

# Metals scarcity: A sobering perspective

## Part I: Our predicament

*Delft University of Technology, Faculty Industrial Design Engineering,  
The Netherlands, December 2, 2009*

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**The core message is included in slide 22 and accompanying text.**



Slide 1

Scarcity is of course something of all times. A prominent difference with the past however is the global scale of our current predicament. From the perspective shown here, Earth is just one giant Easter Island.

“The free market will solve it”, not to worry?



2 Metals scarcity: A sobering perspective; Part I: Our predicament

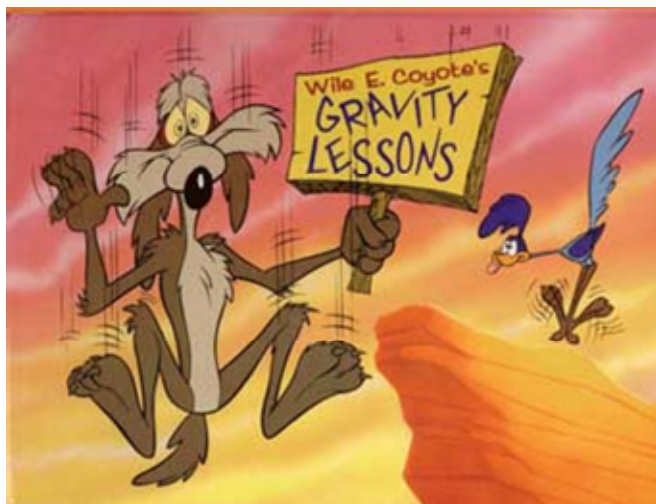
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## Slide 2

The free market has given us tremendous benefits, but it is by no means a cure for all trouble (witness e.g. the current financial crisis). Moreover, financial products are human abstractions without physical limits, whereas raw materials and the products and services built on these raw materials do have physical limits.

Is unlimited growth possible?



3 Metals scarcity: A sobering perspective; Part I: Our predicament

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## Slide 3

The law of gravity is quite obvious. But the second law of thermodynamics is less obvious and is being violated frequently in proposals and schemes to enable continued growth in energy and materials consumption. That 2<sup>nd</sup> law means amongst others that energy conversions will always be accompanied by losses. It takes energy to concentrate energy and if the rate and scale of energy consumption continue to be kept well above ambient levels, we'll soon hit physical limits.

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  - Primary production of metals will decrease globally, preliminary estimate of timing and sequence
- **Consequences of metals scarcity**
  - Forget painless transition towards sustainable economy
  - Bottleneck dead ahead
  - Will technology save us?
- **Solution framework with intrinsic value (preview to Part II)**
  - Amongst others the **Elements of Hope**

4

Metals scarcity: A sobering perspective; Part I: Our predicament

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### Slide 4

This presentation (Part I) can be quite alarming to the unprepared mind and could serve as a wake-up call for the many unaware, but is in no way meant to invite pessimism or defeatism. Part II of this presentation will explore meaningful actions to (try to partially) adapt to a world which is less affluent with energy and metals.

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5

Metals scarcity: A sobering perspective; Part I: Our predicament

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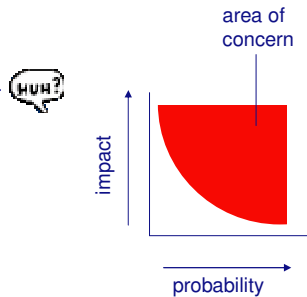


### Slide 5

Awareness at the level of business and government can be raised by approaching metals scarcity (and scarcity in general) as a matter of risk assessment.

## Way ahead: which decisions to take?

- Reality too complex to fully understand
  - inherent limitations on predictability of the future
  - keep wide safety margin
  - allow for “black swans”
- Multiple futures or opposite scenario's
  - which options have intrinsic values either way (least regret options)?
  - which options “hedge” against risks (probability x impact)?



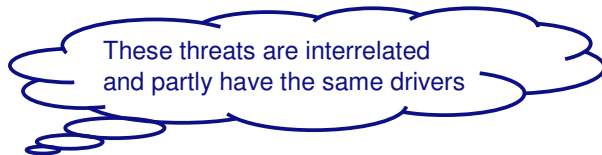
### Slide 6

A helpful way of evaluating what decisions best to take is to draw a roadmap. In part II I'll propose a preliminary (and very incomplete) roadmap which gives specific measures of performance to be realized within a specific timeframe in order to stimulate discussion. The roadmap can be based on multiple futures scenario planning which is not so much about predicting the future (which is virtually impossible) but about making the correct choices today to reduce risks. The best choices to be identified are the so-called “least-regret” choices which work both ways (in the worst- and best-case scenarios) as these choices have intrinsic value.

## Balance between F.E.A.R. (Fake Evidence Appearing Real) and Blind Optimism

### Threats:

- Energy crisis
- Financial crisis (if energy can't grow, debt can't grow)
- Resource crisis (including metals, water, agricultural products)
- Natural disasters, environmental degradation and climate change
- Armed conflicts and war (including cyber warfare)
- Political instability and extremism
- Pandemics
- .....



### Slide 7

Risk assessment has to strike a balance between fear (called sometimes Fake Evidence Appearing Real) and blind, unfounded optimism. What are the main threats to our civilization, urging us to make a transition towards sustainability? These are the interrelated crises of energy, finance, resources, natural disasters (together with environmental degradation and climate change), armed conflicts & war (including cyber warfare) and pandemics. I probably forgot a few ;).

These threats partly have the same drivers like population growth and consumption growth. Earlier this year, the IMF (within the context of the current financial crisis) stated that a “healthy” world economy should grow by 3% or more annually. Sustained growth of 3% per year means a doubling time of consumption every 24 years. Compare this with the average growth of China’s economy during the last 15 years and associated growth in metals consumption: 10% or more per year, meaning a doubling time of 7 years (or shorter). How long do you think this is going to last without problems? What do you think of the likelihood of the global economy resuming and then maintaining an average annual growth rate of at least 3%?

What is the estimated timing of these events, so what’s the urgency? See the following slide:

## Big Trouble ahead

- **Energy scarcity: coming decade**  
peak regular oil: right now, peak all fossil fuels  $\pm 2020$ ?
- **Financial crisis: right now**  
no return to “business as usual”?
- **Metal minerals scarcity: coming decade**  
driven by energy scarcity
- **Scarcity of water and agricultural products: increasing**  
**scary in the long term**
- **Environmental degradation: right now**
- **Armed conflicts and war: increasing**  
man's natural tendency to compete for scarce resources
- **Political instability and extremism: coming decade?**  
demographic time bombs in Middle East and Northern Africa, populism in Western World
- **Pandemics, (accelerating) climate change, World War III**  
probability? impact? **possibly far-reaching consequences**

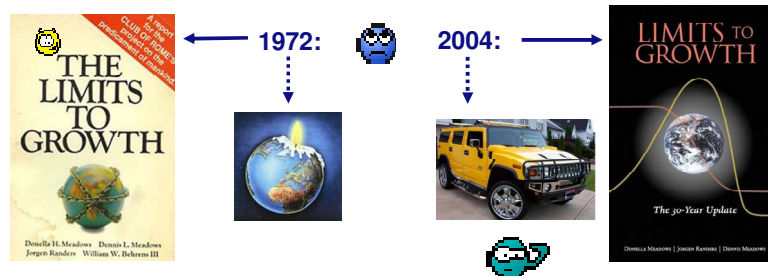


### Slide 8

Metals scarcity, the subject of the remainder of this presentation, is only one of several major challenges coming our way. The most pressing problem in the longer run will probably be water and food scarcity: you could make a living with (much) less energy and (much) less metals, but we can't survive without water and food. Many scarcity problems could be dwarfed by the potentially very disruptive effects of pandemics, climate change or global war, but we'll face already enough challenges without this category.

## Too late to prevent painless transition

Weren't we warned ?!



Inertia is not just a law of physics

“Hope for the best, prepare for the rest”

Not so much crisis prevention but crisis management

### Slide 9

We have wasted valuable time and lost a valuable opportunity of meaningful actions some 30 years ago. People like Jimmy Carter apparently were too far ahead of the crowd, just as the authors of Limits to Growth.

Military wisdom is partly applicable to society as a whole, e.g. “better safe than sorry” or “hope for the best, prepare for the rest”. Do we wait until we have 100% proof of trouble with no fall-back strategy at that moment in time? Will we start constructing a fire engine for a yet-to-be-established fire brigade only until some major fire breaks out in town?

It is important to understand that we are already in overshoot (like Wile E. Coyote in slide 3), it's too late for crisis prevention. It's never too late though for proper actions. That doesn't mean that our current predicament is a “problem” with a “solution”, it's more a collection of dilemmas, but nevertheless it's much better to strive for improvements, if only to mitigate part of the effects.

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10

Metals scarcity: A sobering perspective; Part I: Our predicament

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### Slide 10

Metals scarcity is strongly linked with energy scarcity (some people call mining “a way of converting energy into metals”).

To make a distinction between the word “mineral” and the word “metal”, I would like the example of the metal aluminium which is being concentrated from the mineral bauxite (which contains aluminium oxide).

## Resource scarcity

- Resources can indeed get scarce within a **problematic short timeframe**
- Of course elements don't disappear, but what does disappear at an accelerating rate are the producible higher **concentrations**
- Conventional measures neglect the required **timeliness** in combination with the required **scale**

11

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### Slide 11

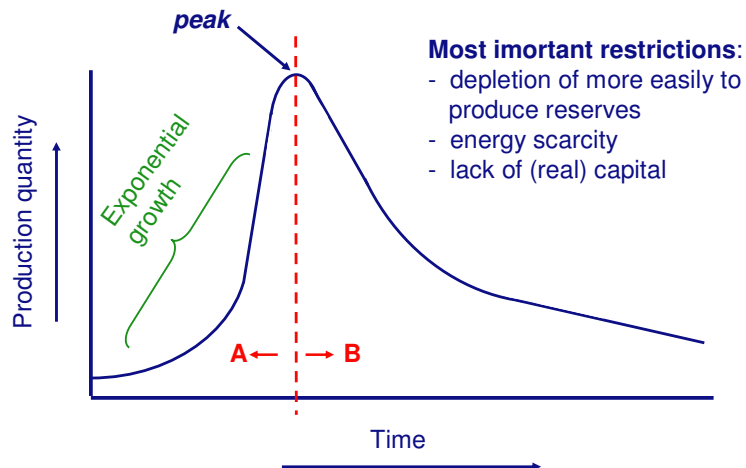
The first bullet is not obvious and will be explained further on. The lack of time is also a dominant factor with other scarcities and their associated transitions.

The second bullet will be explained in further detail.

Third bullet: timelines and ability to scale are amongst the most important benchmarks to evaluate the feasibility of proposed solutions.



## What matters is production **rate**



### Slide 12

What is meant by peak production?

After a period of accelerated production growth the law of the diminishing returns sets in, after which a (small or broad) plateau is reached where production can no longer grow. The graph illustrates this and the top of the graph is called the production peak. It's quite possible that more production will take place after the peak (part B of the graph) than before the peak (part A of the graph), but the maximum production in a given year is much more important than the stuff left under the ground for future production.

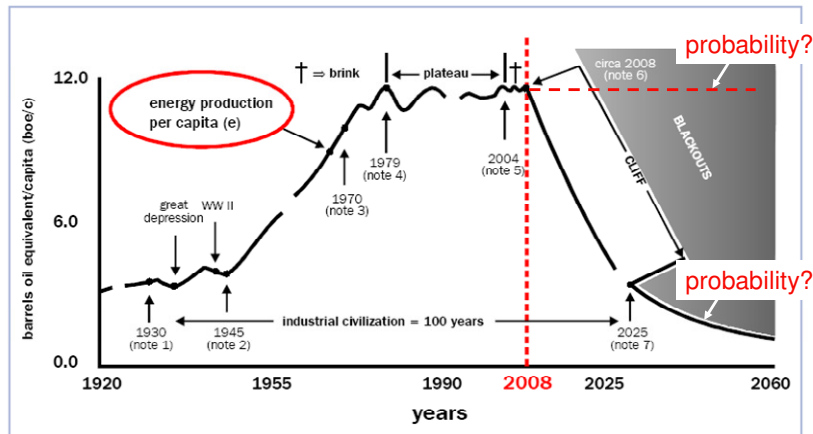
I would like to lend a phrase from the peak oil community and apply it to mineral resources as well: it's not the size of the well that matters but the size of the tap.

In reality a production profile will of course have ups and downs superimposed on the smooth curve shown here, but this is the common (simplified) picture.

You can already have scarcity (defined as demand exceeding supply) in part A of the curve. I will give examples with slide 22.

The most important factors determining this styled production curve are the depletion of the more easily to produce reserves (the "low hanging fruit", see also slides 15 and 16), energy scarcity (slide 13) and lack of real purchasing power (as opposed to pseudo purchasing power). People who want to understand the meaning of pseudo purchasing power are invited to google the words fractional reserve banking and fiat currency. Money is a paper promise for future products and services. Where do you think the "real" value of money is heading to in a world with increasing amounts of (mostly digital, abstract) money, while supply of products and services based on primary, physical goods (like energy and metals) is not able to keep up with the money supply?

## Decreasing energy production per capita



Source: The Olduvai Theory, Richard C. Duncan, 1989 and 2006

13

Metals scarcity: A sobering perspective; Part I: Our predicament

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### Slide 13

If we look at history (left of the vertical dotted red line) we see that the energy production relative to the global population hasn't been able to grow for quite some time. During the 30 years of this "plateau", global energy production has grown but so has global population. And the world's population will continue to grow for a while. What's the probability of continuation of this plateau for years to come (horizontal red dotted line)? What's the probability of a steep decline in energy per capita according to the black line? For the coming decades, reality will probably lie somewhere inbetween these lines, meaning a declining energy availability per capita. This graph is pretty scary if you think about its implications. It's even worse than a zero sum game: even zero growth at one part of the globe will inevitable cause shrinkage at another part of the globe.

This wouldn't have to be such a big issue if we would have a less energy intensive economy, but we are still far away from that.

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14

Metals scarcity: A sobering perspective; Part I: Our predicament

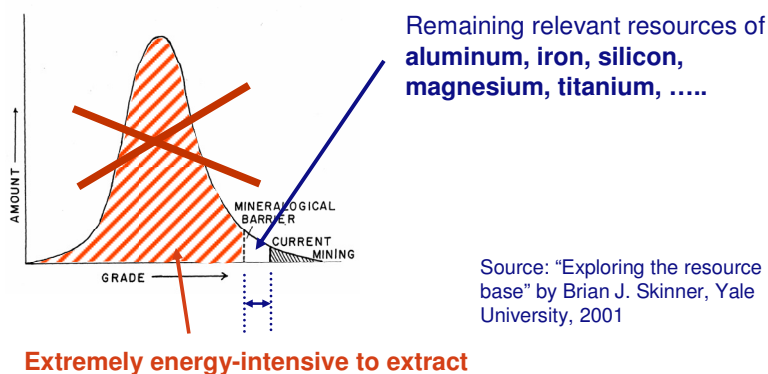
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### Slide 14

There are some striking similarities between energy production curves and metal minerals production curves, but also a number of distinct differences. An important difference is the likelihood of a much more asymmetric production profile compared to fossil fuels, resulting in a long fat tail after the production peak.

Mineralogical barrier for elements  $\geq 0.1\%$   
(mass) earth's crust



15

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### Slide 15

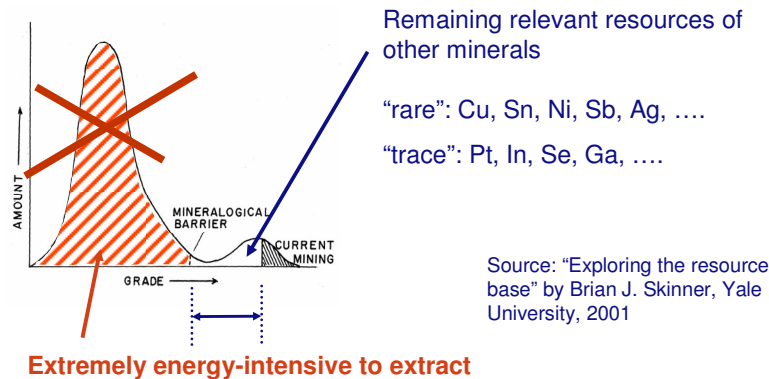
In an energy constrained world the vast majority of resources is out of reach and it is becoming increasingly more difficult to sustain or even grow current production rates of metals.

The absolute amounts of various metal minerals in the earth's crust are large beyond imagination, but the bulk of it might as well not be there because it's out of reach because of the required energy involved in extraction. Most of the minerals occur in practically useless

low concentrations: below the so-called mineralogical barrier (a certain low ore grade), essentially you should pull the source material (e.g. a piece of rock) chemically apart to extract the individual metals.

Again I would like to use the saying “it’s not the size of the well that matters but the size of the tap”. About a quarter of the earth’s crust consists of silicon, yet we are already short (for years) on pure enough silicon to make high efficiency solar cells. Of course we can purify the less favourable sources of silicon (as we indeed do), but this takes (lots of) energy.

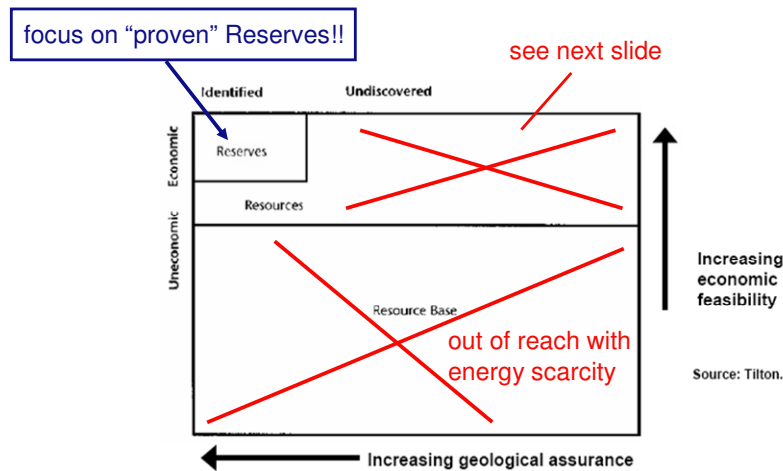
### Mineralogical barrier for elements < 0.1% (mass) earth’s crust



#### Slide 16

This graph might be valid for all non-abundant metal minerals and it shows that the situation here might be even less favourable than with the more abundant metal minerals because there’s a dip in the graph at lower ore grades. This may aggravate metal minerals scarcity.

## “Reserves” will not continue to be replenished



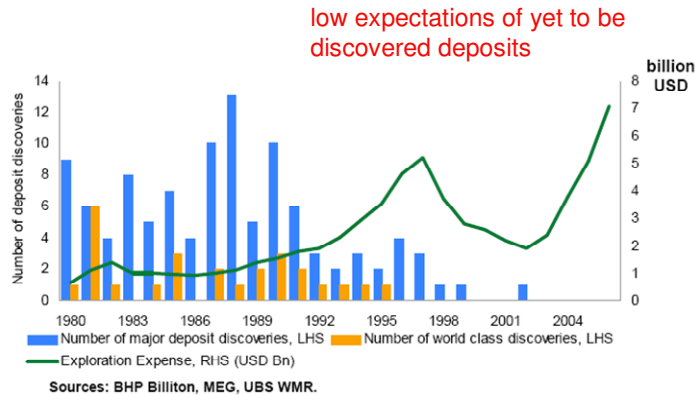
### Slide 17

A typical critique on stating that we are running into metals scarcity is the notion that the free market (the laws of demand and supply) will upgrade parts of the resources or the resource base into reserves once reserves start to get tight. This has been the case for decades when there was cheap and abundant energy available. However with energy scarcity, the big lower part of the graph on slide 17 is out of reach (red crossed lines at the bottom). We should also let go of the notion that vast amounts of rich ore deposits lie waiting somewhere to be discovered (red crossed lines at the top), see slide 18.

So we should focus on reserves and not on the huge amounts of resources and the vast resource base. Of course there are many cases to be made to argue that the boundaries of the reserves may be stretched in favour of larger quantities; however there are as many cases to be made to argue that with an energy crisis not even the currently stated reserves remain within our reach to be exploited.

More importantly, what is often overlooked is the decrease in quality of reserves. Again a typical critique is that the reserves to production rates of most metals have remained more or less constant during the last decades. However, not only the quantity but also the quality should be taken into consideration. Many reserves today are much harder to produce than reserves a couple of decades ago. Extremely put: would you prefer a rich open pit deposit near your processing factories or a low ore grade deposit buried deep beneath rock and soil in a remote and inhospitable area? The extractable quantities of metals could be the same in both cases (“the same reserves” in quantity), but at different energy consumption (and other consumables) and at different investment cost.

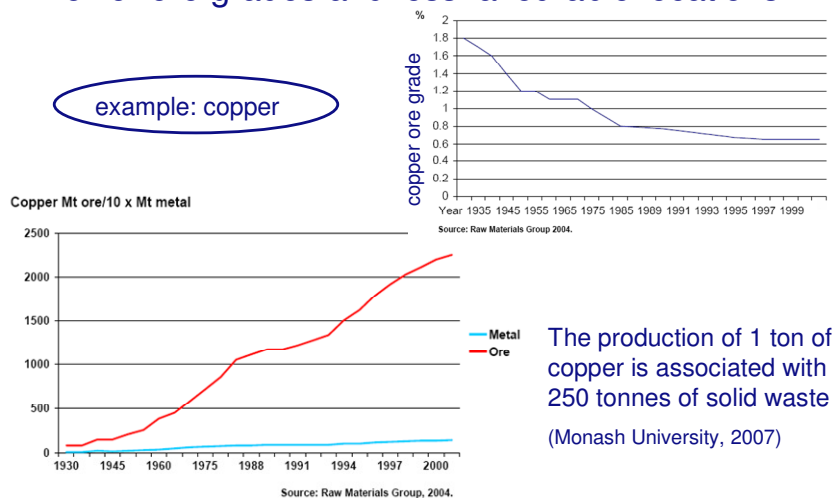
## Discovery rate of major mineral deposits



### Slide 18

In analogy with scarcity of conventional oil: it's unlikely that we will find another "Saudi-Arabia" or another "North Sea" of rich mineral deposits.

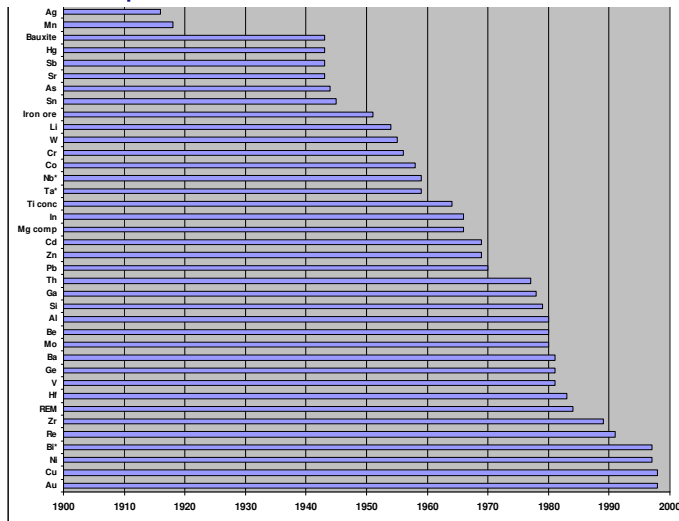
## Decreasing quality of reserves: lower ore grades and less favourable locations



### Slide 19

A typical critique on stating that we are running into metals scarcity is the notion that "you will find 300 times more ore as you lower the ore grade with a factor of 10". This misses the point that you need much more energy to keep extracting the same amount of metal. Lower ore grades increase energy expenditures because of the increasing amounts of solids which have to be processed to keep up the production rate of concentrated metal. But even when the ore grade is more or less stable (example: copper over the last few decades), you still need increasingly more energy to extract the same amount of copper because you have to go to more remote locations (often at less favourable conditions) and dig deeper to get to the ores.

## In the USA primary production of most metals peaked before the 1980s



Source: Chris Clugston, "Continuously less and less", October 2009

20

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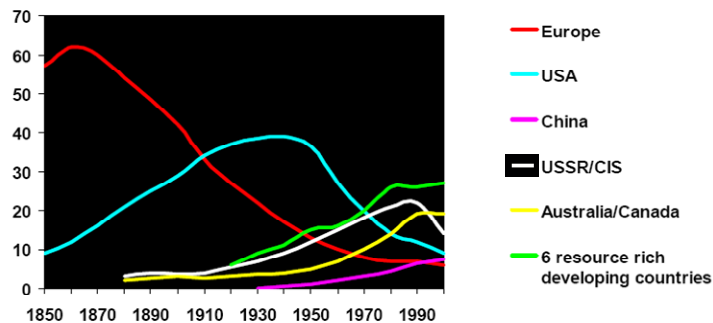


### Slide 20

The United States of America, in fact half a continent in size, have had their peak in primary production of most metals some 30 years ago (primary production is production from ores and excludes recycling). These include not only silver (1916) but also widely applied metals like manganese and zinc. This does not mean of course that you couldn't mine and produce manganese and zinc anymore in the USA, but it means that it's partly not worthwhile anymore to do this in the USA. A similar picture of peak production, in another order and timing than shown here for the USA, will manifest itself globally.

## Europe and the US have already depleted a significant part of their accessible resources

% of global mining



Sources: Raw Materials Data, Stockholm 2004, Sames, Raw Materials Group

21

Metals scarcity: A sobering perspective; Part I: Our predicament

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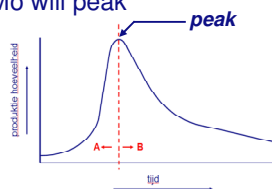
### Slide 21

As with oil and gas, global (or average) metals scarcity will be preceded by spot shortages due to the non-linear distribution and non-linear depletion of metal mineral resources across the globe. The industrial revolution started in Europe and later the US became an industrial giant,

so it comes as no big surprise that both Europe and the US have depleted a large part of their accessible resources. Metals are obtaining geopolitical meaning, as fossils fuels already do have, and can and will be used as a means of power politics.

## Globally, primary production of most metals possibly peaks before $\pm 2025$

- Already scarce:
  - silver and gold (“canary in coalmine”)
- A large number of metals required for the “green revolution”:
  - the platinum group (Pt, Pd, Rh, Ru, Ir, Os)
  - Most of the rare earth metals (La, Nd, Sm, Tb, ...)
  - various metals which are being produced as by-products in low quantities: Ga, Ge, In, Te, ...
- Next: tin, zinc and lead + As, Ba, Bi, Cd, Li, Nb, Sb, Ta, W, Zr, ...
- When copper and nickel peak, also Co en Mo will peak (possibly before  $\pm 2035$ )
- Non-linear distribution across the globe  $\rightarrow$  **regional shortages well before global shortages!**



### Slide 22

The peak in primary production of most metals may be reached no later than halfway the 2020s. According to my personal opinion it may be much sooner, around a decade or so sooner, meaning that most metals will have a primary production profile (see right bottom corner of this slide) with a longer and fatter tail than would be the case with a later peak. This will be caused by (amongst others) the ongoing depletion of the more easily to be exploited metal mineral reserves, (approaching and reaching) peak energy production and a lack of sufficient real capital to satisfy increasing investment requirements to grow or just maintain global primary production of metals.

**I would like to emphasize (to prevent being misinterpreted) that we are not running out of metals in 2015 or in 2025, quite the contrary: humankind will produce more metals than ever before in the near to mid-term future. But primary production of most metals will probably no longer be able to grow a half or one-and-a-half decade from now and will decline after that.** We will still be producing metals in the long term (especially common metals like iron and aluminium), but mostly no longer in the quantities we have grown accustomed to.

Precious metals like silver and gold are already scarce right now (scarce meaning that demand exceeds supply). Gold is the proverbial canary in the coalmine in this respect: we are going to great lengths to produce gold, we process on average 200,000 tons of solids to concentrate 1 ton of gold. Despite demand for gold being much larger than supply, primary production couldn't grow for almost a decade now.

Good examples of metals becoming scarce despite not yet having reached or surpassed peak production (production still in part A of the graph at the right bottom corner of this slide) are various metals which are necessary for the “green revolution”, i.e. the transition towards a more sustainable economy. These include the platinum group metals, most of the rare earth metals (the rare earth metals are all 15 lanthanides plus yttrium plus scandium) and various minor metals like gallium, germanium, indium and tellurium which are mostly dependent on other (base) metals for primary production. We are not able to increase primary production of



these metals fast enough to satisfy surging demand. Their applications include high efficiency solar cells, permanent-magnet drives and generators (wind mills, hybrid cars, electric cars), catalysts for cars and for petrochemical cracking, fuel cells, batteries and various electronic devices (from touch screens and harddrives to energy saving lighting).

In the medium term the base metals tin, zinc and lead will reach peak primary production and so will a number of metals associated with primary production of these base metals plus some other metals. This large group of metals includes those necessary for the green revolution as well, like many metals required for different types of batteries (zinc, lead, cadmium, lithium) and tantalum required for compact capacitors in mobile electronic devices like mobile phones. But the consequences of metals scarcity will be serious for established sectors like the automotive and the chemical industries as well. An example is tungsten, with many applications in (amongst others) machining and steels.

No later than halfway the 2030s the base metals copper and nickel and their associated by-products cobalt and molybdenum may also reach their primary production peak. The meaning of an end to the production growth of a metal as important for our industrial civilization as copper should be obvious. At this point, primarily we have metals like aluminium and iron (and possibly magnesium) left at our disposal to sustain or even continue growing their primary production.

The situation pictured above would be alarming even if it were only valid for a handful of these metals.

Yet the problem is even more serious and urgent, because the timing pictured above involves a global mean derivative. In reality spot shortages will occur well before global shortages hit. More often than not, the largest part of global primary production takes place in just a few countries. The geopolitical ramifications of this could turn out to be severe.

Metals scarcity wouldn't have to be such a big issue if we would have a less material intensive economy, but we are still far away from that.

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### Slide 23

Take away message here is: without a shift from scarce to less scarce metals, a large-scale transition towards a more sustainable economy (large-scale meaning at current or growing consumption levels) doesn't stand a chance.

## Consequences of metals scarcity

- Strong volatility of cost (see next slides)
- Cost hard to bear (both in inflation and deflation scenario)
- Supply disruptions (exportquotas and exportstops)
- **Metals scarcity and energy scarcity reinforce one another!**

• Transition towards sustainable economy is not feasible w.r.t. timeliness and scale without extreme measures

- Direct threat to our prosperity
- Scarcity often leads to conflict → high risk of instability



### Slide 24

Scarcity will manifest itself in one way or the other in cost (see also slides 25 and 26). But the absolute cost level in itself is probably an insufficient indicator of scarcity. First the absence of price stability is probably much more important than the absolute price level: uncertainty is not very helpful in making investment decisions. Secondly, scarcity can also manifest itself at low price levels, meaning during a period of deflation. In the third place, money is rather useless if it can't buy you the necessary items, see the 3<sup>rd</sup> bullet in this slide. For a number of the rare earth metals, China is already using export quotas (since 2004) and considering export stops in the near future.

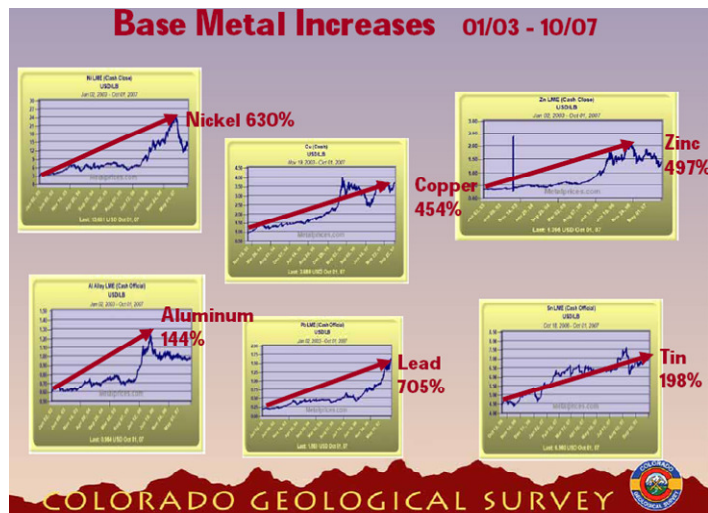
Because the energy sector is one of the largest metals consumers, metals scarcity will aggravate energy scarcity and energy scarcity in turn will aggravate metals scarcity. The energy sector uses lots of metals within its whole chain of exploration, production, storage and distribution up to conversion into the desired forms of energy.

It will be obvious by now that we cannot let things take their course if we want to realize a timely and extensive transition towards a sustainable economy.

Metals scarcity (like energy scarcity) poses a direct threat to our prosperity. Resource poor countries like The Netherlands and Japan have to import most of the material input for their domestic industry.

History shows us that scarcity of various kinds often leads to conflict. It's no longer sufficient to look at the global geopolitical situation from the perspective of the availability and distribution of fossil fuels, water and food; we should add metals to this list.

## High price volatility prior to current crisis (1 from 2)



25 Metals scarcity: A sobering perspective; Part I: Our predicament

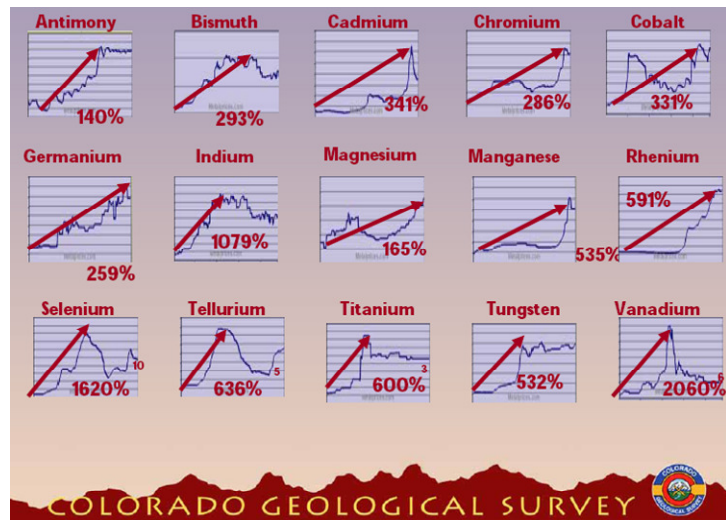
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### Slide 25

Price levels of a number of base metals rose between 144% and 705% (measured to peak levels) during the period 2003-2007.

## High price volatility prior to current crisis (2 from 2)



26 Metals scarcity: A sobering perspective; Part I: Our predicament

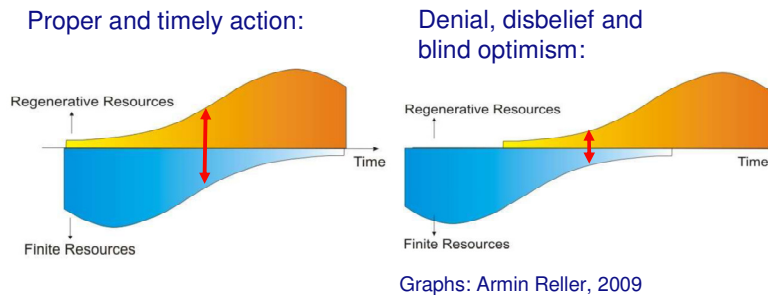
Dr.ir. A.M. Dierden, December 2, 2009



### Slide 26

Price levels of many metals showed high spikes during the period 2003-2007. An extreme example is given by vanadium which price temporarily rose by 2060%.

## Passing through the bottleneck: Weight Watchers or extreme surgery?



### Slide 27

I think it's rather obvious that we'll have to go through a difficult transition the coming decades. The blue production in the graph (any resource like energy, raw material, water, food) could be interpreted as "business as usual" and overall production might grow for some time but will hit a maximum level and decline thereafter. The orange production could be interpreted as "sustainable". The message is that we have to take timely action to prevent us from having to squeeze ourselves in future through the bottleneck as illustrated at the right side of slide 27. This right hand part sketches a situation you don't want to react upon, you'd rather like to anticipate to such a situation. In the right hand situation you might have to resort to notional amputation to fit through the bottleneck, at the left side we might get away with a rigorous diet if and when we start early enough (and keep up with it).

## Wat does this mean (globally)?

- Globally we'll loose, regionally there will be winners
- Access to resources:
  - by owning them
  - by buying them (with real purchasing power)
  - by force



### Slide 28

So I think it's rather obvious that we'll have to go through a difficult transition and we'll end up with a world facing a situation worse than a zero sum game. But as always, there will be winners and losers.

Access to raw materials will then primarily be realized by 3 options: (1) by owning (part of) the production chains, (2) by using surplus of other products and services to be able to buy raw materials and associated products and (3) by taking them by force. Option 1 could imply repatriating (part of) the manufacturing industries back to developed countries.

Resource poor countries have to utilize even more than now their inventiveness and creativity. A country like The Netherlands will also have to put more emphasis on agriculture (food as well as non-food products) and a more intense use of its continental shelf in the North Sea to be more self-sufficient and create more surplus of domestic goods and services (option 2) to trade for non-domestic goods like metals and associated products.

## Technology softens the consequences, don't expect miracles



- Timeliness?  
(think in decades, not years)
- Economic scalability?
- Are we making the right choices?



### Slide 29

You cannot beat the second law of thermodynamics (see text with slide 3) using technology. As with the free market (slide 2) technology has given us tremendous benefits and with technology the magic box of tricks is far from being depleted, but it is by no means a cure for all trouble. Timelines and ability to scale are amongst the most important benchmarks to filter feasible propositions. Besides this, we should also ask ourselves if we should resort to technology: sometimes behavioural change is much more effective (and maybe also much more difficult).

## Contents of Part I

- **Risk assessment**
  - Big Trouble ahead
- **Resource scarcity**
  - Production rate versus ultimate producible quantity
  - Energy scarcity
- **Metals scarcity**
  - Decreasing quality of reserves
  - Primary production of metals will decrease globally, preliminary estimate of timing and sequence
- **Consequences of metals scarcity**
  - Forget painless transition towards sustainable economy
  - Bottleneck dead ahead
  - Will technology save us?
- **Solution framework with intrinsic value (preview to Part II)**
  - Amongst others the **Elements of Hope**

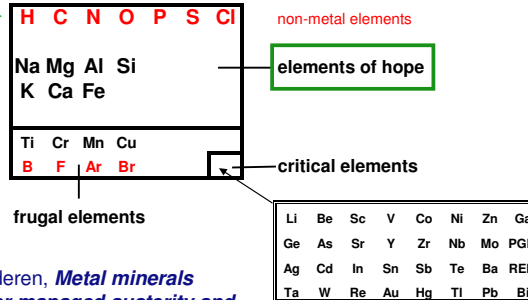


### Slide 30

One of the most holistic approaches to connect metals scarcity with the transition towards a more sustainable society is using the elements I baptized "Elements of Hope", see part II.

## Solution framework with intrinsic benefits, applicable to energy as well as metals

1. Use less (sounds like .....)
2. Longer life
3. Re-use and recycle
4. Substitute .....→
5. Product and process (re)design
6. Buffers



Source: A.M. Diederer, *Metal minerals scarcity: a call for managed austerity and the elements of hope*, March 10, 2009



### Slide 31

There are six solution directions to diminish our dependence on scarce metals: using less, longer product lifetime, more intensive recycling, substitution with less scarce metals, a new product design philosophy and adapted inventory management. These are “least regret” solution directions because they are meaningful no matter how the future is going to unfold, they are solution directions with intrinsic value. They are applicable to energy scarcity as well as to metals scarcity.

Realization of this solution framework challenges people’s ingenuity and creativity and offers meaning and purpose. “Using less” requires nothing less than some form of managed austerity. Also technology can play an important role by enabling dematerialization (like film tapes which have been replaced by digital photos). A number of solution frameworks are facilitated by reducing complexity in order to enhance quality and diminish waste.

I will elaborate on this in Part II of this presentation.

Let's prevent this from happening:



CREW, you fixed the burgee upside down !



### Slide 32

Metals scarcity is real and urgent. Proper and interconnected solutions take time to develop and implement. Let us prevent going back to the order of the day after hearing or reading this information and let us prevent thinking this is something to worry about later.

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See also my March 10, 2009 paper “*Metal minerals scarcity: A call for managed austerity and the elements of hope*”, published (with 198 comments) at the website TheOilDrum.com on May 4, 2009 (<http://europe.theoil Drum.com/node/5239>) and as a paper (pdf) at <http://www.materialscarcity.nl/Downloads.aspx>.

### Recommended further reading:

- Bardi, U., Pagani, M., **Peak Minerals**, ASPO-Italy and Dipartimento di Chimica dell'Università di Firenze, posted October 15, 2007 at the website The Oil Drum: Europe, <http://www.theoil Drum.com/node/3086>
- Bardi, U., **The Universal Mining Machine**, posted January 23, 2008 at the website The Oil Drum, <http://europe.theoil Drum.com/node/3451>
- Angerer, G., et. al., **Rohstoffe für Zukunftstechnologien** (in German), Fraunhofer-Institut, Germany, 2009, ISBN 978-3-8167-7957-5, downloadable as pdf from the internet (<http://publica.fraunhofer.de/eprints/urn:nbn:de:0011-n-910079.pdf>)
- Clugston, C., **Continuously less and less**, October 2009, downloadable as pdf from the internet (<http://www.wakeupamerika.com/PDFs/Continuously-Less-and-Less.pdf>)
- Bol, D., Wouters, H., **Material Scarcity – An M2i Study**, Materials innovation institute, Delft, The Netherlands, November 2009, downloadable as pdf from the internet ([http://www.m2i.nl/images/stories/m2i%20material\\_scarcity%20report.pdf](http://www.m2i.nl/images/stories/m2i%20material_scarcity%20report.pdf))