMR coefficients of natural gas and natural gas power generation

4.2.4 TMR coefficient of nuclear power generation

4.3 TMR coefficients of non-metallic mineral resources

4.4 TMR coefficients of biomass resources

4.4.1 TMR coefficients of farm products

4.4.2 TMR coefficient of wood

4.5 Deriving TMR coefficients for metal ingots

4.6 Comparison with the TMR coefficients of the Wuppertal Institute for Climate, Environment and Energy

5. Example of Analysis Using TMR

5.1 Correlation with other indices

5.2 Analysis using TMR

5.2.1 Correspondence between Consumer-end Weight (the actual weight of equipment/units) and Resource-end Weight

5.2.2 Results of recycling analysis

5.2.3 Total resource consumption

5.2.4 Relationship between per capita GDP and per capita TMR

5.2.5 Examination of GDP

6. Concluding Remarks

References

1. Introduction

In 1997, Schmidt-Bleek et al.^{1), 2)} proposed the concept of “ecological rucksacks.” This refers to the volume of sand, rock, etc., that remains in the “resource-end” (resource production country) when humans use resources such as iron or copper. They proposed that TMR, which is the total of ecological rucksacks and direct and indirect input into the economy, should be used as an index of resource consumption. In other words, up until then, measures taken at the “back-end” involved controlling the generation of waste, controlling the emission of toxic substances, and promoting recycling. However, it is obvious that the index of “front-end” like TMR is more effective than that of “back-end” and they proposed that indices such as TMR/GDP and DMI (i.e., Direct Material Input)/GDP should be used to create policies for reducing resource consumption. With these concepts, the authors thought that resource consumption, resource productivity, environmental efficiency, etc., should be examined based on “Resource-end Weight” or TMR, and in 2001 proposed TMR coefficients for metal ores required for this purpose, and a method for calculating these coefficients³⁾.

After that, the concept of Resource-end Weight was examined and developed from various perspectives, especially by Halada, et al.⁴⁾⁻⁶⁾, and in March 2008 it was adopted as a supplementary index in the Environment Ministry’s *Fundamental Plan for Establishing a Sound Material-Cycle Society*.

In order to promote a wider understanding and application of TMR concepts, the purpose of the present overview is to report on methods for deriving TMR coefficients and to present some examples of their application by the authors. Here, some of the TMR coefficients for ores were corrected by reviewing the base numbers that have been used for calculating the TMR coefficients of ores. We hope that when using TMR coefficients, the reader will proceed with his or her investigations using the coefficients presented in this overview.

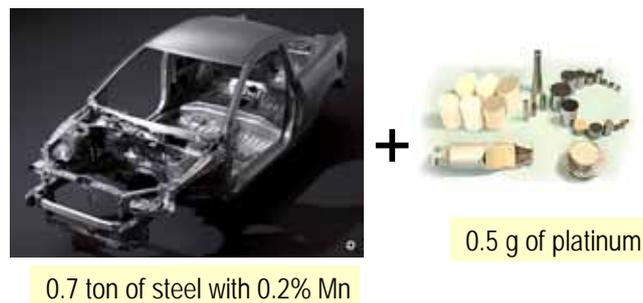
Please note that while the term Total Material Requirement (TMR) is used here, it has exactly the same meaning as Resource-end Weight. In the following report, “Resource-end Weight” and “TMR” will be used interchangeably.

2. Background to the Idea of “Resource-end Weight”

One of the bases of the increasingly serious global environmental problems is the dramatic increase in the use of materials in a steadily increasing pattern since the Industrial Revolution⁸⁾. In response, there has been a necessity for paradigm shift towards dematerialization, service industries. However, in order to test these points and try to find the direction to a proper solution, it is necessary to quantify and create indices that are grounded in science.

Figure 1 The necessity of additivity based on TMR

How do we add the impact of various materials in any products?



Is $700 + 0.0005$ kg a material consumption of automobile?

“Additivity” is required for management of products

In response, the authors have considered the following and have proposed a new approach based on Resource-end Weight. More specifically, Resource-end Weight is the amount of ore, sand and rock that have been excavated from the earth by humans to obtain the energy and materials needed to support their modern material civilization (Note 1). By using the Resource-end Weight per ton of metal (hereafter called *TMR coefficient* for simplicity) for amount such as 0.7 ton of iron and 0.5 gram of platinum that cannot be compared to one another, they can be treated uniformly as Resource-end Weight (Fig. 1). By taking this approach, we can pave the way for enabling resource consumption, resource productivity, environmental efficiency, and etc., to be understood and investigated in an integrated manner.

For example, as will be discussed later, the respective TMR coefficients of iron and platinum are 8 t-TMR/t (Fe) and 520,000 t-TMR/t (Pt), 0.7 ton of iron and 0.5 gram of platinum are converted into the same unit as 5.6 and 0.26 t-TMR, respectively, which can enable mutual comparisons, summation, and so on. In addition, we can see that for the earth, the consumption of 15.4 gram of platinum is the equivalent of the consumption of approximately 1 ton of iron.

 Note 1: Strictly speaking, this figure includes the total of all materials required for clearing forests, water utilization, and altering the hydrology, as well as restoring the altered land to its original state and preserving the scenery. However, in their series of investigations, the authors ignored all of these aspects except water utilization.

3. Definition of Resource-end Weight (TMR)

In the extraction of resources that have been bestowed upon humanity by the earth, when emphasis is given to the aspect of amount “received” from the earth, it has come to be called *Resource-end Weight*, and when emphasis is given to the aspect of the total amount of materials involved, then it has come to be called *Total Material Requirement* (TMR). In either case, we can see this as being the environmental load that is, at least once, imposed on the earth by the extraction of resources by humans (although if the rock and sand piled up in resource production countries is buried back in the mine, it disappears from view, so there is a debate over whether or not this can be called environmental load).

The term TMR is defined on page 8 of *Resource Flows*⁹⁾ published by the World Resource Institute. According to that definition, it can be expressed mathematically by the following formula:

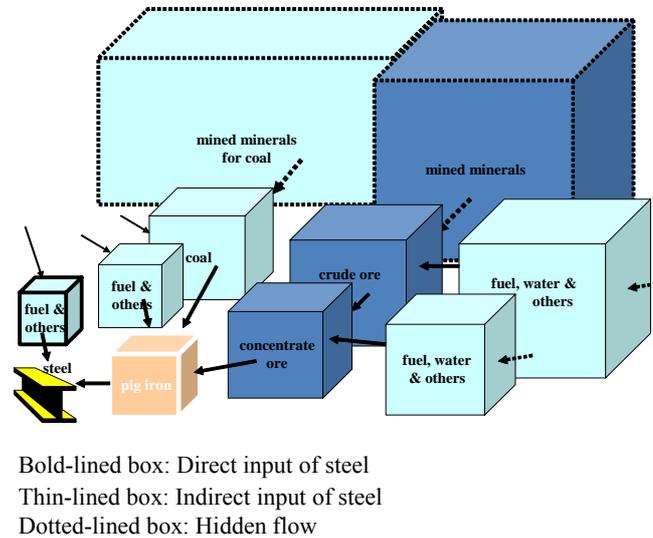
$$\begin{aligned} (\text{TMR}) = & \quad (\text{Amounts of directly input materials}) + \quad (\text{Amounts of indirectly input materials}) \\ & \quad \quad \quad + \quad (\text{Amounts of hidden material flow}) \end{aligned} \quad (1)$$

Here, the amounts of directly and indirectly input materials are the respective amounts of materials that are directly and indirectly input as human economic activities. These are also collectively called commodity material flow, which is the amount that can be obtained from various economic statistics sources. Hidden materials flow (HMF) is the amount of material that is moved, stirred up, etc., as a result of actions that are neither directly nor indirectly involved with materials used in economic activities. This includes the total amount of materials required to move sand and rock, clear forests, utilize water, and alter the hydrology, as well as restore the altered land to its original state and preserve the scenery. The total of all such materials is called Total Material Requirement (TMR). In other words, it has exactly the same meaning as Resource-end Weight. However, for purposes of brevity, the terms TMR and TMR coefficient will be used here.

Figure 2 shows the concept of TMR for the example of steel. The direct inputs into the steel materials in the lower left of the figure are pig iron, fuel and miscellaneous related materials that are depicted as a bold-outline rectangular parallelepiped. To obtain these materials (especially pig iron), it is necessary to have indirectly input materials such as iron ore and coke. Moreover, each of these require indirect inputs such as fuel, fluxing agents, and ferro-alloys that are needed for processing. Furthermore, because crude ore exists in the ground, holes must be dug to where the ore is, and tunnels and adits excavated. Or, the upper ground layer(s) must be removed to create an open pit from which the ore can be excavated. The earth and sand, overburden and gangue minerals that comprise the ore, the water that gushes out as a result of excavation, etc., are not the objects of financial transactions, so they are not clearly listed in economic statistics, etc., but they represent the amount of materials that is directly related to environmental load. As previously mentioned, this part is called hidden material flow (HMF). HMF exists not only for iron ore, but also for coal. Strictly speaking, it is absolutely the existence of all inputs on the boundary between human society and global environment (i.e., earth), but in Figure 2 it is only the parts that are related to iron ore and coal, and is shown as by the broken line rectangular parallelepiped. The total of all the rectangular parallelepipeds shown in this figure is the TMR (= Resource-end Weight) (however, double-counts are naturally avoided). The HMF shown by the broken line rectangular parallelepiped in the figure is called an “ecological rucksack.” In Japan, it is sometimes metaphorically referred to as a “zairyō no haigorei”¹⁰⁾ or “ghost behind the materials.”

It should be noted that in their series of investigations of TMR, the authors basically targeted sand, rock and water. However the air was not part of the integrated calculations, as its calculation basis was not clearly defined. In addition, besides the items mentioned in the previous note that were ignored, there was room to also consider the TMR of hydroelectric plants, but it was considered to be 0 (zero) here.

Figure 2 Concept of “TMR: Total Materials Requirement”



4. TMR Coefficient and its Derivation

4.1 TMR coefficients of metallic ores

When deriving the Resource-end Weight or Total Material Requirement (TMR), the authors first focused on objectively obtaining the Hidden Material Flow (HMF) for the mining of ores, which is considered to have the largest impact. In this case, the concomitant materials include ore-related materials such as earth and sand and overburden, as well as water in the mine, etc. However, due to the unreliability of the water-related data and the noticeable inequality in covered areas, the first step was limited to just the amount of soil and rock produced during excavation (however, the amount of water involved was later added to the consideration).

In addition, it would have been easier to handle the numerical values by including in the data such things as fuel, materials, etc., that are input into smelting, refining, and metal working, and indirectly input materials as energy sources, but at that time indirect input data related to energy consumed in smelting, etc., were not available. Therefore, we decided to limit our consideration to sand and rock, because preparing the TMR coefficients of ores for which energy factors had little influence may avoid possible quantitative confusion when TMR data for energy become available in the future. In other words, the total volume of sand and rock (crude ore, earth and sand, overburden, and gangue etc.) excavated to obtain one unit (1 ton) of metal was calculated as *ore-TMR coefficients*.

4.1.1 Estimates based on actual operating data

First, an attempt was made to estimate *ore-TMR coefficients* for iron, copper, zinc, and lead from actual operating data. The reason these metals were selected was that they are the most widely traded metals in the world and mine information is readily available. Moreover, in Japan, there is a long history of mining and metallurgy, so in the interviews it was relatively easy to obtain mine-related information with a technical background. Furthermore, coal is also necessary for the production of steel, and since the situation is about the same, it was included as a target for the survey.

Regarding the values that were required for the calculations, several mines were visited and interviews were conducted with people involved with the mining industry and mining information they possessed was used as reference to examine the production and content of concentrates, and the

respective ratios of tailings and the overburden to concentrate. The number of mines that had collected such information were 33 for coal, 40 for iron, 101 for copper, 93 for zinc, and 96 for lead. The stripping ratio (this is called rock-to-ore ratio for some ores) is a proportion of the sum of the overburden stripped (mainly from open pit mining) and earth and sand (mainly from underground mining) for crude ore. In addition, tailings from processed (dressed) ore are gangue minerals having a low metal content that are removed during the dressing process. While the metals in tailings are sometimes recovered later, quantitatively it is quite small, so it was ignored at first. Based on these values, the total excavated amount and the metal content were derived as follows:

$$\begin{aligned} & \text{(Total mined material)} \\ & = \{(\text{Stripping ratio}) + 1\} \times \{(\text{Tailings ratio})+1\} \times (\text{Amount of concentrate produced}) \end{aligned} \quad (2)$$

and

$$\text{(Amount of metal)} = 0.01 \times (\text{Amount of concentrate produced}) \times (\text{Concentrate content (\%)})(3)$$

where, the tailings ratio in equation (2) is the tailings-to-concentrate ratio. Figures 3 through 7 show the relation between total mined material and ore production for coal, iron, copper, zinc and lead, respectively. It should be noted that the cover ratios for world production in these plots are as follows: iron, ca. 80%; copper and lead, ca. 66%; zinc, ca. 55%; and coal, ca. 25%. The reason why the cover ratio for coal is so low is that it was not possible to obtain accurate information on the state of coal mines in China, which accounts for 1/3 of world production. Based on this information, the TMR for the ore required to produce 1t of coal and each of the metals is derived as follows:

$$\text{(Ore-TMR per ton)} = (\text{Total mined material}) / (\text{Amount of metal}) \quad (4)$$

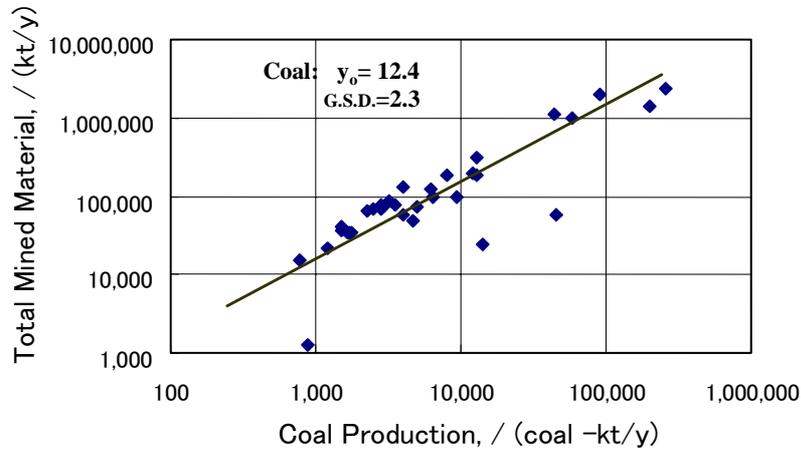
It should be noted that in the present calculations, there were sometimes mines that were both open pit and underground. However, because it would have been too complicated to try to classify each mine in precise detail, for simplicity and representativeness, Equation (4) was used to calculate ore-TMR per ton as background data without further distinction. In cases where distinct differences in mining methods should be necessary such as in LCA, etc., it is better to replace the simplified ore-TMR with the detailed calculated values as foreground data. The results of the calculations were as follows: Coal, 12.4 t-TMR/t-Coal; iron, 5.1 t-TMR/t-Fe; copper, 304 t-TMR/t-Cu; zinc, 34 t-TMR/t-Zn; and lead, 95 t-TMR/t-Pb. These values are shown as straight lines with a slope of 1 for the ore-TMR coefficient with the y-intercept in Figures 3-7 (log-log plots).

4.1.2 Estimating TMR based on crude ore content

The calculation method based on the abovementioned operational data had apparently high reliability, but the geometric standard deviations in Figures 3-7 ranged from 1.7 (for iron) to 4.0 (for copper) in which (numeric value of) data are distributed in a wide range. It is difficult to accept that these ore-TMR values are considered a representative value as an index. Therefore, these values should be used in rough analyses based on approximation methods such as preliminary LCA.

In addition, to obtain a more accurate representative value, the ore-TMR as a representative value should be used in conjunction with a parameter that can express the dispersion. However, for that purpose there are many parts that would require an examination of the distribution function patterns, dispersion types that are easy to work with LCA-type methods. Increasing the accuracy of these dispersions is a topic for future examination. At the same time, from the perspective of using TMR as an approximated representative value for rough analyses, we considered methods for making estimates of TMR of the ore of various metals from more easily obtainable information.

Figure 3 Relation between coal production and total mined material



Total mined mineral of each mining site are plotted to the coal production of each site. Total mined minerals consist of crude ore, earth and sand, overburden, gangue mineral and others. The liner line with unit slope and intercept $y_0 = 12.4$ shows that total mined minerals are in 12.4 times proportional to coal production. G.S.D. means geological standard deviation.

Figure 4 Relation between iron ore production and total mined material

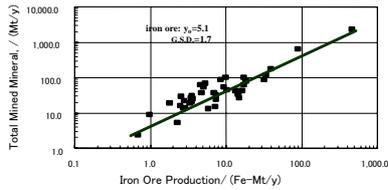


Figure 5 Relation between copper ore production and total mined material

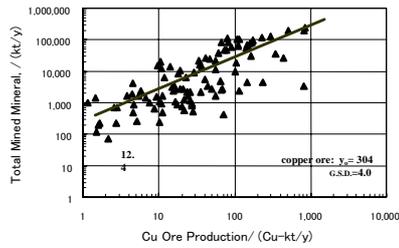


Figure 6 Relation between zinc ore production and total mined material

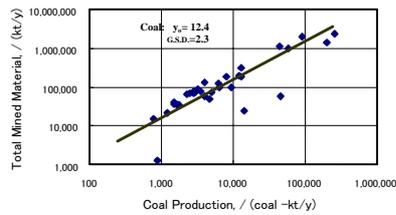
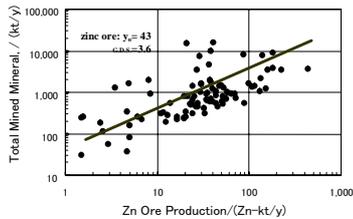


Figure 7 Relation between lead ore production and total mined material



For simplification, as an item that includes $\{(Stripping\ ratio) + 1\}$ of Equation (2), we derive Equation (5):

$$\begin{aligned} (Rock/ore\ ratio)_i &= (Total\ mined\ material)_i / (Amount\ of\ crude\ ore)_i \\ &= \{(Stripping\ ratio) + 1\}_i \end{aligned} \quad (5)$$

Here, we assume that this value is constant for a metal i . In this assumption, the rock/ore ratio mainly depends on the form of the deposit, which depends on the metal. Thus this is a suitable approximated assumption. In the same way, as the crude ore content depends on the existence form of the metal component in the ore and the form depends on the metal, we can assume it to be roughly constant (depending on the metal). Because the amount of concentrate here is the crude ore minus the amount of tailings, the relationship can be expressed as follows:

$$(Concentrate\ content\ \%) = (Crude\ ore\ content\ \%) \times \{(Concentrate/tailings\ ratio) + 1\} \quad (6)$$

By substituting Equations (5) and (6) into Equations (2) and (3), respectively, Equations (4), i.e., the TMR (ore part) per unit of metal i , can be expressed as follows:

$$\begin{aligned} &(Ore-TMR\ per\ ton\ (i.e.,\ Ore-TMR\ coefficient)) \\ &= \{(Rock/ore-ratio) \times (Concentrate\ content\ \%) \times (Amount\ of\ concentrate\ production)\} \\ &\quad / \{(Crude\ ore\ content\ \%) / \{0.01 \times (Amount\ of\ concentrate\ production) \times (Concentrate\ content\ \%)\}\} \\ &= (Rock/ore-ratio) / (Crude\ ore\ content\ \%) \end{aligned} \quad (7)$$

Though the concentrate content and its processing parameter, the concentrate/tailings ratio, depend largely on the economic feasibility of the mine such as its geographical conditions, these two terms are eliminated from the equation, and thus we can obtain a simple equation (7).

Regarding the rock/ore-ratio, the Mining and Quarrying Trends¹²⁾, which is a part of the United States Bureau of Mines' Metal Yearbook¹¹⁾, features publicly disclosed data on crude ore and extracted amount of iron, gold, copper, zinc, and other metals in the USA. In addition, these values can be derived as the total of the metals in the previously mentioned survey data.

Figure 8 shows a juxtaposition of plots of different data from different source. As can be seen in the figure, the extracted volume is roughly twice as many as the crude ore volume, regardless of the source or type of metal, and this relationship can be expressed approximately as

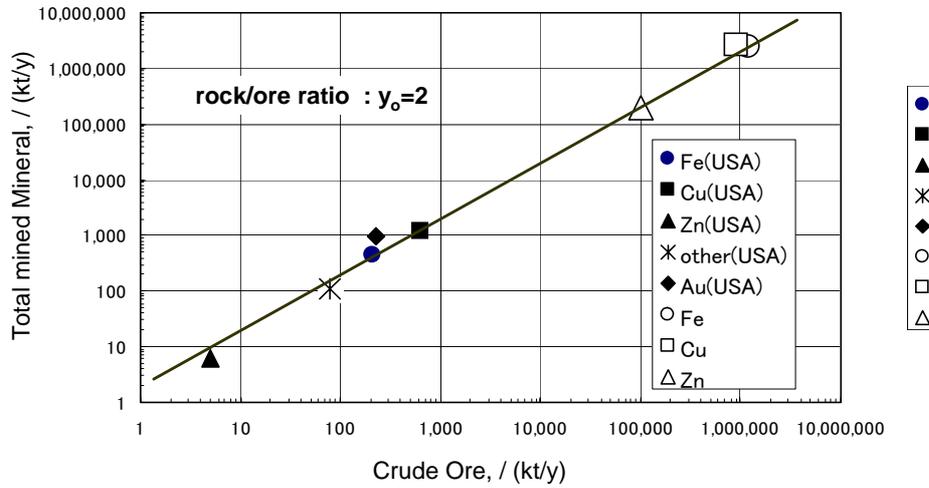
$$(Rock/ore-ratio) \quad 2.0 \quad (8)$$

that is, the following relationship can be derived:

$$(Ore-TMR\ coefficient) = 2.0 / \{0.01 \times (Crude\ ore\ content\ \%)\} \quad (9)$$

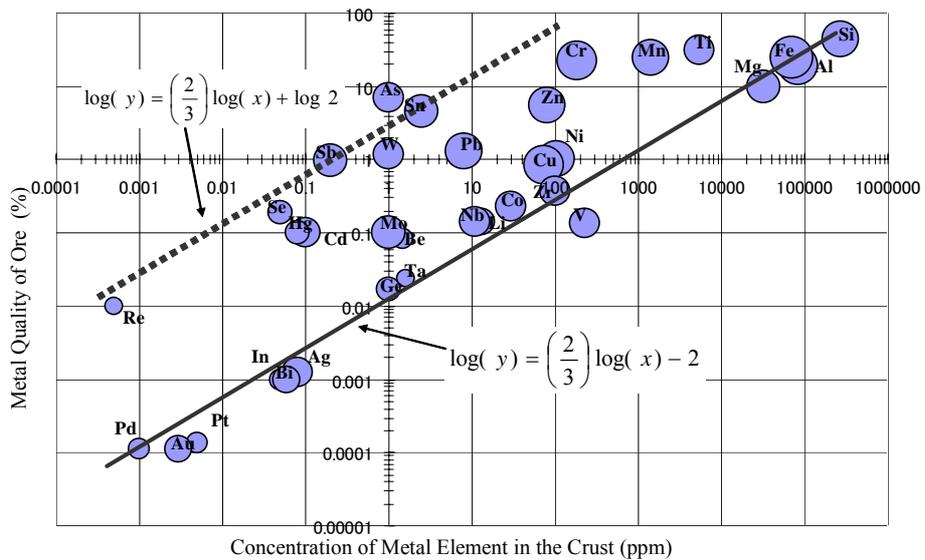
In this way, we can make an approximate estimate of the ore-TMR coefficient of the target metal from only the crude ore content data, without the need for detailed mine operational data. The ore-TMR coefficients calculated using Equation (9) are shown in Table 1, along with the crude ore content used. It should be noted that the crude ore contents were basically derived from the Current State of Mineral Ores¹³⁾, but latest information on ore amount and crude ore content was picked up from on-line news flashes (in 2000) about the mining industry put out by the Metal Mining Agency of Japan. The crude ore content used here was the weighted average of the ores.

Figure 8 Estimates of rock/ore ratio



Plotting the amount of extracted ore to total mined material gives a straight line with an intercept of 2 and slope of 1. This gives us a rock/ore-ratio of 2.

Figure 9 Relation between crustal abundance of metal element and ore grade



The size of the circles corresponds to the logarithms of world production in 2000. Nearly all metals exist in the region between straight lines having a slope of 2/3 and intersects of 2 and 0.01.

4.1.3 Estimating TMR by crustal abundance

The use of above mentioned methods which include crude ore content has made it possible to estimate the ore-TMR coefficients of various metals for which it has been difficult to obtain actual operational data from mines. But there are still some metals for which it is difficult to obtain grade data of crude ore, partly because the information would have an effect on commercial transactions and partly because their applications are still in the development stage. Although the utilization volume of such metals is low, even in trace amounts there is a fear that they can have a big effect on TMR values. These include materials that should be checked for environmental impact when developing new materials that are used as trace catalysts, doping agents and so on. For such cases, we considered methods for estimating ore-TMR coefficients from generally obtainable numerical data.

In Equation (9), the only item remaining as a parameter is crude ore content. Figure 9 shows the crude ore content plotted against crustal abundance¹⁰⁾. Excluding the few exceptions nearly all metals exist in the region between straight lines having a slope of 2/3 and intersects of 2 and 0.01. In addition, nearly all metals groups classified as lithophile elements or having relatively low production volume exist near a straight line having an intercept of 0.01. If we tentatively call this straight line the base ore grade, then there exists the following two-thirds exponent relationship:

$$(\text{Base ore grade \%}) = 0.01 \times (\text{Crustal abundance ppm})^{2/3} \quad (10)$$

In addition, we can confirm the same type of two-thirds exponent relationship with the straight line of the upper limit. In order to understand the reason for deriving this relationship, it may be necessary to take various approaches, including considering the origins of deposits. However, we only have a 2-dimensional perception of the region of the usable part of the earth's crust even though we intuitively know the thickness of the crust has 3 dimensions, and this perception may be manifested in some way. However, we have not gone so far in the present matter, and we simply consider that this estimation equation (Eq. 10) was obtained from some empirical relations. Thus, for rare metals whose data of crude ore content is difficult to obtain, substituting Equation (10) into Equation (9) gives us the following Equation (11),

$$(\text{Ore-TMR coefficient [t/t]}) = 20000.0 \times (\text{Crustal abundance ppm})^{-2/3} \quad (11)$$

4.1.4 Interpretation and discussion of the TMR coefficients of metal ores

So far, we have derived TMR coefficients for metal ores. Table 1 shows the results, along with crude ore contents and crustal abundance. Regarding the ore-TMR coefficients in the table, the values derived from actual surveys are shown in bold type, the values estimated from the crude ore contents in Equation (9) are shown in normal type, and the values estimated from the crustal abundance in Equation (11) are shown in italics. It should be noted that Table 1 is exactly the same as Table 1 in Reference 3), but the crustal abundance after that was subjected to numerical revision to unify the values with those of the Chronological Scientific Tables. As a result of this and other reasons, several of the ore-TMR coefficients in the table differ from those of Reference 3). When using the authors' values, it is hoped that this Table 1 will be used as a formal table.

In addition, the products of multiplying these ore-TMR coefficients by the production amounts for 2000 were derived as total global ore-TMR (Mt/y), and the metals in Table 1 are arranged in the order of their total global ore-TMR. We can interpret this order as reflecting, to a certain degree, the degree of impact that the total utilized amount has on the global environmental. From this table, we found that the ore-TMR coefficient of gold that has not received much attention about its environmental implications in the manufacturing of products is much larger than the coefficient of iron which is consumed in very large quantities, and that ore-TMR coefficients of noble metals are generally ranked in higher positions. These findings should arouse a new concern when using these metals in products and devices.

Furthermore, the ore-TMR coefficients of these metals are values that were estimated not from

Table 1 Ore-TMR coefficient and total global ore-TMR value for each metal

	Ore-TMR coefficient ^{a)}	Total global ore-TMR value (Mt/y)	Global production (t/y) ^{b)}	Crude ore content (%) ^{c)}	Crustal abundance (ppm) ^{d)}		Ore-TMR coefficient ^{e)}	Total global ore-TMR value (Mt/y)	Global production (t/y) ^{b)}	Crude ore content (%) ^{c)}	Crustal abundance (ppm) ^{d)}
Au	1,800,000.0	4,400.0	2,445.0	0.00011 ^{b)}	0.003	Br	39,000.0	20.0	520.0		0.37
Cu	300.0	3,900.0	12,900,000.0	0.84^{b)}	75	B	4,300.0	18.4	4,270.0		10
Fe	5.1	2,900.0	571,000,000.0	25^{b)}	70700	Li	1,400.0	18.0	13,000.0	0.14	13
Ag	160,000.0	2,900.0	17,900.0	0.0013 ^{b)}	0.08	Tb	30,000.0	17.0	574 ^{g)}		0.6
U	21,000.0	1,000.0	45807 ^{e)}		0.91	Gd	10,000.0	16.0	1640 ^{g)}		3.3
Bi	150,000.0	570.0	3,780.0		0.06	Ru	800,000.0	16.0	19.99 ^{f)}	0.00025 ^{b)}	0.001
Sn	2,500.0	500.0	200,000.0	0.07	2.5	Si	4.5	15.0	3,400,000.0	44	267700
Zn	43.0	340.0	8,000,000.0	5.5^{b)}	80	Zr	540.0	7.7	14,250.0	0.37	100
Pd	1,800,000.0	320.0	177.0	0.00011 ^{b)}	0.001	Ir	2,400,000.0	7.6	3.18 ^{g)}	0.000084 ^{b)}	0.0001
Pb	95.0	280.0	2,980,000.0	1.33^{b)}	8	Y	2,700.0	6.5	2,400.0		20
Pt	1,400,000.0	250.0	178.0	0.00014 ^{b)}	0.005	Ta	12,000.0	6.2	513.0	0.017 ^{b)}	1
Ni	200.0	250.0	1,230,000.0	1.02 ^{b)}	105	Dy	9,000.0	5.9	656 ^{g)}		3.7
Al	10	240	23900000		84100	Mg	20.0	5.7	284,000.0	10	32000
Mo	2,000.0	220.0	112,000.0	0.1 ^{b)}	1	W	170.0	5.4	31,500.0	1.2 ^{b)}	1
Sr	500	150	304000		260	Lu	45,000.0	5.2	114.8 ^{g)}		0.3
Cr	8.9	120.0	13,700,000.0	23 ^{b)}	185	Hg	2,000.0	3.6	1,800.0	0.1	0.08
Ce	2000	70	35014 ^{g)}		33	Er	12,000.0	3.0	246 ^{g)}		2.2
V	1,500.0	63.0	42,000.0	0.14	230	Tm	40,000.0	2.7	65.6 ^{g)}		0.32
Rh	2,600,000.0	62.0	23.96 ^{f)}	0.000078 ^{b)}	0.001	Ho	25,000.0	2.5	98.4 ^{g)}		0.78
Mn	8.0	60.0	7,450,000.0	25 ^{b)}	1400	Eu	20,000.0	1.6	82 ^{g)}		1.1
La	3,100.0	59.0	18860 ^{g)}		16	Se	1,000.0	1.4	1,400.0	0.2 ^{b)}	0.05
In	200,000.0	44.0	220.0	0.001	0.05	Hf	10,000.0	1.2	123.5		3
Nd	3,100.0	43.0	13940 ^{g)}		16	As	29.0	1.2	40,000.0	6.9	1.8

Cd	2,000.0	39.0	19,300.0	0.1	0.1	Re	20,000.0	0.9	43.0	0.01	0.0005
Te	<i>270,000.0</i>	<i>34.0</i>	<i>125.0</i>		<i>0.02</i>	Be	2,400.0	0.9	356.0	0.08	1.5
Nb	1,400.0	33.0	23,600.0	0.14	11	<i>Ga</i>	<i>3,000.0</i>	<i>0.7</i>	<i>210.0</i>		<i>18</i>
Co	870.0	28.0	32,300.0	0.23 ^{b)}	29	Ge	8,300.0	0.5	58.0	0.024	1.6
<i>Pr</i>	<i>8,000.0</i>	<i>27.0</i>	<i>3362^{g)}</i>		<i>3.9</i>	<i>Th</i>	<i>9,000.0</i>	<i>0.4</i>	<i>45.0</i>		<i>3.5</i>
Sb	200.0	24.2	121,000.0	0.99 ^{b)}	0.2	Ti	6.3	0.3	51,000.0	31	5400
<i>Yb</i>	<i>12,000.0</i>	<i>23.6</i>	<i>1958^{g)}</i>		2.2	Os	2,000,000.0	0.1	0.06 ^{g)}	0.0001 ^{b)}	0.001
<i>Sm</i>	<i>9,000.0</i>	<i>22.1</i>	<i>2460^{g)}</i>		3.5						

a) The bold type shows data from actual operations, italics show data estimated from crustal abundance, and the other values were estimated from crude ore content.

b) Reference 11

c) Reference 13

d) Reference 14

e) "Global Nuclear Market, trend information" at the following website; <http://criepi.denken.or.jp/criepi/mic/seisaku/sgold1999/keikou/trend45.htm>

f) Production of platinum group metals for 2000 was pro-rated based on consumption in the United States.

g) Production of rare earths for 2000 was pro-rated based on consumption in the United States.

h) Average of the values in reference 22

k) Average of the values for iron ore derived in the present study.

crustal abundance but were calculated based on the crude ore content. Compared with such metals as uranium and bismuth, these results have a relatively high degree of reliability. While uranium and bismuth have a relatively high ranking, they were estimated from crustal abundance. For future discussions, deriving the ore-TMR coefficients of these metals, which are nuclear fuels, excellent lead substitutes, respectively, will require the acquisition of data based on actual operations.

The height of the ranking here can be interpreted to be of importance for acquiring and disclosing such data. In addition, copper occupies a higher place on the table than iron, but iron ore gives rise to high amounts of ore-TMR for coke. Since the TMR coefficient for iron was limited to the iron ore part, the total TMR for iron, when its smelting is taken into consideration, can be expected to be higher than that for copper as iron-refining (steel-making) consumes a lot of coke which has a large TMR coefficient.

The low position of titanium is quite noticeable. This is because of titanium's limited applications, despite the abundance of the resource. From an ore-TMR coefficient perspective, it would be important to develop applications for such materials. However, like the case of coke and iron, the data for titanium do not include incidental materials used for electrical power, so ultimately it will be necessary to include the energy inputs and treat the data as total TMR. It is the same way with middle-ranking Si, which is used as a high-purity raw material for semiconductors. In the future, the estimation of incidental TMR from energy use should be done in the same way as in the present study. This is an issue that still must be resolved in order to evaluate the environmental impacts of these materials.

In addition, the two-thirds exponent rule between the crustal abundance and the crude ore content that were clarified as empirical principles during the course of the present study can be used for a variety of applications besides the estimation of TMR, and so on. It may be used, for example, to examine resource depletion by handling changes in ore grade by shifting from the line of intercept \log_2 to the line of intercept 0.01. It is hoped that this will be discussed from a wide variety of perspectives such as mineralogy, study of mineral deposits, and organized quantitative studies, among others.

4.1.5 Conclusions of section 4

In Section 4.1, calculations were made for ore-TMR's for various metal ores as base data for the Resource-end Weight or Total Material Requirement (TMR) that is a parameter that expresses the relation between materials and the global environment. The ore-TMR coefficients calculated by actual operational data were for coal, iron, copper, zinc and lead. When it was difficult to get the actual operational data, then estimates were made based on crude ore content, as follows:

$$(\text{Ore-TMR coefficient}) = 200 / \{(\text{Crude ore content \%})\} \quad (9)$$

Furthermore, in cases where even crude ore content was not obtainable, calculations were made with the following equation:

$$(\text{Ore-TMR coefficient [t/t]}) = 20000 \times (\text{Crustal abundance [ppm]})^{-2/3} \quad (11)$$

These numbers are indeed extremely rough approximations, but they may provide for designer at the stages of conceptual design a hint for proceeding with a "right material at the right place" approach in combination with the functions of materials which consider the environmental impacts of these materials. It is hoped that the exchange of such numerical environmental data will form a base for selecting Eco-materials while concurrently proceeding with environmentally-sound design. It is also hoped that people involved with these materials will use these calculations as a stepping stone for deriving more reliable evaluation of coefficients based on resource productivity, TMR which includes energy, and etc., and for providing the most thorough information disclosure.

4.2 TMR coefficients for energy resources

In the preceding section, TMR coefficients were derived for metal ores. This section is an overview of the TMR coefficients of energy, non-metallic mineral resources, and biomass resources based primarily on a report by Nakajima et al.¹⁵⁾. The section concludes with a brief look at TMR coefficients of metal ingots.

4.2.1 TMR coefficients of petroleum resources and thermal (oil-based) power generation

In the TMR related to oil resources, there are many cases, in which, during the peak production period of an oil well, oil is brought to the surface using the earth's natural pressure, so it was determined that there were almost no related materials associated with mining oil. However, in considering the life cycle of an oil well, when the earth pressure decreases and production declines, water is pumped in the well to bring out more crude oil. This method is called "water flooding," while using pressure from explosions to force the oil to the surface is called "fire flooding." In these phase, oil is extracted not as 100% pure petroleum but as a mixture of crude oil and water. The ratio of water to oil is abbreviated as "WOR." The WOR value increases with the age of an oil well, sometimes the WOR value becomes almost 100 when an oil well reaches the end of its life. When the lifetime of the oil well is T, the production volume and WOR at the time of t are y(t) and w(t), respectively, TMR coefficient of oil is expressed as follows:

$$TMR_{oil} = \frac{\int_0^T y(t) \cdot (w(t) + 1) dt}{\int_0^T y(t) dt}$$

The relation between the production volume and the WOR value was reviewed by Purvis et al. ("Analysis of production-performance graphs," J. Canadian Petroleum, July-August 1985), and R. Baker showed the relation between the WOR value and total production volume based on actual operating data ("Reservoir Management for Water Floods II," J. Canadian Petroleum Technology, Vol. 37 (1998) No. 1, 12-17). Integrating and averaging values on the graph result in a TMR coefficient of 7.4 kg/L. It should be noted that the temporary rise and then decline of this WOR curve was due to increased productivity obtained through new methods such as "water flooding." By dividing the 7.4 kg/L TMR coefficient of petroleum extraction obtained in this way by the calorific value of oil 38.7 MJ/L (2000 Comprehensive Energy Statistics, Planning and Coordination Division, Director-General's Secretariat, Agency for Natural Resources and Energy), we obtain a TMR coefficient of oil combustion of 0.19 kg/MJ.

Furthermore, in Uchiyama et al's (Yoji Uchiyama, Hiromi Yamamoto; "Analysis of Energy Revenues of Electrical Power Plants", Central Research Institute of Electric Power Industry report, (1991) pp.8-31)data, 1,448.8 ML of oil was required to produce 6,169 GWh of electrical energy; thus, the TMR coefficient for thermal power generation was $7.40 \times 1.4488/6.169 = 1.74$ kg/kWh, that is 0.48 kg/MJ.

4.2.2 TMR coefficients of coal and coal-powered power generation

The combustion of 1 kg of coal produces 32.2 MJ of energy. Put another way, it takes 0.03 kg of coal to produce 1 MJ of energy. Previously, in figure 3, a value of 12.4 t/t was derived for TMR of coal from actual coal mine data; from that, the TMR coefficient per MJ of coal combustion was calculated to be 0.39 kg/MJ.

Furthermore, according to the data of Uchiyama et al., in the case of coal-fired power generation, it takes 2.336 Mt of coal to produce 6,084 GWh of electrical power; thus, the TMR coefficient of coal-fired power generation is $12.4 \times 2.336/6.084 = 4.76$ kg/kWh, or 1.32 kg/MJ.

4.2.3 TMR coefficients of natural gas and natural gas power generation

In the case of electrical power produced from natural gas, it is necessary to derive TMR coefficient that includes extraction of the crude gas. Because natural gas is extracted in a gaseous state, it is difficult to estimate TMR coefficient. However, in the case of Japan and the oil fields with which it does business, natural gas is derived simultaneously from petroleum extraction, so an average value of petroleum volume accompanied with natural gas was derived and multiplied by the TMR coefficient of petroleum to approximate a value for natural gas TMR coefficient. From the website of Technology Research Center of the Japan National Oil Corporation¹⁷⁾, the natural gas/oil ratio from natural gas fields was weight-averaged with the production volume obtained from the following data.

Oil field	Oil	Natural gas
JAPEX U.S.	20.7 KL/d	700 Km ³ /d
JAPEX Gulf	4.77 KL/d	868 Km ³ /d
Gebang (Sumatra)	51 KL/d	364 Km ³ /d
Sanga Sanga	6.3 ML/d	33.6 Mm ³ /d
Yufutsu	241.8 KL/d	256.1 Km ³ /d
Sarukawa	77.8 KL/d	5.7 Km ³ /d
Yuri	49.4 KL/d	27.4 Km ³ /d
Iwafuneoki	661.7 KL/d	306.2 Km ³ /d
Higashi-Niigata	240.7 KL/d	658.5 Km ³ /d
Yoshii	101.0 KL/d	578.4 Km ³ /d
Katagai	83.9 KL/d	813.9 Km ³ /d

The average value of the natural gas/oil ratio was 4.88 m³/L, meaning that 0.2 L of crude oil was produced per m³ of natural gas at the same time. Assigning a specific gravity of 0.85 and calculating this value by the 7.4 TMR coefficient of crude oil, that is, $0.2 \times 0.85 \times 7.4$, gives a TMR coefficient of 1.26 kg/m³. Assuming the natural gas to be methane and assigning it a combustion heat value of 9,700 kcal/m³ = 40.6 MJ/m³ gives a TMR coefficient of 0.031 kg per MJ of natural gas.

Furthermore, according to the data of Uchiyama et al., in the case of natural gas-fired power generation, it takes 1.1145 Mt of natural gas to produce 6,169 GWh of electrical power; converting into methane gives a value of 63,300 TJ = 1,963 Gt-TMR from the volume of $1.1145 \times 22.4/16 = 1.56$ Gm³. Thus, the TMR coefficient of natural gas-fired power generation is 0.088 kg/MJ.

4.2.4 TMR coefficient of nuclear power generation

In the case of nuclear power generation, according to Uchiyama et al., 127 ton of U in the form of UF₆ is consumed to produce 5,868 GWh of electrical power. The TMR coefficient of uranium ore is 21,000, so the power generation can be quantified as $127 \text{ ton}/5,868 \text{ GWh} \times 21,000 = 0.455 \text{ kg/kWh}$, meaning the TMR coefficient of nuclear power generation is 0.13 kg/MJ.

It should be noted that the 21,000 value of TMR coefficient for uranium was estimated from crustal abundance data because of deficiencies in data on actual mines deposits. However, information released on the Ningyotoge facilities which were all closed down on March 23, 2001 stated that 55,650 ton of uranium were taken from open pit mining operations, which also resulted in the production of about 55,000 m³ of uranium slag and smelter waste; 34,000 m³ of slag was disposed of in a tailing dam, and 251,000 m³ of uranium waste soil was disposed of at the mine facilities.

Assigning a specific gravity of 1 to the slag and waste soil gives a ratio of $(251 + 34 + 55 + 55.65) \text{ kt}/(55.65) \text{ kt} = 7.11$. According to Uchiyama et al.'s "Analysis of Energy Revenues of Electrical Power Plants," 25.4 t/y of UO₂ is used to produce 6,347 GWh/y at a 1 GW light-water reactor. Thus from the uranium ore production of 57,800 t/y, and a calculated grade of $25.4 \times$

$(285/317)/57,800 = 0.04\%$, results in a value of $7.11/0.04(\%) = 35,500$ which, even under the relatively bad conditions of Japanese mines is at roughly the same order, and the estimations from the crustal abundance data also appear to be reasonable as the first approximation.

Figures 10 and 11, and Tables 2 and 3 show, respectively, the calculation results for energy resource TMR coefficient and electrical power TMR coefficient obtained from the present study. Here, TMR(s) indicates the solid components such as soil and tailings, and TMR(aq) shows the water component. It should be noted that the electrical power for OECD was calculated based on a power resource structure of 50% oil-fired power generation, 19% coal-fired power generation, 13% natural gas and 16% nuclear power.

Figure 10 TMR of energy resources

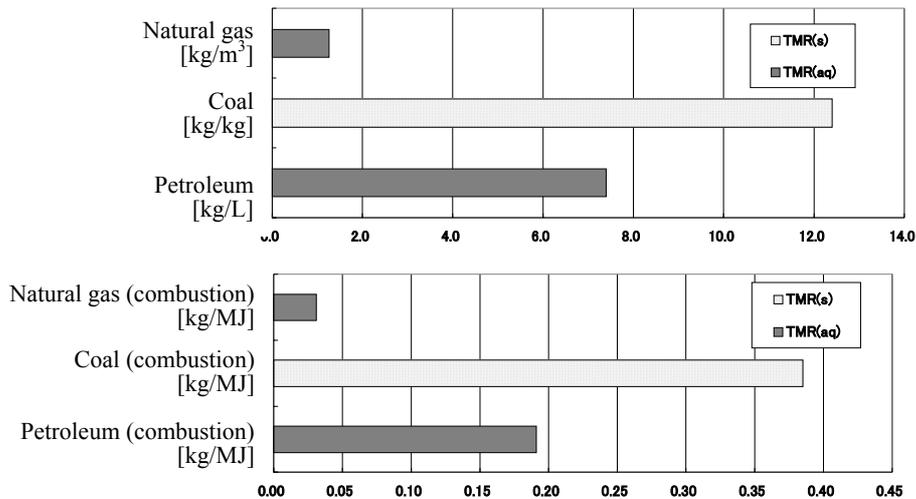


Figure 11 TMR of electrical power

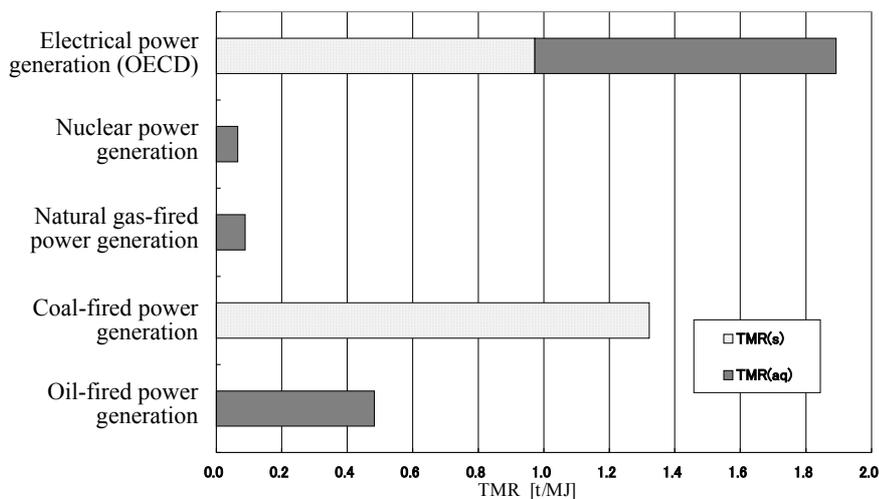


Table 2 TMR of energy resources

	Units	TMR (s)	TMR(aq)	TMR(total)
Petroleum	kg/L	-	7.40	7.40
Coal	kg/kg	12.40	-	12.40
Natural gas	kg/m ³	-	1.26	1.26
Petroleum (combustion)	kg/MJ	-	0.19	0.19
Coal (combustion)	kg/MJ	0.39	-	0.39
Natural gas (combustion)	kg/MJ	-	0.03	0.03

Table 3 TMR of electrical power

	Units	TMR(s)	TMR(aq)	TMR(total)
Oil-fired	kg/MJ	-	0.48	0.48
Coal-fired	kg/MJ	1.32	-	1.32
Natural gas-fired	kg/MJ	-	0.09	0.09
Nuclear	kg/MJ	0.13	-	0.13
Electrical power (OECD)	kg/kwh	0.97	0.92	1.89

4.3 TMR coefficients of non-metallic mineral resources

Estimates were made for the TMR coefficient of non-metallic minerals such as limestone, dolomite, and refractory clay based on the statistical reserve survey¹⁸⁾ released by the Agency for Natural Resources and Energy. Tables 4 and 5 show data related to reserves of non-metallic minerals. Here, “ore reserves” refers to the amount of deposits in the ground, while “minable reserves” refers to the amount of crude mineral that is recoverable from existing mineral deposit/ores (that is, this includes the amount of earth and sand that is mixed in with the mined ore). In addition, the percent actual mining yield is derived by the following equation:

$$\begin{aligned} & \text{Percent actual mining yield} \\ & = (\text{Minable reserves} \times (1 - \text{mixing rate of earth and sand}) / \text{ore reserves}) \times 100 \end{aligned}$$

Using these data, calculations were made of the TMR coefficient of non-metallic minerals. The following is an example of how the TMR coefficient of a non-metallic mineral, white silica sand, was calculated. Because the percent actual mining yield of white silica sand is 58.6%, its TMR coefficient is $1/0.586 = 1.71$ t/t. Furthermore, the grade of crude sand is 90.9%, so the TMR coefficient per component of the raw sand is $1/0.586/0.909 = 1.88$ t/t. The same method is used to calculate the TMR coefficient of other non-metallic minerals. Table 6 shows the TMR values calculated for non-metallic minerals. These calculations do not take into consideration the amount of rock and soil that is removed before mining begins. Therefore, for greater accuracy it is necessary to consider this in the TMR calculations.

Table 4 Reserves of non-metallic (silica rock, agalmatolite, limestone and dolomite)

1. Silica rock

(1) White silica rock (as of April 1, 2004)					Number of surveyed quarries: 30	
	Ore reserves		Minable reserves		Percent actual mining yield (%)	Percent of impurities (%)
	Reserves (1000 t)	Grade (%)	Reserves (1000 t)	Grade (%)		
Confirmed value	241,888	88.4	194,819	88.7		
Estimated value	125,738	91.0	90,874	90.6		
Predicted value	332,816	93.9	176,336	93.4		
Total	700,442	91.5	462,028	90.9	58.6	11.1

(2) Natural silica sand (as of April 1, 2004)					Number of surveyed quarries: 40	
	Ore reserves		Minable reserves		Percent actual mining yield (%)	Percent of impurities (%)
	Reserves (1000 t)	Grade (%)	Reserves (1000 t)	Grade (%)		
Confirmed value	42,162	80.1	33,846	77.6		
Estimated value	23,836	77.6	18,210	75.4		
Predicted value	25,732	72.7	21,567	73.5		
Total	91,730	77.4	73,623	75.8	73.3	8.7

(3) Gairome silica sand (as of April 1, 2004)					Number of surveyed quarries: 13	
	Ore reserves		Minable reserves		Percent actual mining yield (%)	Percent of impurities (%)
	Reserves (1000 t)	Grade (%)	Reserves (1000 t)	Grade (%)		
Confirmed value	6,445	47.7	5,303	47.9		
Estimated value	3,292	47.8	2,857	48.0		
Predicted value	11,177	53.1	11,004	53.2		
Total	20,914	50.6	19,164	50.9	91.6	0

2. Agalmatolite (as of April 1, 2004)				Number of surveyed quarries: 26	
	Ore reserves (1000 t)	Minable reserves (1000 t)		Percent actual mining yield (%)	Percent of impurities (%)
Confirmed value	30,954	21,484			
Estimated value	36,787	19,709			
Predicted value	49,510	18,525			
Total	117,251	59,718	39.7	22.1	

3. Limestone (as of April 1, 2004)					Number of surveyed quarries: 277	
	Ore reserves		Minable reserves		Percent actual mining yield (%)	Percent of impurities (%)
	Reserves (1000 t)	Grade (%)	Reserves (1000 t)	Grade (%)		
Confirmed value	11,178,284	54.2	9,182,301	53.8		
Estimated value	10,190,585	54.0	8,179,035	53.8		
Predicted value	39,463,981	54.3	23,010,743	53.6		
Total	60,832,850	54.3	40,372,079	53.7	58.5	11.8

4. Dolomite (as of April 1, 2004)					Number of surveyed quarries: 17	
	Ore reserves		Minable reserves		Percent actual mining yield (%)	Percent of impurities (%)
	Reserves (1000 t)	Grade (%)	Reserves (1000 t)	Grade (%)		
Confirmed value	441,708	17.9	338,568	17.8		
Estimated value	294,133	17.8	217,212	17.7		
Predicted value	683,064	16.7	357,176	16.4		
Total	1,418,905	17.3	912,956	17.2	60.2	6.5

Table 5 Reserves of non-metallic (fire resistant) mineral ores

5. Refractory clay

(1) Kaolin (As of April 1, 2004)		Number of surveyed quarries: 6		
	Ore reserves (1000 t)	Minable reserves (1000 t)	Percent actual mining yield (%)	Percent of impurities (%)
Confirmed value	2,787	2,193		
Estimated value	1,731	1,413		
Predicted value	2,214	1,478		
Total	6,732	5,085	70.9	6.2

(2) Shale clay (As of April 1, 1997)		Number of surveyed quarries: 3		
	Ore reserves (1000 t)	Minable reserves (1000 t)	Percent actual mining yield (%)	Percent of impurities (%)
Confirmed value	746.5	435.5		
Estimated value	1,604.0	997.0		
Predicted value	3,185.0	2,107.0		
Total	5,535.5	3,539.5	46.9	26.7

(3) Kibushi clay (As of April 1, 2004)		Number of surveyed quarries: 35		
	Ore reserves (1000 t)	Minable reserves (1000 t)	Percent actual mining yield (%)	Percent of impurities (%)
Confirmed value	3,253	3,084		
Estimated value	1,889	1,772		
Predicted value	8,501	8,193		
Total	13,643	13,049	95.6	0.0

(4) Gairome clay (As of April 1, 2004)		Number of surveyed quarries: 33		
	Ore reserves (1000 t)	Minable reserves (1000 t)	Percent actual mining yield (%)	Percent of impurities (%)
Confirmed value	8,625	6,886		
Estimated value	4,666	4,038		
Predicted value	13,422	12,649		
Total	26,713	23,573	88.2	0.0

Table 6 TMR coefficients of non-metallic minerals

	Ore-TMR (t)		
		Per ore (t)	Per component (t)
Silica rock	White silica rock	1.71	1.88
	Natural silica sand	1.36	1.80
	Gairome silica sand	1.09	2.14
Agalmatolite		2.52	-
Limestone		1.71	3.18
Dolomite		1.66	9.66
Refractory clay	Kaolin	1.41	1.99
	Shale clay	2.13	4.55
	Kibushi clay	1.05	1.09
	Gairome clay	1.13	1.29

4.4 TMR coefficients of biomass resources

4.4.1 TMR coefficients of farm products

Farm products are not only eaten, but also used to make bioplastics, biofuels, and various types of industrial materials, and materials for industrial fuels. In the present research, calculations were made of the TMR coefficient of agricultural materials (biomass) based on the Monthly Statistics of Agriculture, Forestry and Fisheries¹⁹⁾. Table 7 shows the area and yield of various types of crops covered in these statistics.

Using the above data and the TMR of soil, the TMR coefficients of farm crops were calculated. Soil TMR coefficient was calculated based as follows: Assuming an apparent specific gravity of 1.2 and depth of plowing of 5 cm of soil used for vegetable cultivation, the value was 60 t/a; for an apparent specific gravity of 1.6 and depth of plowing of 12 cm, a value of 192 t/10a was obtained. The following is an example of TMR coefficient calculated for a farm crop, in this case rice. Assuming production of 513 kg per 10 ares, TMR coefficient would be $(10/0.513) \times (192/10) = 374.2$ t/t. The same type of method can be used to calculate TMR coefficients for other crops. Table 8 shows the results of calculations for TMR coefficient of farm crops.

Table 7 Area and yield of farm crops (2004)

	Planted area	Yield per 10a	Production
	ha	kg	t
Rice	1,701,000	513	8,730,000
Wheat	212,600	405	860,300
Two-rowed barley	37,200	355	131,900
Six-rowed barley	17,600	291	51,200
Naked barley	5,060	306	15,500
Soybeans	136,800	119	163,200
Azuki beans	42,600	212	90,500
Kidney beans	11,800	231	27,300
Peanuts	9,110	234	21,300
Potatoes	-	4,504	-
Sweet potatoes	40,300	2,500	1,009,000
Sweet potatoes (starchy substrate)	5,510	3,110	171,500
Pasture grass	788,300	3,897	30,723,000
Early harvested corn	87,400	5,330	4,659,000

Table 8 TMR of farm products

	TMR (t/t)		TMR (t/t)
Rice	374.1	Kidney beans	259.7
Wheat	148.3	Peanuts	256.4
Two-rowed barley	169.2	Potatoes	13.3
Six-rowed barley	206.3	Sweet potatoes	24.0
Naked barley	195.9	Sweet potatoes (starchy substrate)	19.3
Soybeans	504.2	Pasture grass	15.4
Azuki beans	283.0	Early harvested corn	11.3

4.4.2 TMR coefficient of wood

The TMR coefficient of wood was calculated based on the website of Thinktank Kyoto²⁰⁾ at the Kyoto Civic Activity Center. Table 9 shows volumes of production and thinning acquired from the website for Japanese cedar (sugi) and Japanese cypress (hinoki). Here, we can see that the rate of thinned wood is about 50%. Furthermore, since the website shows the utilization rate of wood per tree to be 25%, we obtain a wood TMR coefficient of $1/0.5/0.25 = 8$ t/t.

Table 9 Production and thinning volume of cedar and cypress (FY 2000)

Classification		Southern area of Kyoto	Middle area of Kyoto	Chutan	Tango	Total in Kyoto
Forest area (ha)		27,502	149,109	94,503	60,949	332,063
Resource amount	Material production (m ³)	1,328	60,092	8,357	6,269	76,046
	Thinned wood amount (m ³)	5,825	48,200	16,642	4,204	74,871
	Total (m ³)	7,153	108,292	24,999	10,473	150,917

Area classification is compliance with the Kyoto Forest and Forestry Development Plan.

4.5 Deriving TMR coefficients for metal ingots

In the previous sections, we have derived coefficients for ore-TMR and energy-TMR. This now enables us to derive TMR coefficients for metal ingots. This TMRs were calculated based on the following assumptions:

- (1) The allocation of by-products was made based on the price of metal ingots.
- (2) In cases where extraction energy was got, the TMR of world average primary energy was added to the ore-TMR coefficients. For cases where the extraction energy was not got, it was obtained by assuming that the extraction energy is equal to 10 times of the sum of the standard free energy change for reducing the contained metal (G_0) and its melting enthalpy (H_{m0}). The horizontal axis in Figure 12 shows the sum of G_0 and H_{m0} , and the vertical axis shows the energy required for actual refining. As we can see in the figure, most of the metals are concentrated on a line about 10 times that of the horizontal axis. Table 10 and Figure 13 show the TMR coefficients of metal ingots derived in this hypothetical manner. According to the figure and table, TMR coefficient of Pt is 520,000. However, actual operational data from the Anglo-American Platinum Co. in Figure 14 show a value of 1,200,000, which is roughly double this value.

Figure 12 Relationship between the theoretical energy and the energy required for actual smelting

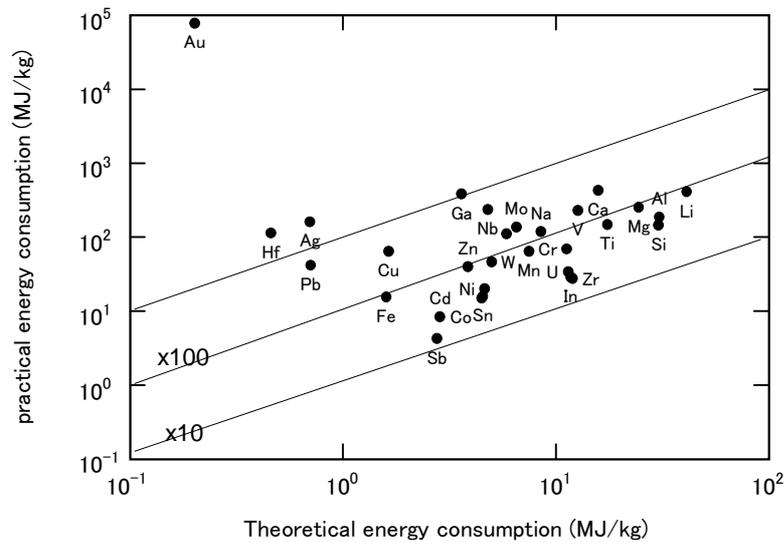


Figure 13 TMR coefficients (t/t) of metal ingots on the periodic table

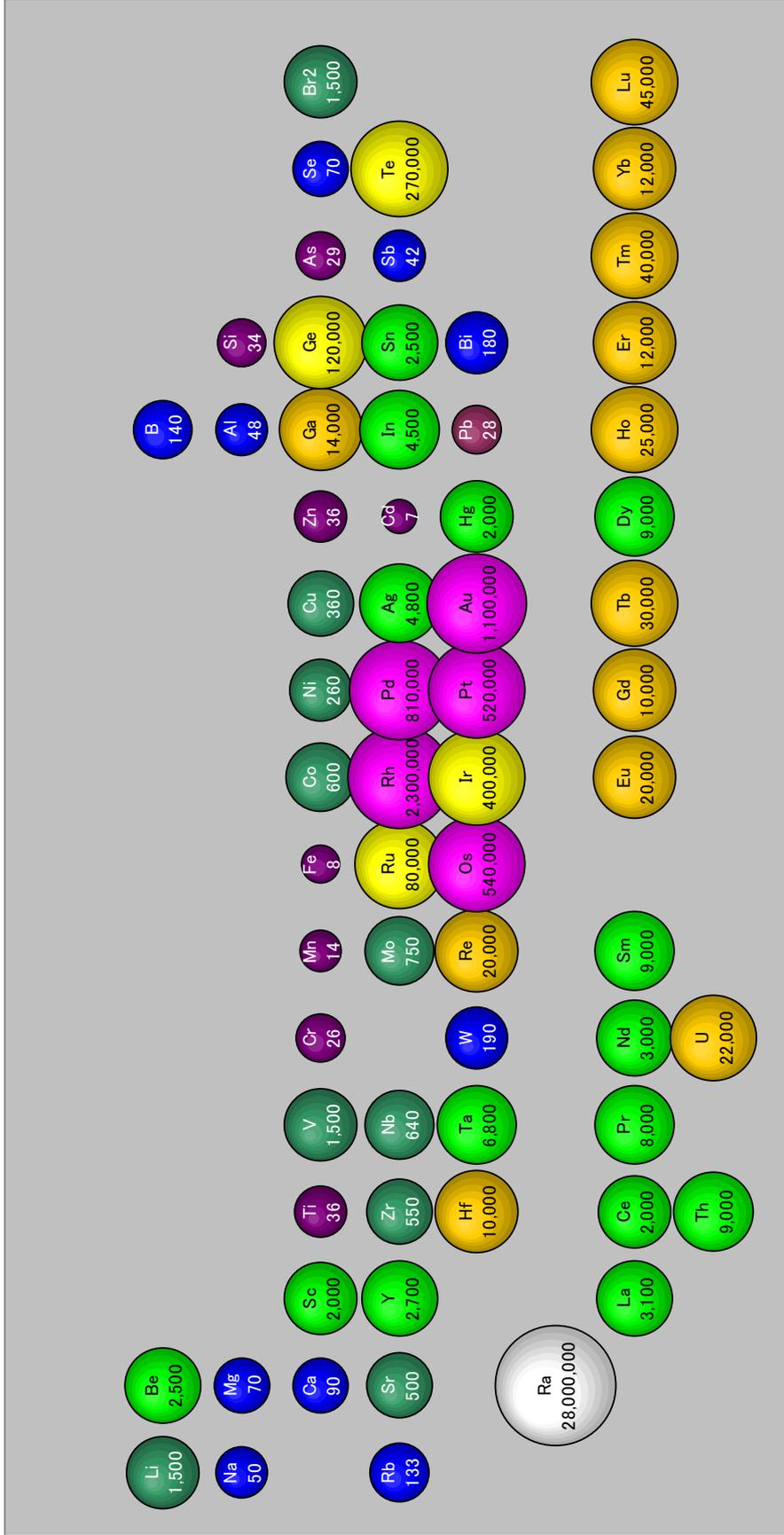


Table 10 TMR coefficient of each element (t/t)

Elements	TMR coefficient						
Li	1,500	Co	600	Cd	7	Tm	40,000
Be	2,500	Ni	260	In	4,500	Yb	12,000
B	140	Cu	360	Sn	2,500	Lu	45,000
F2	210	Zn	36	Sb	42	Hf	10,000
Na	50	Ga	14,000	Te	270,000	Ta	6,800
Mg	70	Ge	120,000	I2	45,000	W	190
Al	48	As	29	Cs	11	Re	20,000
Si	34	Se	70	Ba	510	Os	540,000
P2	220	Br2	1,500	La	3,100	Ir	400,000
S	520	Rb	130	Ce	2,000	Pt	520,000
Cl2	52	Sr	500	Pr	8,000	Au	1,100,000
K	54	Y	2,700	Nd	3,000	Hg	2,000
Ca	90	Zr	550	Sm	9,000	Tl	450
Sc	2,000	Nb	640	Eu	20,000	Pb	28
Ti	36	Mo	750	Gd	10,000	Bi	180
V	1,500	Ru	80,000	Tb	20,000	Ra	280,000,000
Cr	26	Rh	2,300,000	Dy	9,000	Th	9,000
Mn	14	Pd	810,000	Ho	25,000	U	22,000
Fe	8	Ag	4,800	Er	12,000		

Figure 14 Actual operational data of platinum group

Anglo American Platinum Co.Ltd.'s production and used

Materials	2004	2003
Rock mined (1000ton)	84,953	78,294
Ore milled (1000ton)	37,925	33,546
Water used (1000m3)	32,804	31,224
coal (1000ton)	106.6	100.4
LPG (1000ton)	5.5	4.4
fuels (1000liter)	54,284	50,655

Refined products	2004	2003
Platinum (ton)	69.55	65.43
Palladium (ton)	37.16	33.76
Rhodium (ton)	7.18	6.59
Gold (ton)	3.12	3.29

4.6 Comparison with the TMR coefficients of the Wuppertal Institute for Climate, Environment and Energy

Table 11 shows the values of TMR coefficients²¹⁾ disclosed by the Wuppertal Institute for Climate, Environment and Energy. While they are listed as “material intensity” here, they are used in the same vein as TMR coefficients here. According to the abiotic materials in the table, there are only 15 types of metals listed. For Wuppertal’s 37 kg/kg for aluminum, the authors’ TMR was 48 kg/kg; for Wuppertal’s 16 kg/kg for lead, the authors’ TMR was 28 kg/kg. Wuppertal shows 540,000 kg/kg for gold, as opposed to the authors’ TMR of 1,100,000 kg/kg, while the two values for iron were roughly the same, at about 8 kg/kg. They correspond to each other within plus minus 2 times.

Table 11 TMR value published by Wuppertal Institute for Climate, Environment and Energy

Material intensity of materials, fuels, transport services

Version 2; 28.10.2003

material	specification	Material intensity [t/t] / Materialintensitaet [t/t.]				
		abiotic material	biotic material	water	air	moved soil
Metals / Metalle						
aluminum	primary					
Aluminium	primaer	37		1047.7	10.87	Europe
	secondary					
	sekundaer	0.85		30.7	0.948	Europe
	wrought alloy					
	Knetlegierung	35.28		996.8	10.374	Europe
	cast alloy					
	Gusslegierung	8.11		234.1	2.932	Europe
	average					
	Durchschnitt	18.98		539.2	5.909	Europe
lead	estimated					
Blei	abgeschaetzt	15.6				World
ferrochromium	low carbon, 60% Cr					
Ferrochrom	niedriggekohl 60% Cr	21.58		504.9	5.075	World
	high carbon, 75% Cr					
	hochgekohl 75% Cr	13.54		221.4	2.3	World
ferro manganese	high carbon, 75% Mn					
Ferromangan	hochgekohl 75% Mn	16.69		193.8	2.231	World
ferro molybdenum	estimated					
Ferromolybdan	abgeschaetzt	748		1286	9.5	World
ferro nickel	25% Ni					
Ferronickel	25% Ni	60.33		615.9	9.726	World
gold	estimated					
Gold	abgeschaetzt	540,000.00				World
copper	50% primary, 50% secondary					
Kupfer	50% primaer; 50% sekundaer	179.07		236.39	1.16	World
	secondary					
	sekundaer	2.38		85.5	1.319	World
	primary					
	primaer	348.47		367.2	1.603	World
nickel						
Nickel		141.29		233.3	40.825	Germany
platinum						
Platin		320,300.00		193000	13800	World
silver	estimated					
Silber	abgeschaetzt	7,500.00				World
steel	plate, hot dipped galvanised, basic oxygen steel					
Stahl	Oxygenstahl; Blech, feuerverzinkt	9.32		81.9	0.772	World
	Rebar, Wire Rod, Engineering Steel;					
	electric arc furnace route					
	Traeger, Draht. Masch.baustahl;					
	Elektrolitbogenfler Route	1.47		58.8	0.519	World
	Rebar, Wire Rod, Engineering Steel; blast					
	furnace route					
	Trieer, Draht. Masch.baustahl; Hochoten					
	Route	8.14		63.7	0.444	World
	Plate, blast furnace Route					
	Grobblech.Hochofenroute	8.05		55.7	0.436	World
	Hot Rolled, blast furnace Route					
	Warmband. Hochotenroute	7.63		56	0.414	World
	plate, electrogalvanised, blast furnace					
	Oxygenstahl Blech, feuerverzinkt	9.42		75.4	0.65	World
	Cold Rolled, blast furnace Route					
	Kaltfeinblech. Hochofenroute	8.51		74.8	0.492	World
stainless steel	18%Cr; 9%Ni					
Edelstahl (rostfrei)	18%Cr; 9%Ni	14.43		205.1	2.825	Europe
	17%Cr; 12%Ni					
	17%Cr; 12%Ni	17.94		240.3	3.382	Europe
tin	Import-Mix Germany					
Zinn	Import-Mix Deutschland	8,486.00		10958	149	Germany
zinc	electrolytic					
Zink	elektrolytisch	22.18		343.7	2.282	Germany
	high-grade zinc, (secondary) IS					
	Feinzink (sekundaer) IS-Ofen	19.36		86.5	42.29	Germany
	mix					
	Mix	21.76		305.1	8.283	Germany

5. Example of Analysis Using TMR

5.1 Correlation with other indices

An attempt was made to compare the TMR coefficients derived in 4.5 with production volumes and prices of metals. The results are shown in Figures 15 and 16. In Figure 15, iron, with a low TMR coefficient of 8 kg/kg and production that reaches 1 billion tons, is shown in the lower right, while the upper left shows results of platinum group metals. Overall, there is a clear negative correlation between production volume and the TMR coefficient. In Figure 16, there is the opposite finding—a positive correlation is seen between TMR coefficient and prices, with a distinct trend in which the more earth is excavated, the higher the price is.

Figure 15 Relation between TMR coefficient and world production volume

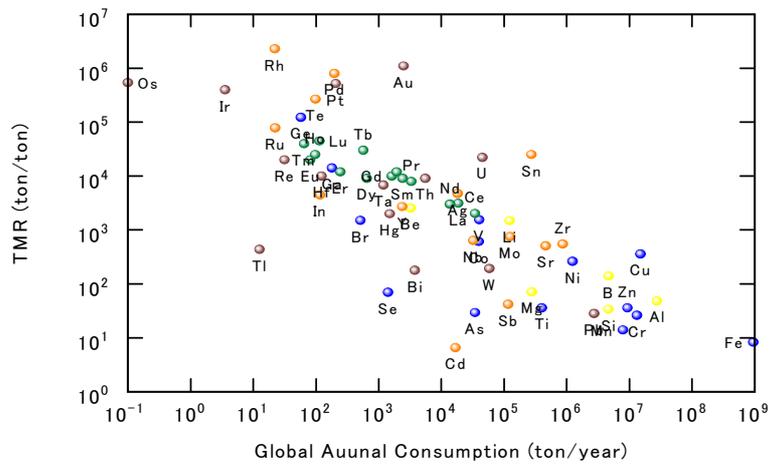
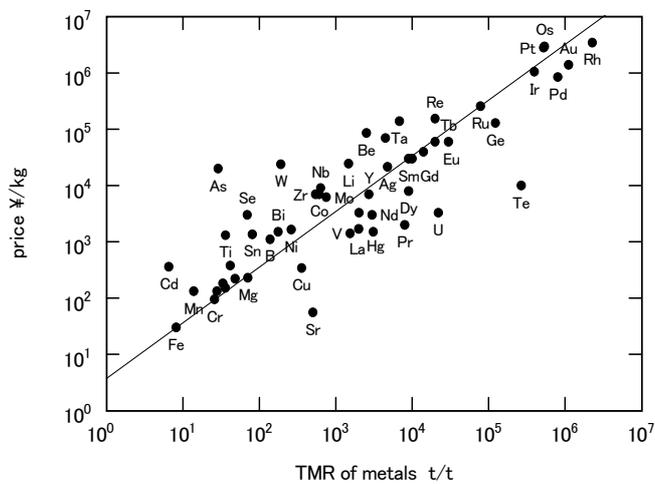


Figure 16 Relation between TMR coefficient of metals and price

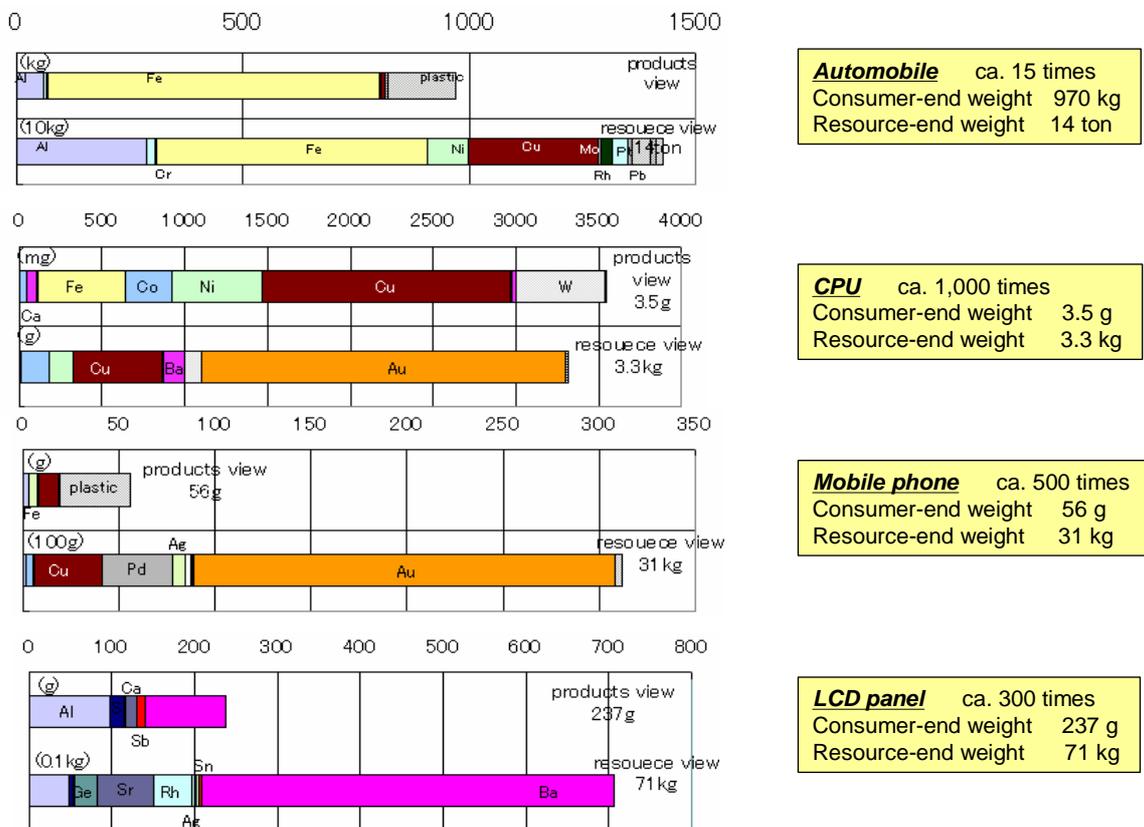


5.2 Analysis using TMR

5.2.1 Correspondence between Consumer-end Weight (the actual weight of equipment/units) and Resource-end Weight

Figure 17 shows the correspondence between Consumer-end Weight and Resource-end Weight for passenger vehicles, CPUs, mobile telephones, and LCD panels. Because automobiles are made with a large amount of conventional materials (such as aluminum, steel, copper, stainless, etc.), the Consumer-end Weight is about 15 times higher than the actual weight, but for CPUs, mobile telephones, and LCD panels, it ranges from 300 to 1,000 times higher, clearly indicating a heavy load of some sort on the global environment. The contribution of gold is particularly noticeable.

Figure 17 Consumer-end Weight and Resource-end Weight of various products



5.2.2 Results of recycling analysis

Figure 18 shows the recycled contents of end-of-life automobiles in terms of actual weight and Resource-end Weight. In terms of actual weight, the recycling of steel stands out, but in terms of Resource-end Weight, the recycling of aluminum and copper stands out.

Figure 18 Recycling, actual weight flow and TMR flow of automobiles

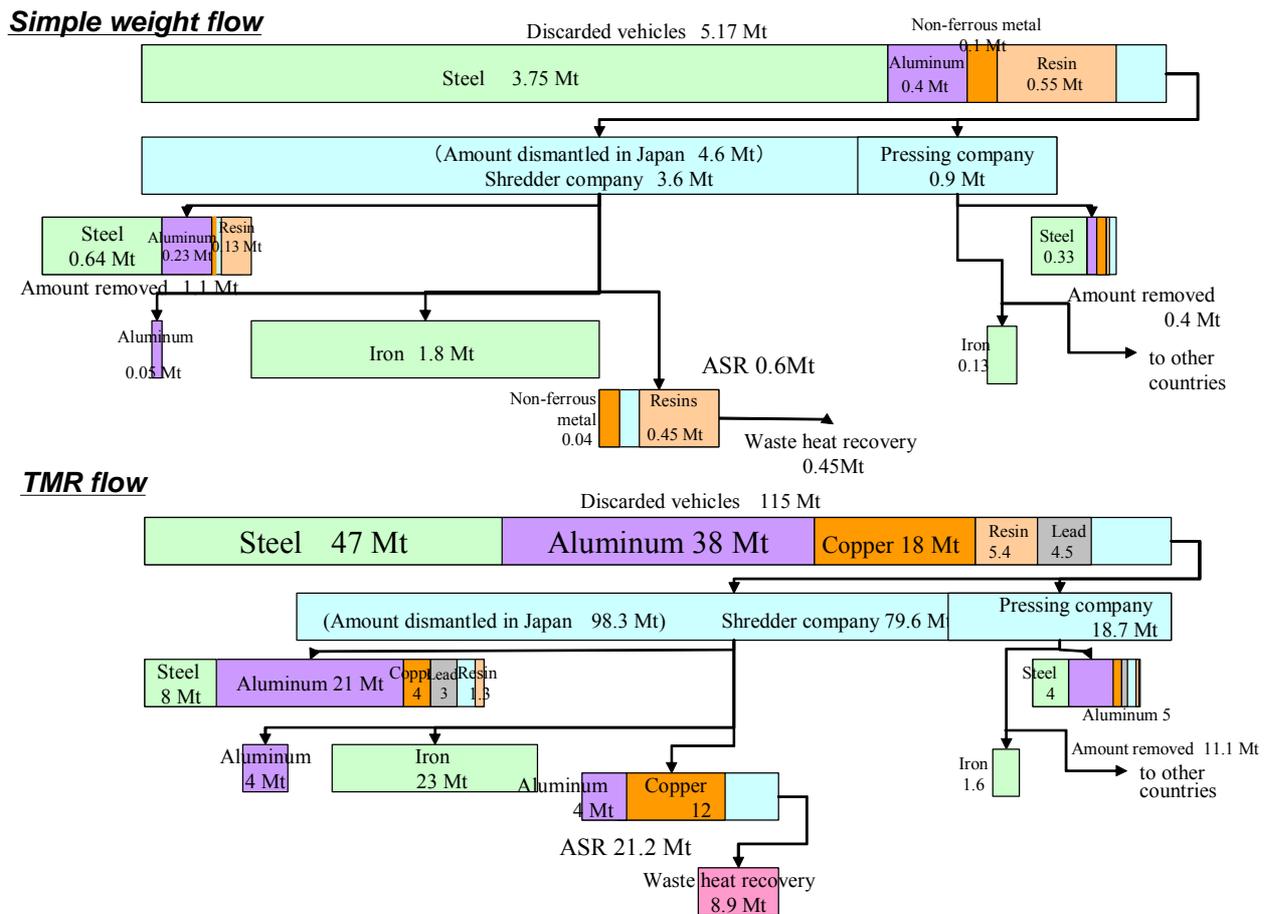
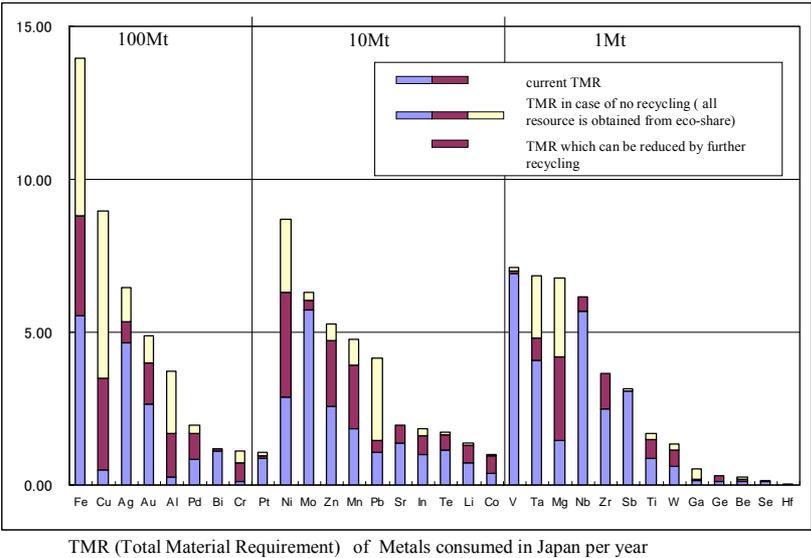


Figure 19 shows the TMR values for the current production state of iron, copper, silver, gold, and other metals in Japan. It shows not only that the TMR of metals in the current state is being reduced by recycling, but also the extent to which the current state can be changed by further promoting recycling. While each metal shows a large TMR value, we can see that recycling could greatly reduce the Resource-end Weight.

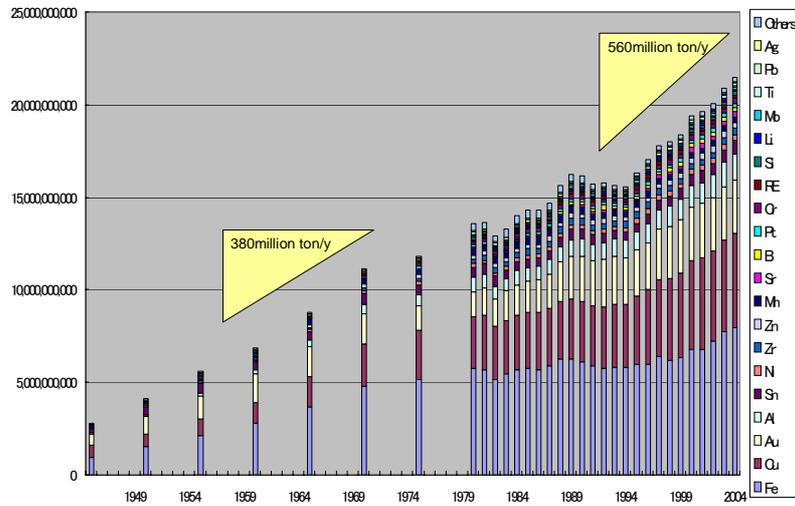
Figure 19 Annual TMR for various metals in Japan



5.2.3 Total resource consumption

By multiplying the production volumes of each metal by the TMR coefficients, we can understand to what extent humans have excavated the earth to obtain metallic elements (= Total Resource-end Weight). Figure 20 shows Total Resource-end Weight (Total TMR) corresponding to total annual production of these metals in the world. The total annual TMR in 2004 reached roughly 22 billion tons. A breakdown of this figure shows that iron has a low TMR coefficient but overwhelmingly accounts for the largest share, at 40%. That is followed by copper at 20%. What is particularly noteworthy here is that gold, which is used in relatively low volumes, has TMR values that are higher than those of aluminum. Gold is widely used in the electronics industry, and is a material which must be considered in the discussion of global sustainability. The elements shown in the legend of the figure are those having the 20 highest TMR values in 2004. Despite the fact that platinum, rare earths, and silver, among others, are used in relatively low amounts like gold, they still rank in the Top 20.

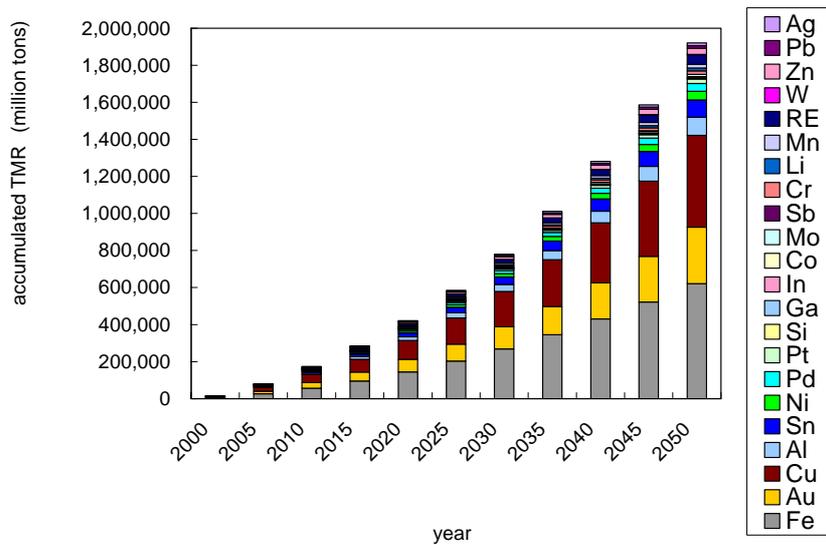
Figure 20 Variations in annual TMR in the world (ton)



Looking at Total TMR trends in the figure, we can see a general steadily increasing, which is especially noticeable since the late 1990s, which showed an increase of about 560 million tons/year, much greater than the 380 million tons/year in the 1960s and 1970s when limits to growth was a hot topic.

We considered how Total Global TMR might increase in the future. The results are shown in Figure 21. The area to the right of 2005 in the figure is an extrapolation of the relation between consumption of each metal and per capita GDP up to the year 2050 which was made using a three-step linear model. According to the figure, world annual TMR will surpass 2 trillion tons around 2050.

Figure 21 Projected global annual TMR

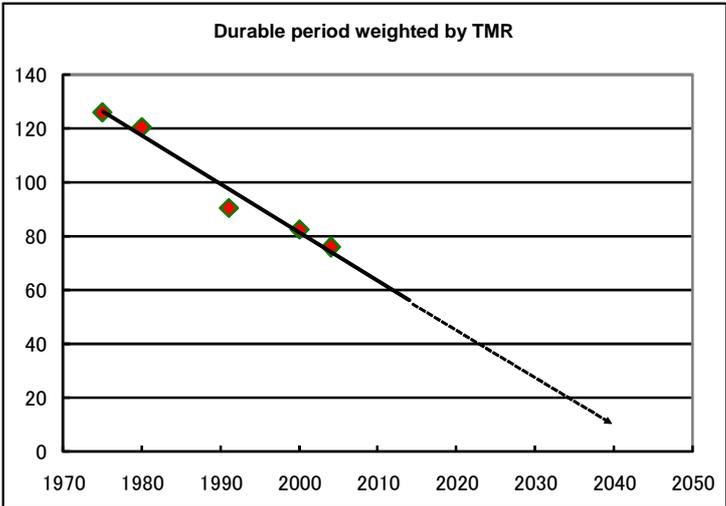


Dividing the proven reserves of each year that were weighted with TMR coefficients (reserve-equivalent TMR of each year) by the metal production that was weighted by the TMR coefficient for that year gives the number of years of resource life for metallic elements overall in that year. In other words,

$$\begin{aligned} &\text{Total life of a metal resource} \\ &= \frac{\sum \{(\text{TMR coefficient of Metal } i) \times (\text{Proven reserves of the metal resource } i \text{ at that year})\}}{\sum \{(\text{TMR coefficient of Metal } i) \times (\text{Annual production of Metal } i)\}} \end{aligned}$$

Figure 22 plots the trends of total life of a metal resource for various years. In most cases, the number of years of an individual metal’s life varies depending on, for example, increases in the proven reserves. However, the overall trend, which is weighted by the TMR coefficient, shows the life to be unquestionably decreasing: in 1970s, it exceeded 120 years, but in 2004 it fell to less than 80 years. While being an extrapolated value, it appears that the overall figure will fall below 10 years by 2040.

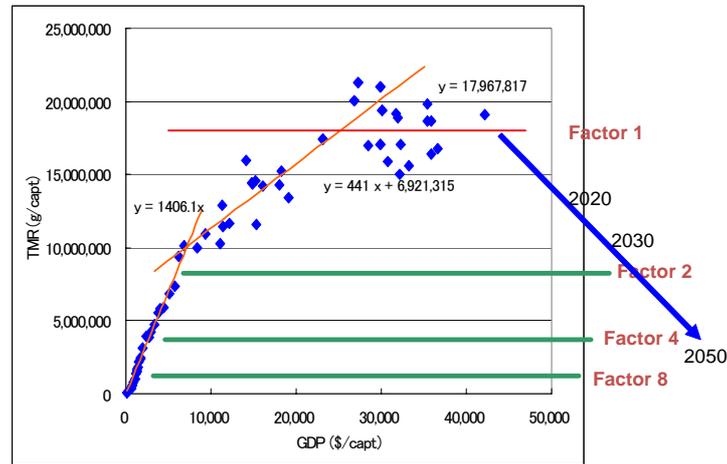
Figure 22 Future prediction of total life of metal resource (years)



5.2.4 Relationship between per capita GDP and per capita TMR

Figure 23 shows the relationship between per capita GDP and per capita TMR in Japan. The dots in the figure correspond to years of post-war Japan. As per capita GDP grew, the per capita TMR grew remarkably to around the 8,000 dollar value on the horizontal axis. This may be interpreted to mean that economic growth during this stage involved the consumption of large quantities of resources. After the roughly \$8,000 mark, the increase in the vertical axis began to slow down, and appears to stagnate after passing roughly the \$25,000 mark. This indicates a transition toward a service-based economy with high GDP and less consumption of resources. The figure shows levels reached by values on the vertical axis when the resource efficiency rate becomes two, four, and eight times higher. As we head toward 2050, it will be necessary to vastly increase the efficiency of resource use so that we can reduce TMR consumption and increase the life of resources.

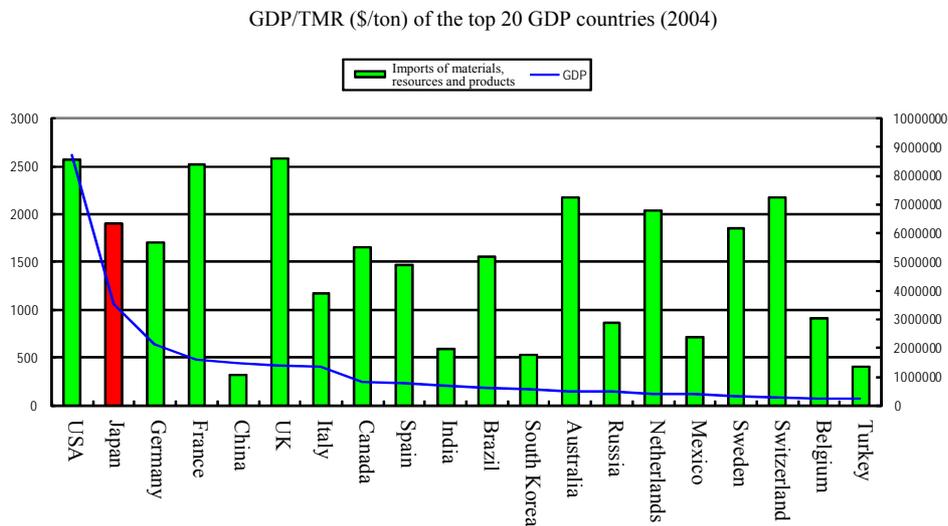
Figure 23 Relationship between GDP and TMR in postwar Japan



5.2.5 Examination of GDP

Figure 24 shows the resource productivity of various countries in terms of dollars per TMR ton. This was calculated by dividing the GDP (dollars) by the Total TMR of consumed materials of each country. The latter was derived by multiplying the resinous materials and metals that comprise materials, resources and products consumed in these countries by the TMR coefficient of each material, and summing up all TMR values of each material. The figure shows countries with GDPs of at least \$100 billion. The curve in the figure shows GDP (right scale). In Western countries where the economy is becoming increasingly service-oriented, resource productivity is increasing, and Japan is following this pattern. The GDP and resource productivity of China, which is already being called the “world’s factory,” are still less than half those of Japan.

Figure 24 Resource productivity of various countries in terms of GDP/TMR



6. Concluding Remarks

This report is a brief introduction to the work that the authors have so far proposed and investigated on Resource-end Weight, which is also known as Total Material Requirement or TMR. This introduction has included a rather detailed look at how TMR coefficients were derived, so it should be able to assist the reader in understanding not only the meaning and accuracy of TMR coefficients, but also such things as problem points and limits. The authors would be pleased if many researchers would use this material for further investigations, including examinations of case studies and discuss the practicality and limits of this approach.

References

- 1) F. Schmidt-Bleek: "Factor 10 Eko Koritsu Kakumei" (translated by Takeshi Sasaki), Springer Verlag, Tokyo, (1997)
- 2) World Resources Institute: "Resource Flows the Material Basis of Industrial Economies" (April 1997)
- 3) Kohmei Halada, Kiyoshi Ijima, Nozomu Katagiri, and Takahiko Okura: J. Japan Inst. Metals 65 (7), (2001), pp. 564-570
- 4) K. Halada and K. Ijima: "Resource Productivity of Magnesium," Materia Japan 43 (4), (2004), pp. 264-269
- 5) Kenichi Nakajima, Kohmei Halada, Kiyoshi Ijima, and Tetsuya Nagasaka: "Kanyobusshitsu Soryo no Santei - Energy Shigen Oyobi Kogyozairyo no LCA," Journal of Life-cycle Assessment, Japan 2 (2), (2006), pp. 152-158
- 6) Kenichi Nakajima, Keisuke Yamamoto, Kazuko Nakano, Kotaro Kuroda, Kohmei Halada, and Tetsuya Nagasaka: "Kanyobusshitsu Soryo (TMR) ni Motozuku Shiyozumi Keitai Denwa Recycle Flow Kaiseki," Journal of Life-cycle Assessment, Japan 2 (4), (2006) pp. 341-346
- 7) Ministry of the Environment: "Fundamental Plan for Establishing a Sound Material-Cycle Society" (online)
<http://www.env.go.jp/recycle/circul/keikaku/keikaku_2.pdf>,
<http://www.env.go.jp/recycle/circul/keikaku/gaiyo_2.pdf> (refer to September 18, 2008)
- 8) Eco Material Society: "Chikyu no Genkai," edited by Hiroshi Mizutani, Union of Japanese Scientists and Engineers, Tokyo, (1999)
- 9) Reference 2), p. 8
- 10) Kunihiro Takeda: "Recycle Shitewa Ikenai," Seishun Publishing Co., Ltd., Tokyo, (2000)
- 11) U.S. Geological Survey Minerals Information: Minerals year book, (2001), published on the web: <http://minerals.usgs.gov/minerals/pubs/commodity/myb/>.
- 12) J. K. Moore: Mining and Quarrying Trends in the web of U.S. Geological Survey Minerals Information (2001)
- 13) Takashi Nishiyama: "Kobutsu Shigen no Genjo," Arumu Shuppansha, Tokyo, (1992)
- 14) National Astronomical Observatory of Japan: "Chronological Scientific Tables 2000," Maruzen Co., Ltd., (2000)
- 15) Kenichi Nakajima, Kiyoshi Ijima, and Kohmei Halada: "Estimation of Total Materials Requirement - Energy Resources and Industrial Materials, NIMS-EMC Materials Data for the Environment 10 (3), (2006)
- 16) K. Halada and K. Ijima: "Resource Productivity of Magnesium", Materia Japan, 43 (4), (2004) pp. 264-269
- 17) Japan Oil Development Organization (online),
http://www.japex.co.jp/infomation/jigyot_index4.html
- 18) Agency of Natural Resources and Energy: Ore Reserve Statistical Survey (online)
<http://www.enecho.meti.go.jp/info/statistics/image/050622maizo.pdf> (refer to January 15, 2006)
- 19) Statistics Department, Ministry of Agriculture, Forestry and Fisheries: Monthly Report of Statistics of Agriculture, Forestry and Fisheries (2005)
- 20) Ministry of Agriculture, Forestry and Fisheries: "Rural development project utilizing wooden biomass resources in a typical mountain village," Thinktank KYOTO
<http://sintank.kdn.jp/rep/chapter2.pdf> (refer to May 20, 2005)
- 21) "Wuppertal Institute for Climate, Environment and Energy," Wuppertal Institute, (online)
http://www.wupperinst.org/uploads/tx_wibeitrag/MIT_v2.pdf (refer to January 21, 2009)
- 22) Metal Mining Agency of Japan: "News Flash" 2000 (01)-2000 (49), (2000), published on the web: <http://www.mmaj.go.jp/>

NIMS-EMC Materials Data for the Environment

- No. 1 Estimation of CO₂ Emission and Energy Consumption in Extraction of Metals (March, 2004)
- No. 2 Fundamental Survey for Lead Material Flow in Japan (March, 2004)
- No. 3 Worldwide Supply and Demand of Platinum Group Metals and Trends in the Recycling of Autocatalyst in Japan (March, 2004)
- No. 4 LCA-Based Investigation of Technological Application Scenarios of Surplus Iron Scrap in Converters and Electric Furnaces (March, 2004)
- No. 5 Aluminum Material Flow in Japan (March, 2004)
- No. 6 Investigation on the Utilization and Application of Biomass (March, 2005)
- No. 7 Current Status of Recycling of Nonferrous Metals in China and Discarded Electric Appliances, etc. (March, 2005)
- No. 8 Characterization Factors in the Category of the "Utilization of Mineral Resources" (March, 2005)
- No. 9 Flow of Iron Material in China (scheduled for publication)
- No. 10 Estimation of Total Materials Requirement
Energy Resources and Industrial Materials (March, 2006)
- No. 11 Material Flow (scheduled for publication)
- No. 12 Appraisal of Effective Utilization of Resources from the Point of View of Social Stock (March, 2006)
- No.13 Review of the Current State of Nickel, Cobalt, Vanadium, and Rare Earth Metals (scheduled for publication)
- No.14 Survey Research on Ethical and Social Effects of Nano-Technology (scheduled for publication)
- No.15 China Survey Report, by Masanori Shimada (scheduled for publication)
- No.16 Investigation of the Grand Design for a Material Lease Society (scheduled for publication)
- No.17 Evaluation of Steel Structures in Public Infrastructure as a Hibernation Stock (scheduled for publication)
- No.18 Overview of Total Material Requirement (TMR) (March, 2009)

