The Universal Mining Machine

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The coal mine of Garzweiler, Germany, in a Google Earth image. The satellite has caught two giant mining machines at work. Measured with the google ruler, each "arm" of the machines measures about 120 m (ca. 400 ft). These are not universal mining machines, but give some idea of the scale of modern mining operations. The Garzweiler mine is said to hold more than a billion tons of coal reserves.

Introduction

In a science fiction story that I had in my hands, many years ago, a group of explores stranded on a remote planet needed to build a new spaceship using local materials. They had no time and no resources for traditional mining, so they built a "universal mining machine" that extracted elements from the planet's crust. The machine crushed rock, heated it and transformed it into an atomic plasma. The ions in the plasma were accelerated and then separated according to mass by a magnetic field. In input, you had just ordinary rock; at the output, you had all the elements present in the original rock, each neatly packed in its own box.

That story (I think it was by Poul Anderson) has always fascinated me. Why can't we build a machine like that here, on Earth, and stop worrying about running out of mineral resources? Some economists seem to think of depletion in these terms, indeed; as if they really had a universal mining machine ready. A favorite statement that you can hear on this subject is that there is no such thing as finite resources. Prices create resources depending on what you need. If prices are high enough, you can always make a profit even extracting from a very low grade ore.

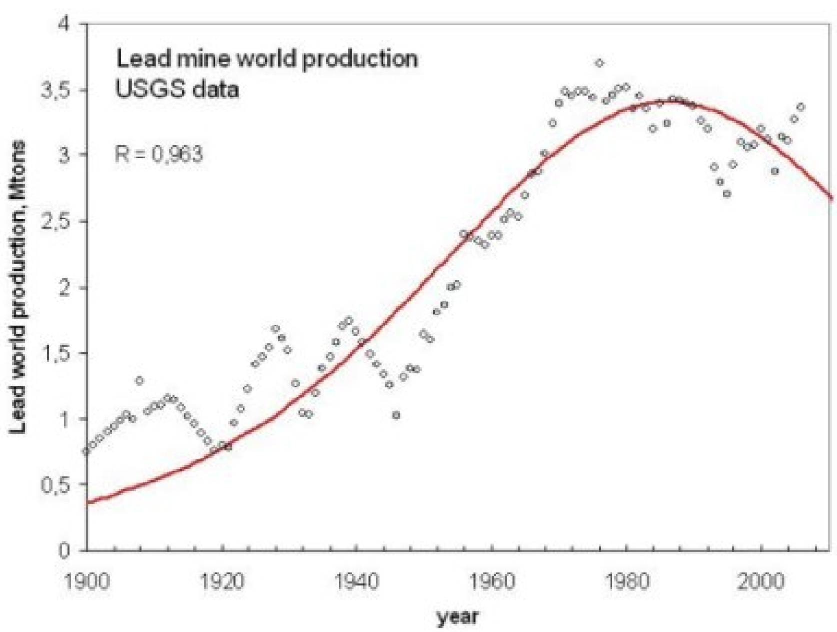
Since you can't run out of crust to mine, you'll never run out of anything or, at least, you'll see no problems for a long, long time. Julian Simon, author of the successful book “The Ultimate Resource” (1985), was perhaps the champion of this school of thought. Among other things, he said that we have mineral resources for “7 billions of years” (Simon 1995).

Recently, this kind of enthusiasm about the abundance of resources seems to have become less popular. However, the general opinion is still one of optimism, as shown in innumerable articles in the mainstream press whenever the question of depletion is taken up. Unfortunately, there are problems with the idea that non-physical entities, prices, can create physical entities, mineral resources. Prices are just tags, labels that you stick on something. If you need to extract and process something, it is not enough to change the label on it: you need *energy*.

Energy is the physical entity that defines what you can extract and what you can't. In a way, Simon and his followers are right in saying that the amount of mineral resources is not fixed. But the amount of extractable resources is defined not by prices but by the amount of energy you can afford to employ for extraction. And, unlike prices, energy is a limited resource.

In the future, the energy supply it may well go down as fossil fuels are gradually depleted. If we consider also the problem of the progressive depletion of high grade ores, it is clear that the extractive industry faces a a formidable challenge. How long can we keep on mining at the present levels? Will we be able to keep the industrial society working? Is there anything like "sustainable mining?"

These questions are difficult to answer but can’t be ignored any longer. Several recently published papers emphasize the finiteness of the resources and the likely problems that we will be soon facing (Gordon et al (2006), Ayres (2007), Pickard (2007), Cohen (2007)). In a recent work published on “The Oil Drum” Ugo Bardi and Marco Pagani (2007) have shown that the mineral production of several metals and compounds has peaked and is now declining. Other metal commodities show signs of impending peaks. All that, of course, is evidenced also by the increasing price trends of all mineral commodities in the past few years. Clearly, we are not talking of something far away in the future but of something that may be starting to occur right now.



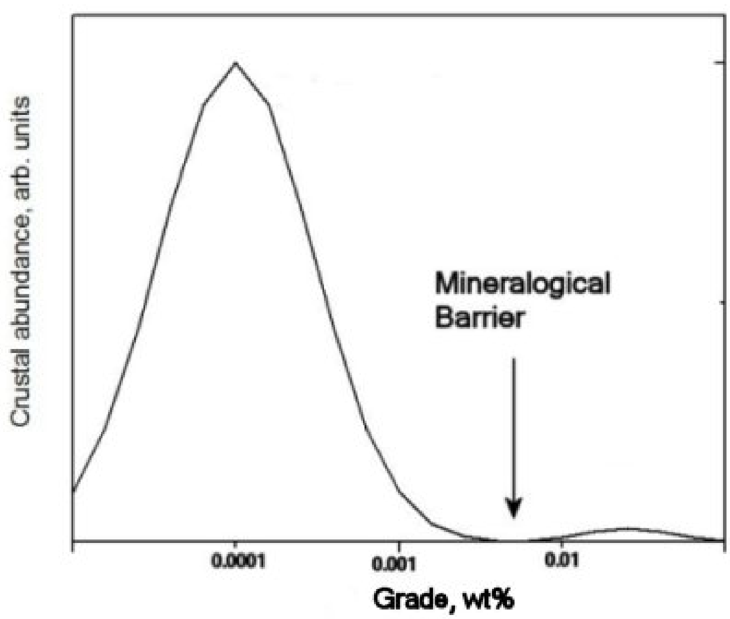
An example of the "bell shaped" production curve of some mineral resources, in this case, lead. From Bardi and Pagani 2007

Earth's mineral resources

The Earth's crust is said to contain 88 elements in concentrations that spread over at least seven orders of magnitude. Some elements are defined as “common,” with concentrations over 0.1% in weight. Of these, five are technologically important in metallic form: iron, aluminium, magnesium, silicon, and titanium. All the other metals exist in lower concentrations, sometimes much lower. Most metals of technological importance are defined as "rare" and exist mostly as low concentration substituents in ordinary rock, that is, dispersed at the atomic level in silicates and other oxides. The average crustal abundance of rare elements, such as copper, zinc, lead and others, is below 0.01% (100 ppm). Some, such as gold, platinum and rhodium, are very rare and exist in the crust as a few parts per billion or even less. However, most rare elements also form specific chemical compounds that can be found at relatively high concentrations in regions called "deposits". Those deposits from which we actually extract minerals are called "ores".

The total amount of mineral deposits in the crust is often described as inversely proportional to grade ("Lasky's law"). That is, low grade deposits are much more common than high grade ones and contain a much larger amount of materials. As a consequence, when the progressive depletions of high grade ores forces the mining industry to move to low grade ores, you have the counterintuitive effect that the amount of resources available increases ("you don't run out of resources, you run into them", as Odell said in 1994). This apparent abundance is one of the reasons for the great optimism of some people about the availability of minerals. Unfortunately, this abundance is an illusion for several reasons; one is that Lasky's law is not valid for the whole range of crustal concentration.

According to Brian Skinner (1976, 1979), the amount of a resource in Earth's crust is not simply inversely proportional to concentration. Rather, the distribution is "bimodal", that is there is one large peak for the element as a low concentration substituent and a smaller peak for the same element in deposits. The absence of concentrations in between the two peaks is what Skinner terms the "Mineralogical Barrier." The concept is shown in the following figure.



The concept of Skinner's "mineralogical barrier". The relative size of the two peaks is not to scale.

We don't have enough data for building Skinner's diagram to scale but, for a rough estimation of the different size of the two peaks, we can make a quick calculation for the case of copper. For the low concentration peak, we can consider that the average amount of copper in the upper crust is reported to be around 25 parts per million (Wikipedia 2007). Considering a land area of 150 million km2, and an average rock density of 2.6 g/cc, we can calculate something like ten trillion tons of copper available within one km depth from the surface. For the high concentration peak, we lack complete data, but we can consider that the USGS estimates the copper global land based resources as ca. 3 billion tons. The actual size of all the existing copper deposits is surely larger, but it should be not far from this order of magnitude. Therefore, the ratio in size of the two peaks is of at least of a factor one thousand.

There are exceptions to Skinner's model, uranium for instance seems not to have a double peak (Deffeyes 2005) and that may be related to the specific chemical characteristics of uranium ions. Then, of course, the common minerals, iron for instance, exist in high concentrations all over the crust and don't have a real mineralogical barrier. But the bimodal distribution is probably the general condition of practically all the rare metals.

Mining

Mining is a multi-stage process. The first is the extraction phase, in which ore materials are extracted from the ground. Then, there follows the beneficiation stage, where the useful minerals are separated from the waste (also called "gangue"). Further processing stages normally follow; for instance the production of metals requires a reduction stage and a refining one. All these stages require energy. To be exact, we should rather use the concept of "exergy" instead of energy, but in the context of mining the difference is marginal.

Let's make a practical example. Today, we extract copper from ores - mainly chalcopyrite, CuFeS2 - that contain it in concentrations of around 1%-2%. The energy involved in the extraction, processing and refining of copper metal is in the range 30-65 megajoules (MJ) per kilogram (Norgate 2007) with an average value of 50 MJ reported by Ayres (2007). Using the value of 50 MJ, we need about 0,75 exajoules (EJ) for the world’s copper production (15 million tons per year). This is about 0.2% of the world total yearly production of primary energy (400-450 EJ) (Lightfoot 2007).

The following table lists the specific energy needed for the production of some common metals, together with the total energy requirement for the present world production

Metal	Specific production energy MJ/kg	World production (Mtons/year)	Total energy used (EJ)
Steel	22	1100	24
Aluminium	211	33	6.963
Copper	48	15	0.72
Zinc	42	10	0.42
Nickel	160	1.4	0.224
lead	26	3	0.078

Specific and total energy of production for some metals. The data on the specific energy are from Norgate and Rankin (2002). Those on production are from the United States Geological Survey (USGS) for 2005.

Note how the world's production of steel alone requires an amount of energy (24 EJ) equivalent to about 5% of the total of the world's supply (ca. 450 EJ). Since making steel requires coal, this datum is in approximate agreement with the fact that 13% of the world's coal production goes for steel and that coal accounts for about 25% of the world's primary energy (source www.worldcoal.org).

Taken together, these data indicate that the total energy used by the mining and metal producing industry might be of the order of 10% of the total. This estimation seems to be consistent with that of Rabago et al (2001) who report a 4%-7% range and those of Goeller and Weinberg (1978) of 8.5% for the metal industry in the United States only.

Facing the mineralogical barrier

Over the history of mining, we have extracted minerals from high grade ores exploiting the energy provided for free by geochemical processes of the remote past (see De Wit 2005). Ores embed a lot of energy, either generated by the heat of Earth's core or by solar energy in combination with biological processes. The Earth is a geochemically live planet and the existence of ores and deposits is a consequence of that. But the processes that created ores are extremely rare and ores are a finite resource.

There is little hope to find high grade sources of minerals other than those we know already. The planet's crust has been thoroughly explored and digging deeper is not likely to help, since ores form mainly because of geochemical (especially hydrothermal) processes that operate near the surface. The oceans' bottom could be a source of minerals (Roma 2003) but so far not a single gram of anything has been extracted from there. The oceans themselves contain metal ions but in extremely minute concentrations. With the possible exception of uranium (Seko 2003), extracting minerals from seawater is out of question. For instance, all the copper dissolved in the oceans would last for just ten years of the present mine production (Sadiq 1992). Finally, there is the old science fiction of dream of mining the Moon and the asteroids. But, if our problem is energy, then we can't afford the energy cost of traveling there. Besides, the Moon and the asteroids are geochemically "dead" and contain no ores.

Therefore, as we keep mining, we have no choice but to move down progressively towards to low grade ores. In general, the energy required for extracting something from an ore is inversely proportional to the ore grade. That is, it takes ten times more energy to process an ore which contains the useful mineral in a ten times lower concentration (Skinner 1979). This relation holds for ores of the same composition which just change in grade.

We may also completely run out of a certain kind of ore and have to switch to ores of different chemical composition. That has already happened in the past, for instance for native metals. Iron, for instance, was once found in metallic form, ready to be forged, in the form of meteorites. That source has been completely exhausted as a mineral resource long ago. Switching ore normally involves an upward step in the amount of energy required.

Depending on the kind of product, the change in ore grade may have a large effect, or almost none, on the total energy requirement. Aluminium, for instance, is an extreme case in which extraction and beneficiation play a minor role (Norgate and Rankin, 2000). This is not surprising, considering that we extract aluminium from bauxite ores which contain it in a high concentration, about 30%-70% as aluminium oxide. The situation is different from most other metals, where ores usually contain a much smaller fraction of the useful element. Gold is an example in which almost the whole energy requirement is in extraction and beneficiation. Copper is an example of an intermediate situation where about 50% of the energy goes for extraction and beneficiation.

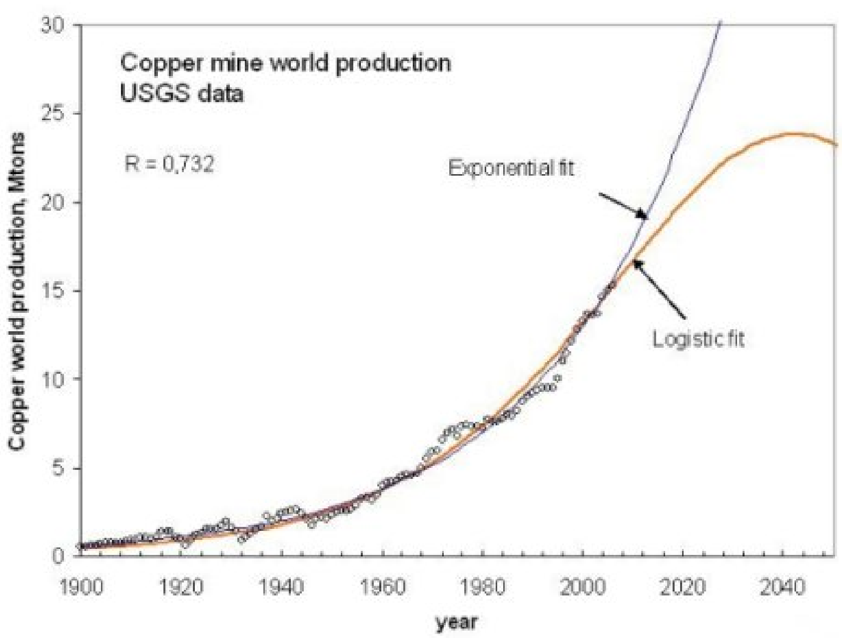
The depletion of high grade ores is a problem that, eventually, will lead us to face Skinner's mineralogical barrier. The amount of minerals on the "other side" of the barrier is huge. If we could manage to extract from this region of concentrations, we wouldn't have problems of depletion forever or at least for the "7 billion years" that Julian Simon mentioned. However, that would require an amount of energy well beyond our present capabilities.

Let's make an approximate calculation for evaluating this energy. Consider copper, again, as an example. Copper is present at concentrations of about 25 ppm in the upper crust (Wikipedia 2007). To extract copper from the undifferentiated crust, we would need to break down rock at the atomic level providing an amount of energy comparable to the energy of formation of the rock. On the average, we can take it as something of the order of 10 MJ/kg. From these data, we can estimate about 400 GJ/kg for the energy of extraction. Now, if we wanted to keep producing 15 million tons of copper per year, as we do nowadays, by extracting it from common rock, this calculation says that we would have to spend 20 times the current worldwide production of primary energy. Prices can't make common rock a source of rare metals any more than ghost shirts could make Indians invulnerable to bullets.

Of course, this is just a rough order of magnitude estimation. We may not need to really pulverize the rock at the atomic level and we may find areas of the crust which contain more copper than average. For instance, Skinner (1979) proposed that we could extract copper from a kind of clay named biotite and that would need a specific energy of extraction approximately ten times larger than the present requirements. If the problem were copper alone, that would be doable. But if we have to raise the energy requirement of a factor of ten for all the rare metals, clearly we rapidly run into levels that we cannot afford, at least at present.

The future of mining

In the short run, we don't seem to face critical problems in terms of ore supply, at least as long as we can keep our energy supply stable. Let's consider copper again as an example. The U.S. Geological Survey (USGS) estimates the world copper reserve base at 950 million tons (2007) (although Grassmann and Meyer (2003) report a lower value). If we could keep a steady extraction rate, we would have around 60 years of copper supply. Of course, the extraction rate has never been constant over the extractive history of copper. A more realistic model (Bardi and Pagani 2007) takes into account the growth and decline of the supply and sees the copper production peak in about 30 years from now.



a projection of the production rate of copper metal from mining. From Bardi and Pagani, 2007

30 years to peaking, or 60 years to total exhaustion, may look uncomfortably close, but it is not tomorrow. In many other cases, we don't seem to be close to total exhaustion (e.g. Cohen 2007). However, there are cases where depletion looks like a more pressing problem, such as for indium, a metal important for the electronics industry and that may be in short supply soon. Also, some metals may be facing serious depletion problems because of an increase in the demand. For instance, if we were to use fuel cells on a large scale for road transportation, the known reserves of platinum would be most likely insufficient for the catalytic electrodes. (Department of

Transport 2007)

These are serious problems, but are marginal in comparison to the real problem we have, which is also much more immediate. Ores, as we said, are defined in terms of the energy necessary for exploitation. To keep mining from the present ore supply, we need at least a constant supply of energy. But, in the near future, our energy supply may go down instead of up. Dwindling energy supply affects all the stages of production of mineral commodities, not just the extraction and beneficiation. That can have immediate and adverse effects on the production of mineral commodities.

Today, the energy used in extracting and processing minerals comes mainly from fossil fuels and, in some cases, it is directly dependent on liquid fuels produced from crude oil. For instance, it is reported (DOE 2007) that 34% of the energy involved in the US mining industry is in the form of diesel fuel. Fossil fuels are a mineral resource that has been heavily exploited in the past and they are undergoing rapid depletion and are expected to peak within a few decades at most. Peaking in the production of a mineral resource is a general phenomenon which is related to the increasing costs of prospection, extraction and processing as the resource becomes rare and more expensive. At present, crude oil is approaching its worldwide production peak ("peak oil") and is expected to start an irreversible productive decline in the coming years (see e.g. www.peakoil.net). The other two main fossil fuels, natural gas and coal, are expected to peak at a later time, but in the coming decades anyway.

We don't need to wait for the actual production peak to see a resource becoming more expensive both in terms of energy and in monetary terms. If it takes more energy to extract and refine oil, this extra investment in energy will directly affect the extraction processes that make use of oil as an energy source. So, if the present trend of decline in the production of fossil fuels continues, we won't be able to exploit all the mineral resources that exist on the "good" side of the mineralogical barrier. If nothing changes, in a not far future we are going to see a decline in the production of all mineral commodities: "peak minerals" (See Bardi and Pagani 2007). Peaking of minerals production poses a serious and immediate problem in terms of maintaining a supply of mineral commodities to the world's economy.

Mitigation strategies

How to react to the future decline of minerals production? There are two ways: either we stimulate or force mines to produce more, or we use more efficiently what we can still manage to produce. We can list a few more detailed strategies: 1) crossing the mineralogical barrier, 2) substituting, 3) recycling, 4) reusing, and 5) doing with less.

1. *Crossing the mineralogical barrier*. This strategy is equivalent to building - and fueling - a real universal mining machine and extract the minerals we need from the undifferentiated crust. That would solve the problem once for all and Julian Simon's dream (resources for 7 billion years) would become true. This kind of mining would be "sustainable", in the sense that it could last as long as we could provide the large amount of energy needed for it. The planet's surface would not look pretty after the passage of these giant lumbering monsters but, if we had enough energy for fueling them, we could probably afford to move the whole operation to space. Probably, nobody would complain for the ruined aesthetics of remote asteroids. However, as we saw, the energy requirements for such a technology are way above anything we can conceive for the near future. It would require a radical technological breakthrough in energy production, perhaps a new form of nuclear fusion technology. We can't dismiss this possibility, but we cannot count on it.

2. *Substitution*. Already in 1976, Brian Skinner had titled one of his papers “A second age of iron?”. He he meant that the future could see a general shift of industrial processes away from rare elements, towards common ones, such as iron. In the same year (1976), Goeller and Weinberg had examined the situation in a paper in which they had proposed what they had called "The principle of infinite substitutability." Their work is cited sometimes as the ultimate demolition of catastrophism. But they had correctly recognized that substitution requires profound changes in technology and society. Something that both Skinner and Goeller&Weinberg

had failed to state explicitly was that substitution requires energy, and often a lot of it.

Let's make a few examples of substitution in order to illustrate the energy problem. A classic one is that of replacing copper with aluminium as a conductive material. Aluminium is one of the common metals in the crust and using it in place of copper looks promising against the problem of ore depletion. Aluminum is a poorer conductor and it is flammable when it overheats but, with some precautions, it is possible to use it for almost all power carrying operations. The problem is that, as we saw, it takes 210 MJ/kg to produce metallic aluminum whereas it takes only around 50 MJ/kg to produce one kg of copper. Since our most pressing problem is energy, not ore grade, the idea of substituting copper with aluminum is a solution for the wrong problem.

Let's make another example. Suppose we have problems with chromium's availability. In this case, we are in trouble with the production of stainless steel, which contains chromium in relatively large amounts. For many structural applications that require strength and resistance to corrosion, stainless steel could be substituted with titanium (Goeller and Weinberg 1976). Unfortunately, titanium is a high melting point metal which requires large amounts of energy for its production. According to Norgate et al. (2007) we need 361 MJ/kg for the production of titanium metal, against just 75 MJ/kg for stainless steel. Again, the substitution strategy turns out to be power hungry.

A further example is mercury. Goeller and Weimberg take mercury as their paradigm of substitutability, since it has been nearly completely phased out from technological uses during the past decades. But it is also true that this substitution has required energy. We have no data for the energy needed to produce a kg of mercury, but probably it was not very large. In most cases, the substitutes required most likely more energy. Consider, for instance, that mercury in vacuum pumps has been substituted by synthetic oil that are manufactured from precursors made from crude oil. This kind of substitution required energy for the synthesis of the oil, as well as for the periodic replacement of the fluid that lasts less than mercury. This, and other kinds of substitution can hardly be defined as steps towards sustainability.

So, substitution is a strategy that can counteract ore depletion but at a high price in terms of energy. It is not as energy hungry as the universal mining machine, but the "universal substitution" of all the rare metals would require more energy than what we can reasonably assume to have in the near and medium term future.

3 . *Recycling* . If we could recycle at 100% efficiency, we would never run out of anything. However, the problem is the same as with conventional mining: recycling takes energy. It doesn’t need the huge amounts of energy that would be necessary for mining undifferentiated rock, nevertheless high efficiency recycling turns out to be very difficult for several reasons.

Managing wastes seems to be a typical example of our tendency of discounting the future at high rates (Hagens 2007). Waste is considered a nuisance rather than a stock of resources. If we don’t find that it is convenient to recycle something, we just dump it in a landfill or we burn it in an incinerator. In both cases, the result is that post-recovery is nearly impossible. In the case of incinerators, the finely dispersed ashes produced are a mix that would require extremely complex and expensive treatments in order to recover specific metals (Shen and Fossberg, 2003) and, at present, it is not done. For landfills, recovery might be easier, but still we dump together valuable metals and potentially toxic waste and that doesn't make recovery easy. At present, landfills are not exploited as sources of minerals at the industrial level although it is reported to be done in third world countries. That is possible, however, only at a high cost in terms of health hazards for of those engaged in the task.

The result is that we manage to recover only a fraction of what we throw away. According to the USGS (Papp 2005), in the United States the average recycling rate is of about 50% in weight for the principal metals produced. The maximum recycling rate is of 74% in the case of lead. Iron is recycled at about 50%; other common metals do less well: both copper and aluminium are not recycled at more than about 30%. Norgate and Rankin (2002) report different values, but the average level of recycling for most common metals remains of the order of 50%.

This is not enough for compensating the decline of mining. If we recycle something at 50% it means that after just 4 cycles of recovery we have lost more than 90% of the material we started with. We would need to do much better than that but, evidently, it is not easy and it would take a radical change in the way industrial production is conceived and managed. That, in turn, would require a degree of centralized planning that is unlikely to materialize until the shortage of materials becomes very serious. Again, it is our tendency of discounting the future at high rates (Hagens 2007)

4 . *Reuse* . Re-using means to produce long lasting products that can be repaired and/or refurbished. Reusing requires some energy, but probably less than any of the other strategies we have considered so far. As an example, we can think of making car bodies in stainless steel or in titanium. The energy required for making stainless steel (Norgate 2007) is about twice that needed for ordinary steel, while titanium would require about ten times as much. However, a car made in stainless steel or titanium would never rust and would last practically forever. Of course, this kind of strategy goes against the grain of everything that is normally thought as a successful strategy in the car business. Designing products in view of reusing them has never been popular and, in general, reuse smacks of poverty; not just with cars. It hard to imagine that with our limited ability of planning ahead (Hagens 2007) we could change our attitude. However, if a crisis of energy hits us, we'll be forced to use the products we have for longer times, with all the limits and problems involved. We might also have to reuse products for purposes they were not designed for. In Southern Europe or North Africa, you can find people who can make ashtrays out of soft drink cans. It is thought as a gadget for tourists, so far, but that might change in the future.

5. *Doing with less* , This is the easiest strategy; one that doesn't require energy at all. Simply, if you can't afford something, you don't use it. It also doesn't require any government intervention. With less energy and less materials available, you may discover that you can't afford a SUV for everyday commuting. So, you may switch to a subcompact. Even better, you can switch to a bicycle; or you may walk. Eventually, you may be able to commute at all. There is a lot of useless fat that society can shed and still function in a way that is recognizable to us. The problem is that, while shedding this and that, society may enter a deadly downward spiral that gradually destroys the world's industrial base. The process may lead us back to where we started before the industrial revolution: to a low population agrarian society with a low energy surplus. Such a society could not maintain the technological level that we have reached.

Interestingly, our farming descendants wouldn’t need to go back to flint knapping. Recovering just a fraction of the more than 50 billion tons of iron that we have produced in the past centuries, they would have have plenty of supply for all their conceivable needs. Just think that at the time of Napoleon, when the industrial revolution had already started, the whole world production of iron and steel was less than a million tons per year, about one thousandth of what it is today. With the scraps recovered from our smelting work, our low tech descendants could go on happily forging swords and ploughs (and perhaps even muskets and cannons) for many thousands of years. The metal leftovers from our civilization would also provide them with thousands of years of supplies of other metals, at least of the kind that can be smelted or forged in a charcoal furnace. That excludes titanium and some exotic metals, but leaves all the rest. Think that our society has produced so much copper metal that an amount of about 200 kg per person is still around in the industrialized world (Gordon 2006). With so much copper, our agrarian descendants would have plenty of bronze for pots and pans and for spectacular pieces of statuary as well. They would even have aluminium; something that our pre-industrial ancestors couldn’t even dream of.

Conclusion and perspectives

Our civilization has deeply changed the chemical composition of the upper crust of the Earth. Elemental deposits that were formed in hundred of thousands of years of geochemical processing (Shen 1997) have been removed, transformed, and in large part dispersed. Hundreds of thousands of years (at least) will be needed to reform these deposits, and times at least of the same order of magnitude will be required for restocking the planet with oil and natural gas. Some minerals, such as coal, have been formed in specific conditions in the remote past and may never reform again in the future in the amounts that existed before we started extraction.

We inherit from past generations a planet that is very different from what it was before the industrial revolution. The cheap and abundant minerals that our ancestors have used to build the industrial society are no more. If we want to keep going along the industrial path, we'll need to develop new strategies to insure a sufficient supply of materials. That will depend mostly on energy. It will be our capability of producing energy that will determine the future choices of society.

If we'll succeed in increasing the energy supply, then substitution can compensate for the decline in ore grade and, if we really can manage to have plenty of energy, we may put into practice the dream of an infinite supply of minerals by mining the asteroids using a universal mining machine. However, such a scenario doesn't look very likely.

It is much more probable that, in the future, we will not be able to compensate the dwindling supply of fossil fuels with nuclear or renewable energy. This will lead to an overall reduction of the world energy supply and, coupled with the gradually depletion of high grade ores, a reduction of the availability of all mineral commodities. The reaction to this situation will be a combination of low energy strategies: recycling, reusing, and doing with less.

In the worst case hypothesis, considering also the likely damage deriving from climate change, the crisis could be so bad that it may push us back to an agrarian society. With the scraps left by our civilization, it would be a metal rich kind of agrarian society, but still a low technology one. Could it ever restart with a new industrial revolution? It is difficult to say. The industrial revolution that we know was strictly linked with the availability of cheap coal and that is gone forever after we burned it. It is hard to run Satanic mills with wood charcoal only; forests tend to run out too fast. Perhaps there will be only one industrial revolution in the history of mankind.

In between these two extremes, mining the asteroids and returning to subsistence agriculture, it is perfectly possible to imagine intermediate scenarios. We may conceive a society that keeps a supply of energy smaller, but not much smaller, than the present one and that manages to use it to keep a reduced, but non zero, supply of minerals. It would have to be extremely careful to avoid wasting materials and it would see some of our habits - air travel, for instance - as dangerous extravagances. It would have to recycle and reuse at a level that would appear difficult to conceive for us. In some ways, the attitude of that society would compare to that of the thrifty world of Japan of the Edo period (JSN 2003). Such a society could maintain our technological level and improve it. It could manage the planet's climate and, perhaps, remedy the damage that we have done to it. It can still engage in the exploration of space, in fundamental research, in the development of artificial intelligence and other cultural and human pursuits that can't be conceived without a healthy surplus of energy and materials.

If we'll ever arrive to such a society, it is difficult to say. We would need to start planning for it already now, but our capability of long term planning is very limited (Hagens 2007). At least, from this discussion, we can say that our immediate concern should not be just energy but also the availability of basic materials for industry.

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References

Ayres, R. 2007, Ecological Economics vol. 61, p. 115 – 128

Bardi, U. and Pagani M. 2007, “Peak Minerals”, The Oil Drum, http://europe.theoildrum.com/node/3086

Cohen, D., 2007 “Earth's natural wealth: an audit”, From issue 2605 of New Scientist magazine, 23 May 2007, page 34-41. http://www.science.org.au/nova/newscientist/027ns_005.htm

Commonwealth Government Initiative, 2000, “Industry, Science and Resources Energy Efficiency Best Practice Program” http://www.industry.gov.au/assets/documents/itrinternet/aluminiumsummary...

Deffeyes, K., 2005 “Beyond Oil”, Hill and Wang ed., New York

Department of transport, 2007 (accessed) "Platinum and hydrogen for fuel cell vehicles" http://www.dft.gov.uk/pgr/roads/environment/research/cqvcf/platinumandhy...

De Wit, M. 2005, "Valuing copper mined from ore deposits"
Ecological Economics, vol. 55 pp. 437– 443

DOE, Department of Energy, 2007 "Mining Energy Bandwidth Analysis Process and Technology Scope
http://www1.eere.energy.gov/industry/mining/pdfs/mining_bandwidth.pdf

Goeller, H.E. Weinberg, (1976)"The Age of Substitutability" The American Economic Review, Vol. 68, No. 6. pp. 1-11.

Gordon R. B., Bertram M., and Graedel T. E., 2006, “Metal stocks and sustainability”, Proceedings of the national academy of sciences, PNAS, January 31, vol. 103, no. 5, pp. 1209–1214

Hagens, N. 2007, “Climate Change, Sabre Tooth Tigers and Devaluing the Future”, http://www.aspo-ireland.org/index.cfm?page=speakerArticles&rbId=8

JSN - Japan for Sustainability newsletter, 2003 http://www.japanfs.org/en/newsletter/200303-1.html

Lightfoot, H.D., 2007, "Understand the three different scales for measuring primary energy and avoid errors", Energy vol 32 pp. 1478–1483

McNulty, 1994, http://www.goldfever.com/gold_sea.htm

Meyer, F. M. & Grassmann, J. (2003) Erzmetall 56, 349–355.

Norgate T. E. and Rankin W.J., 2000 "Greenhouse gas emissions from aluminium production – a life cycle approach", CSIRO paper, www.minerals.csiro.au/sd/CSIRO_Paper_LCA_Al.htm

Norgate. T.E. 2001 "A comparative life cycle assessment of copper production processes", CSiro Minerals Reports DMR 1768
http://www.intec.com.au/docs/media/2001%20Oct-CSIRO%20Life%20Cycle%20Ana...

Norgate, T., Rankin, J., 2002 "Tops at Recycling, Metals in sustainable development", CSIRO sustainability papers, http://www.bml.csiro.au/susnetnl/netwl30E.pdf

Norgate T.E., Jahanshahi, S. Rankin W.J. 2007,"Assessing the environmental impact of metal production processes" Journal of Cleaner Production vol 15 pp 838-848

Odell, P.R., 1994, World oil resources, reserves and production. The Energy Journal (IAEE) 15 Special Issue, pp. 89–113.

Pickard, W.F., Geochemical constraints on sustainable development: Can an advanced global economy achieve long-term stability?
Global and Planetary Change (2007),

Roma, P. 2003, “Resources of the sea floor”Science 31 January 2003Vol. 299. no. 5607, pp. 673 – 674

Seko, N. Katakai, A. Hasegawa, S., Tamada, M., Kasai, N., Takeda, H., Sugo, T., Saito, K., 2003 "Aquaculture of Uranium in Seawater by a Fabric-Adsorbent Submerged System" Nuclear Energy Volume 144, Number 2 Pages 274-278

Skinner, Brian J. 1976. "A Second Iron Age Ahead?"American Scientist, vol. 64 (May-June issue), pp. 258-269.

Skinner, B. 1979, Proc. Natl. Acad. Sci. USA Vol. 76, No. 9, pp. 4212-4217

Simon, J., 1985, http://www.juliansimon.com/writings/Ultimate_Resource/

Simon, J, 1995, The State of Humanity: Steadily Improving
Cato Policy Report, http://www.cato.org/pubs/policy_report/pr-so-js.html

United States Geological Survey (USGS). Mineral commodities information, minerals.usgs.gov/minerals/pubs/commodity/

Papp, J.F. 2005 "Recycling Metals", United States Geological report http://minerals.usgs.gov/minerals/pubs/commodity/recycle/recycmyb05.pdf

Rábago, K.R., Lovins A.B., Feiler T.E., 2001 "Energy and Sustainable Development in the Mining and Minerals Industries", IIED report, http://www.iied.org/mmsd/mmsd_pdfs/041_rabago.pdf

Sadiq, M. 1992 "Toxic Metal Chemistry in Marine Environments" Taylor & Francis, ISBN: 0824786475,

Shen, H. Fossberg, E. 2003 "An overview of recovery of metals from slags" Waste Management Volume 23, Issue 10,Pages 933-949

Stein, H.J., Cathles, L.M., 1997 "The Timing and Duration of Hydrothermal Events" Bulletin of the Society of Economic Geologists Volume 92 November-December Number 7/8 pp. 763-765, http://www.segweb.org/eg/papers/DurationPreface.htm

Wikipedia, 2007 (accessed) "Abundance of the elements" http://en.wikipedia.org/wiki/Abundances_of_the_elements_%28data_page%29