Limits to Growth and Mineral Resources
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Association for the study of peak oil and gas (ASPO)
The International Centre of the Club of Rome
Der geplünderte Planet

Die Zukunft des Menschen im Zeitalter schwindender Ressourcen
THE LIMITS TO GROWTH

The headline-making report on the imminent global disaster facing humanity—and what we can do about it before it's too late. "One of the most important documents of our age!" —Anthony Lewis,
The New York Times

DONELLA H. MEADOWS/DENNIS L. MEADOWS
JØRGEN RANDERS/WILLIAM W. BEHRENS III

A POTOMAC ASSOCIATES BOOK
The Limits to Growth, 1972
The World3 model
Steam engine governor, 19th century
Distinction between Moderators and Governors.

In regulators of the first kind, let \( P \) be the driving-power and \( R \) the resistance, both estimated as if applied to a given axis of the machine. Let \( V \) be the normal velocity, estimated for the same axis, and \( \frac{dx}{dt} \) the actual velocity, and let \( M \) be the moment of inertia of the whole machine reduced to the given axis.

Let the governor be so arranged as to increase the resistance or diminish the driving-power by a quantity \( F \left( \frac{dx}{dt} - V \right) \), then the equation of motion will be

\[
\frac{d}{dt} \left( M \frac{dx}{dt} \right) = P - R - F \left( \frac{dx}{dt} - V \right).
\] (1)

When the machine has obtained its final rate the first term vanishes, and

\[
\frac{dx}{dt} = V + \frac{P - R}{F}.
\] (2)

Hence, if \( P \) is increased or \( R \) diminished, the velocity will be permanently increased. Regulators of this kind, as Mr. Siemens* has observed, should be called moderators rather than governors.

In the second kind of regulator, the force \( F \left( \frac{dx}{dt} - V \right) \), instead of being applied directly to the machine, is applied to an independent moving piece, \( B \), which continually increases the resistance, or diminishes the driving-power, by a quantity depending on the whole motion of \( B \).

If \( y \) represents the whole motion of \( B \), the equation of motion of \( B \) is

\[
\frac{d}{dt} \left( B \frac{dy}{dt} \right) = F \left( \frac{dx}{dt} - V \right),
\] (3)

and that of \( M \)

\[
\frac{d}{dt} \left( M \frac{dx}{dt} \right) = P - R - F \left( \frac{dx}{dt} - V \right) + Gy.
\] (4)

where \( G \) is the resistance applied by \( B \) when \( B \) moves through one unit of space.
System Dynamics Stock and Flow models (“mind-sized” models)
Governor control by system dynamics

Stock and flow model of the governor control system
Stock and flow model of the exploitation of mineral resources
Whaling in the 19th century

U. Bardi and A. Lavacchi, Energies, 2009
The Seneca Effect: when things go wrong, they go wrong fast

U. Bardi, 2011
Stock and flow model of the world system
State of the World

Resources

Industrial output

Population

Food

Pollution

1900  2000  2100
The Bell Curve
Mining requires energy
FIGURE 3-18 The Declining Quality of Copper Ore Mined in the United States

Ores averaging between 2 and 2.5 percent copper were mined in the United States before 1910. Since then there has been a persistent decline in average grade. The peak in the 1930s and the slight rise in the 1980s were caused by economic downturns that shut down marginal mines and left functioning only those with the richest ores. (Sources: U.S. Bureau of Mines; USGS.)
Morency copper mine, Australia
THE NET ENERGY CLIFF

ENERGY AVAILABLE FOR CONSUMPTION

ENERGY USED IN PRODUCTION

LEGACY OIL AND GAS FIELDS

NEW OIL AND GAS DISCOVERIES

WIND

COAL

ALGAL BIOFUELS

SOLAR

TROPICAL CELLULOSIC BIOFUELS

TAR SANDS

TEMPERATE CELLULOSIC BIOFUELS

OIL SHALE

ENERGY RETURN ON ENERGY INVESTED (EROEI)
The Bell Curve
Historical coal production, Europe

Bardi, 2007
Peak oil the US 48 lower states – M.K. Hubbert, 1956
Oil production, recent trends

Fig 28: Production mondiale (OPEP et Non-OPEP) de pétrole brut conventionnel et prévision pour un ultime de 2,1 Tb, en supposant pas de contrainte de la demande

Fig 29: Production mondiale brut -XH, XH, NGL, OPEP et NOPEP

Il y a peu de différence entre les prévisions de 2004 et celles de 2013, l’écart est moindre que la précision des mesures actuelles.
CO₂ emissions since 1850 (red); exponential growth (blue); cuts to hit climate target (dashed). Photograph: guardian.co.uk
Average Price index for Aluminum, copper, gold, iron ore, lead, nickel, silver, tin and zinc.

Bertram et al., Resource Policy, 36(2011)315
The Limits to Growth - 1972
Substituting, recycling, reusing.....
Energy in truth stands not beside but entirely above all other commodities.... With energy almost any feat is possible or easy; without it we are thrown back into the laborious poverty of early times.

William Stanley Jevons, 1866
Acknowledgement – The Club of Rome

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Norilsk mine, Northern Siberia
Lead mine world production
USGS data

R = 0.963
British Coal Production
Case studies

1. Fossil fuels: oil, gas and coal
2. Uranium
3. Industrial metals (Ni, Zn, Cu)
4. Metals for batteries: Li
5. Precious metals (Au, Ag)
6. Noble metals for catalytic applications (Pt group).
7. Materials for electronics (rare earths and others)
8. Phosphates as fertilizers
9. Fertile soil
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Peak year (logistic)</th>
<th>URR (tons) from logistic fitting</th>
<th>URR (tons) from USGS: reserves + cumulative production up to 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>1962</td>
<td>$(5.8 \pm 0.4) \cdot 10^5$</td>
<td>$5.9 \cdot 10^5$</td>
</tr>
<tr>
<td>Tellurium</td>
<td>1984</td>
<td>$(1.0 \pm 0.4) \cdot 10^4$</td>
<td>$2.8 \cdot 10^4$</td>
</tr>
<tr>
<td>Lead</td>
<td>1986</td>
<td>$(3.3 \pm 0.2) \cdot 10^8$</td>
<td>$2.9 \cdot 10^8$</td>
</tr>
<tr>
<td>Cadmium</td>
<td>1989</td>
<td>$(1.33 \pm 0.09) \cdot 10^6$</td>
<td>$1.5 \cdot 10^6$</td>
</tr>
<tr>
<td>Potash</td>
<td>1989</td>
<td>$(1.54 \pm 0.09) \cdot 10^9$</td>
<td>$9.5 \cdot 10^9$</td>
</tr>
<tr>
<td>Phosphate rock</td>
<td>1989</td>
<td>$(8.1 \pm 0.4) \cdot 10^9$</td>
<td>$2.4 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Thallium</td>
<td>1995</td>
<td>$(4.7 \pm 0.3) \cdot 10^2$</td>
<td>$7.6 \cdot 10^2$</td>
</tr>
<tr>
<td>Selenium</td>
<td>1994</td>
<td>$(1.1 \pm 0.14) \cdot 10^5$</td>
<td>$1.6 \cdot 10^5$</td>
</tr>
<tr>
<td>Zirconium minerals</td>
<td>1994</td>
<td>$(3.9 \pm 0.25) \cdot 10^7$</td>
<td>$6.7 \cdot 10^7$</td>
</tr>
<tr>
<td>concentrates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhenium</td>
<td>1998</td>
<td>$(1.0 \pm 0.3) \cdot 10^3$</td>
<td>$3.3 \cdot 10^3$</td>
</tr>
<tr>
<td>Gallium</td>
<td>2002</td>
<td>$(2.5 \pm 0.5) \cdot 10^3$</td>
<td>$1.65 \cdot 10^4$ (?)</td>
</tr>
</tbody>
</table>
William Stanley Jevons: the coal question (1866)
Extraction of tight gas ("fracking")
Shale gas: the double limit of depletion and pollution

U.S. Oil and Gas Rigs

By Ugo Bardi - 2012
Data from Baker and Hughes

STOP FRACKING with our water
Oil: the double limit of depletion and pollution

OIL & GAS PRODUCTION PROFILES
2011 Base Case

Regular Oil ■ Heavy etc □ Deepwater □ Polar □ NGL □ Gas □ Non-Con Gas

Carbon Dioxide Concentration

Average CO₂ for May 9, 2013
400.03 ppm
(single day, not corrected for seasonal variation)

Credit: NOAA/Scripps Institution of Oceanography

Image left from ASPO, right from NASA
Uranium: the double limit of depletion and pollution

World supply of uranium from mining

Left: courtesy from the energy watch group, right from wikipedia commons
Distinction between Moderators and Governors.

In regulators of the first kind, let \( F \) be the driving-power and \( R \) the resistance, both estimated as if applied to a given axis of the machine. Let
\[
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\]

and that of \( M \)
\[
\frac{d}{dt} \left( M \frac{dx}{dt} \right) = P - R - F \left( \frac{dx}{dt} - V \right) + G \frac{dy}{dt} \quad . \quad . \quad . \quad . \quad (4)
\]

where \( G \) is the resistance applied by \( B \) when \( B \) moves through one unit of space.

---

**We have decided to call the entire field of control and communication theory, whether in the machine or in the animal, by the name Cybernetics, which we form from the Greek χυμηντης or steersman.** In choosing this term, we wish to recognize that the first significant paper on feedback mechanisms is an article on governors, which was published by Clerk Maxwell in 1868, and that governor is derived from a Latin corruption of χυμηντης. \(^1\)

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**—NORBERT WIENER**
- Seawater mining
- Seafloor mining
- Landfill mining
- Urban mining
Trevi fountain, Rome
Carbon Dioxide Concentration

Average CO₂ for May 9, 2013
400.03 ppm
(single day, not corrected for seasonal variation)

Credit: NOAA/Scripps Institution of Oceanography
Conclusions and trends

1. Depletion is a question of cost, not a question of amounts

2. The market can make a resource profitable, but it cannot make it cheap.

3. Extractive technology can make a resource accessible, but it can't make it cheap

4. New resources (seafloor, ocean, recycling, etc.) exist, but are not cheap.

5. Climate change is another cost of depletion.
Plundering the planet: main points

1. Mineral depletion is not a question of amounts, it is a question of costs.
2. The market can make extraction convenient, it can't make it cheap
3. Extractive technology can generate new resources, but can't make them cheap
4. Climate change is the other side of depletion.
5. Depletion is now. And it is forever
Two sides of the same coin
The Global Carbon Cycle, Abiotic

Volcanic Emissions → CO₂ → H₂O → H₂CO₃ → H⁺ + HCO₃⁻ → CO₂

0.02 - 0.05

Air-Sea Exchange → 90

Rock Weathering → 0.40

Subduction → 0.38

Metamorphism

CaCO₃

Ocean
The Seneca Effect

"It would be some consolation for the feebleness of our selves and our works if all things should perish as slowly as they come into being; but as it is, increases are of sluggish growth, but the way to ruin is rapid."

Lucius Annaeus Seneca 4 AD – 65 AD
I LIMITI dello SVILUPPO

rapporto del System Dynamics Group
Massachusetts Institute of Technology (MIT)
per il progetto del Club di Roma
sui dilemma dell’umanità

Biblioteca della EST
EDIZIONI SCIENTIFICHE E TECNICHE
MONDADORI
Garzweiler coal mine
Sussex neolithic mines: ca. 10,000 BCE
Georg Bauer, “De Re Metallica” (1556)
Bingham copper mine - Utah
"Sarebbe una consolazione per la debolezza del nostro essere e delle nostre opere se tutte le cose dovessero perire con la stessa lentezza con cui nascono ma, così come stanno le cose, la crescita è lenta ma la strada verso la rovina è rapida."

Lucius Annaeus Seneca 4 AD – 65 AD
Omeostasi
World Model – 6 stocks
3-stock model
Figure 21 – Ultimate United States crude-oil production based on assumed initial reserves of 150 and 200 billion barrels.

Hubbert 1956
Figure 3. Gold production and number of miners during the “Gold Rush” in California fitted using the LV model developed here. The data are from [22].
Source: US DOE, Energy Information Administration
Annual Energy Review 2006
World oil production

Dati ASPO (2008)
World3 – 2004 run
**Fig. 6.** As for Fig. 5 except for CThERM trajectories calculated out to 2100, with the model initialized with conditions in 2008 and assuming that $d\beta/dt = 0$ and $dc/dt = 0$ for a range of values of inverse resilience $1/\rho$ (blue numbers expressed in % yr$^{-1}$ change in the decay coefficient $\gamma$ per CO$_2$ doubling). Small numbers in black correspond to the calculated inflationary pressure $i = \gamma/\beta$ (Eq. 22) in year 2100. Green dashed lines represent the modeled year. Shown for comparison are the IPCC SRES A1F1 and A2 scenarios based on the CThERM linear sink model for CO$_2$. CO$_2$ concentrations for these scenarios using the Bern carbon cycle model are shown by blue diamonds. Historical data from 1 AD to 2008 is added for reference (see Appendix B).
Mother Gaia, I come on behalf of all humans to apologize for destroying nature and beg for forgiveness.

Oh my beloved self-centered humans...

We're sorry for being so selfish. We never meant to kill nature.

That wasn't what I mean by self-centered. Nature is adaptable. No matter what you do to it, it will simply change and take on new forms. It has survived worse things than you.

You are however in the process of changing it so much that you can't live in it. You're not killing nature, you're killing yourself.

That's what I mean by self-centered. You think that just because you can't live, then nothing can.

What?

You're fucking yourself over big time and won't be missed.
Il grande puzzle
Lotka-Volterra model (LV)

\[
\begin{align*}
\frac{dx}{dt} &= x(\alpha - \beta y) \\
\frac{dy}{dt} &= -y(\gamma - \delta x)
\end{align*}
\]

Vito Volterra
1860-1940


$R_{CO_2} = 1.28$ (2009: 386/300... relative to pre-industrial 300 ppm)

Atmospheric $CO_2$ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

2005 27 Gt $CO_2$ = 13 ppm

1.7
11.3 (87%)

Total Atmospheric $CO_2$ = 793 Gt

http://www.esrl.noaa.gov/gmd/ccgg/trends/
Figure 2: Fossil fuel and cement CO2 emissions in billion tons carbon/year (GtC/year)

- Growth rate 1990-1999: 1% per year
- Growth rate 2000-2010: 3.1% per year
- Growth rate 2009: -1.3% per year
- Growth rate 2010: 5.9% per year

Uncertainty (6-10%)
Fig. 1. (a) Evolution of global surface temperature (solid green line). The green dashed line denotes a second possible evolutionary path triggered by a temperature perturbation in the Neoproterozoic era. (b) Evolution of the cumulative biosphere pools for procaryotes (red), eucaryotes (green), and complex multicellular life (brown).
$R_{CO_2} = 1.28$  (2009: 386/300... relative to pre-industrial 300 ppm)

Atmospheric $CO_2$ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

2005 27 Gt $CO_2$ ~ 13 ppm

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