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Eric Carlsen

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## THE LINK BETWEEN METALS AVAILABILITY AND THE ENERGY CRISIS

*By Eric Carlsen\**

Discovery and use of metals represents a pivotal event in man's economic development. Indeed most of the Industrial Revolution which has transformed the Western world can be defined in terms of a vast expansion of metals and energy consumption. From a technological viewpoint it is obvious that none of the immense energy transformations and revolutionary transportation improvements which are the hallmark of developed countries could have taken place without an abundant and diverse supply of metals. Thus, to the extent that future supplies of metals are constrained, the possibilities of further economic growth are severely limited. However, there is a subtle link between problems of energy availability and metals production such that an overall limit to energy may under certain circumstances bring about a halt to increases in annual metals production, despite increased recycling. This article proposes to investigate that link and to speculate on the implications which such a possible future metals barrier could have for future economic growth.

Beyond a certain point the marginal utility to society of increased use of energy in supplying metals might be outweighed by the marginal utility of energy used in alternative ways. Hence the supply of metals could not rise, barring technological improvements of an energy-conserving nature. This article argues that there is good reason for believing that the conditions under which new stocks of metal can be extracted from virgin sources will become far more costly.

### I. GEOLOGICAL AND TECHNOLOGICAL FACTORS IN METALS PRODUCTION

Although the total amount of a given metal in the earth's crust may be enormous, rarely will the metal be present in concentrations that are economically feasible to exploit with present technologies

and prices. Leaner ores than today's commercial<sup>1</sup> grades are physically capable of yielding metal, but the cost will be higher, particularly in real energy terms. Technological improvements can only be expected to offset modest rises in energy costs over time because of the "Law of Entropy." This law states that the natural movement in the universe is from greater concentrations of energy and substances in general to lesser concentrations. Hence to concentrate a substance like metal from its ore requires a great deal of energy. Such is the essence of metals refining. It follows that a greater amount of energy (fuel) is required to produce a given amount of refined metal<sup>2</sup> from a lean ore, than from a rich ore.

Generally, if other factors are held constant, the higher the percentage of metal, the sooner the ore body will be exploited. Hence, barring unprecedented geological discoveries, future metals production must be from ores of lower metallic concentrations because many rich deposits have been exhausted. Thus, what becomes crucial is the rate at which metallic concentrations decline as marginal supplies of metal embodied in ores are exploited. Also of importance is the rate at which energy costs of metals production increase with declining ore grade. Suppose that the cost rise associated with a decline in the percentage of metal in ore was slow and that the available ore tonnage increased geometrically with constant incremental decreases in ore grade measured in terms of metallic concentration. Mathematically, this would mean that large increases in actual metal availability would occur over a significant range of ore grade decline, accompanied by slow increases in the energy costs of procuring such metals. Thus, in the case of the most common metals such as iron, were we to descend from present-day commercial grades of metal all the way down to common rock, the cost increase of virgin metal would be least, based on the low ratio of commercial grade to average crustal abundance (*clarke*).<sup>3</sup>

In the case of many less common metals such as copper, mercury, gold, silver, tungsten, and lead, this assumption of geometrically increasing ore deposits associated with arithmetically declining ore grades cannot be validated.<sup>4</sup> Even if it could, the enormous ratios of commercial ore grade to average crustal abundance would greatly increase exploitation costs. Thus, the corollary statement, that the extractible metal contained in reserves whose grades are only a few times less than those currently minable vastly exceed current commercial reserves, similarly lacks support. Hence, beyond present commercial reserves it can be argued that the cost of virgin metal exploitation will rise precipitously, particularly in terms of the en-

ergy costs of extracting and refining them. Since much of the technological progress to date in mining has been based on falling real costs of energy use, the current energy crisis indicates that energy availability will exert an appreciable constraint on the exploitability of remaining virgin metals.

If we make the plausible assumption that energy used per ton of virgin metal produced varies inversely to the grade of ore utilized beyond present commercial and near-commercial grades,<sup>5</sup> then energy costs of procuring even the present volume of virgin metals annually must increase prohibitively, shortly after present commercial reserves of metals are exhausted.<sup>6</sup> Without unprecedented new discoveries, the various times at which the exhaustion of present commercial reserves must take place at current growth rates of virgin metals consumption are not far off.<sup>7</sup> The upshot is that the past exponential growth paths of metals extraction will not be maintained. More than a few doublings of the present energy currently used to mine virgin metals worldwide would severely shrink the availability of energy for other uses. At this point, then, two things would happen: first, the volume of virgin metals extracted would have to decline; and, second, other ways of satisfying the economy's needs met now by virgin metals would have to be sought.

## II. ECONOMIC FACTORS IN METALS PRODUCTION

Inevitably, the rising costs of virgin metals will provoke a search for substitutes. Generally, these will be metals, because for most purposes the best physical substitute for one metal is another. Even so, using such a substitute means higher costs. After all, the alternative metal would only be pressed into service because the original metal became sufficiently expensive. Furthermore, the initial metal shortage can only speed up the time when there will be a shortage of substitutes and still another frantic search for replacements. Instead, another kind of economizing and substitution process could be increasingly used—recycling.

Recycling in the economic sense is the opposite of "throughput," or the discarding of wastes after the goods they have embodied have been consumed. Two forms of recycling can be distinguished: the first involves the reclamation of industrially valuable materials such as scrap metal from manufacturing operations at the plant site; the second involves the reclamation of materials which have commercially insufficient value for businesses and consumers to salvage and reprocess. Most of the current metals recycling activity consists of the former; its quantitative impact on the economy is apparent in Table I.

TABLE I

Percentage of Metals Production Accounted for by Recycling<sup>8</sup>

<i>Metal</i>	<i>Recycled Percentage of Total Production</i>
lead	52
copper	48
iron	26
aluminum	25
zinc	20

In a way such recycling statistics understate the true proportion of recycling done with metals once they have become embodied in economic goods. For example, stating that 52 percent of the lead used annually comes from recycling sources does not mean that 48 percent ends up as unrecovered waste, or "throughput." Rather, only the equivalent of a fraction of this 48 percent is actually lost to the economic system as discarded waste; the remainder represents an increase in our stock of metals in use.<sup>9</sup> Hence we shall define two recycling coefficients:

$$(1) R_a = \frac{\text{recycled metals}}{\text{virgin metal extracted} + \text{recycled metals}}$$

and

$$(2) R_b = \frac{\text{recycled metals}}{\text{discarded metals} + \text{recycled metals}}$$

Note that  $R_a$  is the one implicitly used in Table I and is lower than  $R_b$ .

As Table I and the analysis above show, the potential for increased recycling is small, particularly in the case of copper, lead and the rarer metals. Furthermore, some loss of the metal in use must occur, whether from rusting, wear, chance loss or economic non-recoverability of discarded metal items too fine, too mixed with other wastes or too geographically dispersed for economic retrieval. In effect, without presorting of metallic refuse items, the problem becomes one of "mining" garbage piles for discarded metals. The problem is analogous to that of refining ever leaner ores, and the above mentioned Law of Entropy applies. Therefore recycling offers only a partial solution to a future metals supply impasse.

Let us review our economy's approach to metallic resource limits thus far. First we pass through a predominantly extractive phase; the stock of metals in use grows rapidly;  $R_a$  is low. This is followed by a stage where extractive activity is joined by recycling activity

as a means of augmenting the flow of metallic raw materials for industry, while metals-in-use stocks continue to grow. Losses to the economy are still vastly exceeded by new additions of virgin metals, but  $R_a$  rises considerably. We are presently in this latter stage.<sup>10</sup> Soon, however, we shall encounter a third stage, metals use under conditions of such increased virgin metals production costs as to cut off the growth of our metals-in-use stocks, even though  $R_a$  and  $R_b$  begin to converge on the value 1.00.<sup>11</sup>

### III. ENERGY COSTS AND THE METALS RESOURCE BARRIER

Formally defining an overall metals resource barrier is not easy if one attempts to take into consideration the myriad known and unknown possibilities of economic adjustments that would be made as the supposed barrier was approached. By way of simplification, assume that some maximal annual amount of energy is economically available,  $\bar{E}$ , for extracting and refining virgin ores as well as collecting, sorting and reprocessing metals from industrial scrap and consumption waste. Actual energy used for metals output,  $E$ , would be less than  $\bar{E}$  until the metals resource barrier was reached.

Suppose that the stocks of metals in use at any one time are  $M_1$ ,  $M_2$ , . . . and  $M_n$ . Each of these allows, through economically optimal use of virgin and recycled metals, some series of annual metals flows  $m_1$ ,  $m_2$ , . . . and  $m_n$ . Because of the desirability of economic growth, however, the  $m_1$  flows are not maximal in the short run consistent with stocks  $M_1$ , because of the greater energy use per ton of metal for virgin metals as opposed to recycled metals.<sup>12</sup> Rather, such seeming misallocation of energy resources is actually directed at increasing the  $M_1$  stocks as a form of net investment, so that future  $m_1$  flows can be greater. As was pointed out above, stocks  $M_1$  will increase as long as virgin flows exceed losses to the economy, with  $\bar{E}$  increasing as poorer and poorer ores are utilized. Such rising energy costs would, of course, increase  $R_b$  for all metals, but a time would come when some set of limits to  $R_b$  would be reached. This would mean an unavoidable percentage loss of metals stock which would still have to be made up from virgin sources. Since the costs of virgin metals extraction would continue to rise, the energy barrier  $\bar{E}$  would be reached sooner or later, with the metals resource barrier defined as that maximal set of metals-in-use stocks and annual metals flows that could be reached with energy input  $\bar{E}$ .

What are some of the implications of this metals resource barrier? Suppose the aggregate energy recycling costs per ton of metal used annually were to reach one-half the cost per ton of metal from pre-

sent day virgin sources as recycling reached a level such that  $R_b = 0.95$ . Then, if  $\bar{E}$  represented total maximal energy use allowable in providing metals,  $0.95\bar{E}/2$  could be allocated to recycling and  $0.05x\bar{E}$  to virgin metals extraction, where  $x =$  ratio of virgin metals energy extraction costs per unit in the future to virgin metals energy extraction costs now.  $\bar{E}$ , the total current energy necessary to produce metals, would be less than  $\bar{E}$  and equal to  $0.95\bar{E}/2 + 0.5x\bar{E}$ . Setting  $\bar{E} = 0.95\bar{E}/2 + 0.05x\bar{E}$ ,  $x = 10.5$ . In energy terms, virgin metals production costs per unit would be 21 times that of recycling unit energy costs, assuming the latter did not change. Were  $R_b$  to reach 0.99, then the economy could stay at the barrier levels of metals stocks and flows until the energy costs of virgin metals exceeded 101 times that of recycled materials. Thus, descent from a maximal metals output barrier would be further delayed and more greatly retarded the higher the level of  $R_b$  that could be attained.

TABLE II

Present Energy Costs in Terms of Pounds of Coal Required  
To Make One Pound of Metal from Virgin Ores  
and Recycled Materials<sup>13</sup>

<i>Metal</i>	<i>From Ore</i>	<i>From Recycled Material</i>
steel	1.11	0.22
aluminum	6.09	0.17 - 0.26
copper	1.98	0.11

However, under our prevailing assumptions, descent would eventually come, unless recycling became a perfect 100 percent. The optimistic side of the picture is that such metal stocks would be much greater than they are today; if  $\bar{E}$  were appreciably greater than  $\bar{E}$  today, then annual metals flows for a substantial period would be far greater than today. However, the assumptions we have made are not inviolable; we shall have to relax them in the next section.

#### IV. THE ECONOMY UNDER CONDITIONS OF A METALS RESOURCE BARRIER

Given some maximal set of metal flows, there is a maximal set of goods and services that can be produced in a given set of proportions, if technology and other resource flows are held constant. Furthermore, unless the production of other goods and services is cur-

tailed, the volume of automobiles, for example, could be assumed to be limited by the annual flow of metals available to the automotive industry. Thus, if each car required one ton of steel and was junked on the average of every 10 years, an annual car production of 10,000,000 units could be maintained by an annual metals flow of 10,000,000 tons. A total stock of 100,000,000 automobiles could be maintained, once this level was reached. 9,500,000 tons of steel would have to come from recycling, if  $R_b = 0.95$  for automobiles, and 500,000 tons of steel would have to be provided annually from virgin sources. Without technological improvements and qualitative changes in automobile manufacture, the erosion of the overall metals stocks would sooner or later reduce the volume of automobiles that could be produced annually, and therefore the stock of automobiles itself.

What compensating technological and qualitative adjustments would have to be made in the automotive industry, if the same stock of automobiles were to be maintained? First, the time an automobile lasted could be lengthened by means of improved construction. This would reduce annual virgin-plus-recycled metals flows required to maintain automobile stocks. However, limits to this type of technological adjustment can be seen. More durable automobiles require the reinforcement of better materials, mostly metal. Second, smaller automobiles could be built, cutting down on annual steel consumption. Third, cars could be designed so as to maximize the percentage of metal recovered consistent with minimizing the unit costs of reprocessing. Fourth, many automobile metal components could be (and are being) replaced by materials made from renewable resources, relegating metals use to vital moving parts. Since materials made from renewable resources such as wood can be increased in stock indefinitely, their potential future relative to that of metals would make them increasingly cheaper in terms of the latter. Such "devalued" automobiles would suffer in such respects as durability, unless an ingenious technology of manufacturing complex durable laminas of mostly renewable materials composition could be developed. Finally, were all-steel automobiles so highly prized in the economy, they would spur the above kinds of technological and qualitative adjustments in the rest of the economy, including energy saving from the less economically desired energy using sectors, so as to spare the requisite annual flow of metals needed to keep automobile stocks at desired levels. Much more likely, however, is the possibility of aggregate automobile stocks falling in the face of greater competitive pressures for energy and



steel use from the rest of the economy. Mass transport, a far more efficient mover of people on the basis of passenger-miles per unit of fuel use, would become far more attractive.

Thus, the economy as a whole could not grow in terms of providing metal-using goods and services unless significant opportunities existed to substitute renewable materials for metals. Overall economic growth, on the other hand, could proceed on the basis of expanding the production of goods and services utilizing primarily renewable materials until some sort of biotic resource barrier was reached.<sup>14</sup> How far this renewable resource barrier could be pushed would again depend on inanimate energy availability, a fact made obvious by the energy-intensive nature of modern agricultural and forestry technology. Finally, technological improvements, by allowing the same volume of goods and services to be produced with fewer inputs could allow some further economic growth despite the imposition of a triad of biotic, energy and metals resource barriers. It is likely, however, that economic growth possibilities after the metals resource barrier is felt would be quite limited, particularly if net metal losses to the economy cause this barrier to press down.

#### V. QUALIFICATION TO THE METALS RESOURCE BARRIER

Heretofore we have assumed that although metals would have different periods until exhaustion of commercial and near-commercial reserves, sooner or later the costs of providing sufficient virgin metals to offset losses would exhaust the amount of energy that could be economically allocated to metals production. Once the particular lean ore grades in use when the metals barrier was encountered were fully depleted, virgin metals costs would rise—ultimately making the energy costs of maintaining the given metal flows prohibitively expensive. It is not at all certain that the following crucial assumption on which this analysis is based is true in the cases of iron and aluminum. That assumption is that the ratio of present grade of commercial ore to average crustal abundance is great enough to accommodate a sufficient multiplication of exploitation costs so as to create the required intolerably high energy cost of future virgin metals use. For example, suppose iron extraction costs double as the grade declines by half. If the average ratio of commercial ore to average crustal abundance is about six, then perhaps six doublings of the energy cost of virgin iron use could occur before the Clarke was reached. Such a 64 fold increase in the cost of virgin iron production might allow the economy to stay indefinitely at the iron resource barrier, provided recycling levels mea-

sured in terms of  $R_b$  reached 98 or 99 percent. Possibly a similar analysis could be made in the case of aluminum, although the author recognizes that grade alone is an insufficiently reliable indicator of the energy use costs for procuring virgin metals. Furthermore, losses to the economic system of iron and aluminum in particular have accumulated and will continue to accumulate substantially and in geographically predictable ways so as to facilitate possible "remining" of such lost metals from landfills and other places where metal residues might build up. Metal containers and other such items thrown away after use would either be nearly completely recycled or withdrawn from container use completely.

At any rate, this analysis suggests that iron and aluminum would have to be increasingly substituted for rarer metals for which metal stock losses would be economically unavoidable in the long run. A metals resource barrier would thus still materialize although in a more complex way than described earlier.

## VI. CONCLUSION

Beyond the sketchy description of possible economic and technological adjustments the economy would make when faced by metals resource barriers, this article cannot go. The proponents of an enforced "Steady State" economy<sup>15</sup> must feel that their case has been strengthened by the arguments presented above. Indeed, one must somewhat darkly conclude that failure to solve our energy problems will pull the metals resource barrier lower and bring it on sooner. In turn, a lowered metals barrier will help the energy ceiling reduce the volume of goods and services that can be made available. Finally, population increase can only insure that per-capita metals and energy availability must drop in the long run no matter how distant in time such natural resource barriers are.

Probably the U.S., and other developed economies, can take certain steps to ease the blow of such a future metals availability crisis without the immediate draconian production constraints proposed in the Club of Rome report, "The Limits to Growth."<sup>16</sup> While this article has been careful to point out that nearly full resort to recycling of metals is only a partial solution, the simple arithmetic of metals energy use costs shows that a large increase in virgin metals extraction and refining costs, expressed in energy terms, could be accommodated by high levels of recycling without a reduction in metals output. Clearly, it would be wise for governments to make sure that the true long-run benefits of recycling are adequately represented in private and public economic decision with respect to

metals use. As the author has argued in another article in this journal,<sup>17</sup> tax and subsidy policies to encourage recycling should be put into effect. Furthermore, research to stimulate the development of whole systems of recycling-oriented technologies should be greatly increased. For example, consumer goods should be designed such that retrieval of metal components and their reconversion into raw materials is done at minimum costs. While the market mechanism can be relied upon to bring about more recycling in the long run, our experience thus far with respect to the energy crisis ruefully shows how much a little governmental anticipation in the form of sufficient gasoline and automobile horsepower taxes could have helped matters.

Other solutions to the future metals supply crisis would involve vastly increased research into developing substitutes made from renewable resources and/or extremely common materials in the earth's crust. Again, since technological response to economic dislocation is not instantaneous, anticipation of future metals shortfalls would pay off greatly in terms of having a fund of technological alternatives for manufacturers to draw upon and further perfect when the time came. Finally, for the myriad uses of metal, for which no practicable substitute may be found, taxes on obviously wasteful methods of metals utilization such as oversize cars would be desirable. Perhaps there may actually be so many ways of combatting a possible future metals crisis as to prevent such resources from representing the ultimate constraint to economic growth, leaving that grim role to energy limits. Nevertheless, because of the extent to which metals and energy constraints are interrelated, it would be unwise to discount the disruptive potential of either.



#### FOOTNOTES

\*Assistant Professor of Economics, Brooklyn College of the City University of New York.

<sup>1</sup>Commercial reserves are those whose metal content is sufficiently high that they can be profitably utilized at current prices and current technologies of extraction and refining. If the price of the metal rises and/or technology improves, the definition of commercial reserves is extended to cover whatever known ore bodies there are of lower grade that as a result can be profitably exploited.

<sup>2</sup>Lovering, T.S., *Mineral Resources from the Land*, RESOURCES AND MAN, at 124, ed. by Preston Cloud, (San Francisco: Freeman, 1969).

<sup>3</sup>For iron and aluminum this ratio is of the order of six and four, respectively.

<sup>4</sup>Lovering, *supra* n. 2, at 116.

<sup>5</sup>This is perhaps a conservative assumption with regard to future virgin metals costs. Extracting an ore of one-half the present grade would double costs of ore removal per unit of metal produced, but might more than double the costs of refining in energy terms. Only some dramatic and perhaps unlikely breakthrough in terms of "leaching" metals from ores in place could vitiate the above assumption.

<sup>6</sup>For example, under this assumption copper ore of 0.2 per cent copper content would yield copper at an energy cost twice as high as that for copper from ores of 0.4 per cent in terms of energy used.

<sup>7</sup>For example, the Club of Rome study made calculations of the time taken to exhaust the world's metals supply by calculating the annual depletions of virgin metals projected into the future on the basis of average worldwide rates of growth, summing them, and determining after what year from the present: (1) currently known global reserves would be exhausted; (2) five times the known volumes of global reserves would be depleted. This pair of exponentially derived indices ranged from a low of 9 and 29 years respectively for gold to a high of 93 and 173 years of iron. *See*, Donella and D. Meadows, *et al.*, *THE LIMITS TO GROWTH*, at 56-60, Washington: Potomac Associates, 1972.

<sup>8</sup>National Association of Secondary Materials Industries, as quoted in *U.S. NEWS AND WORLD REPORT*, at 41, March 26, 1973. The percentages for iron, aluminum and zinc would be much higher, were it not for substantial availability of low cost foreign sources to discourage recycling. *See*, *FORTUNE*, at 111, October 1972.

<sup>9</sup>The generic distinction between stock variable and flow variable is being used here. Stock variables have an instantaneous time aspect; flow variables have a durational time dimension. Thus, the amount of lead in use in our economy at this moment is a stock concept; the amounts of lead extracted from virgin sources, recycled, and discarded annually are all flow concepts.

<sup>10</sup>*See* Table I.

<sup>11</sup>For example, if  $R_b = 0.95$ , and if the total metals-in-use stock is constant, then virgin metals extraction = losses, and  $R_a$  also equals 0.95.

<sup>12</sup>*See, infra*, Table II.

<sup>13</sup>*FORTUNE*, at 110, October 1972.

<sup>14</sup>It has been estimated that plant photosynthetic activity pro-

vides a net total of 164 billion tons of dry organic matter annually. This output represents the aggregate nutrient and biotic energy available to support all other biota, including man. See, Woodwell, G.M., *The Energy Cycle of the Biosphere*, SCIENTIFIC AMERICAN; THE BIOSPHERE, at 31, (San Francisco: Freeman, 1970).

<sup>15</sup>A "Steady State" economy is one in which zero economic growth has been realized.

<sup>16</sup>See, Donella and Meadows, *supra* n. 7.

<sup>17</sup>Carlsen, E., *The Economics of Recycling*, 2 ENVIRONMENTAL AFFAIRS 653 (Spring 1973).