Future raw material availability on a finite planet: How much can we substitute, recycle or afford?

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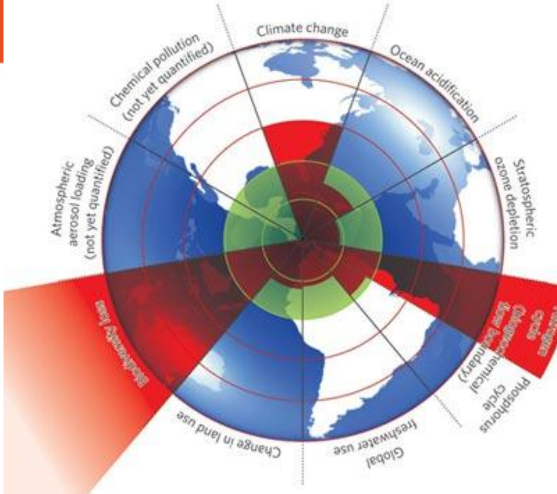
Cobalt Conference, Brussels, 23-24 March, 2015



The Earth is **shrinking**

YEAR
Global hectares of surface per person

Ecological footprint = the land we need to provide daily needs and take up the waste.
Now we are using 1.5 Earths per year.

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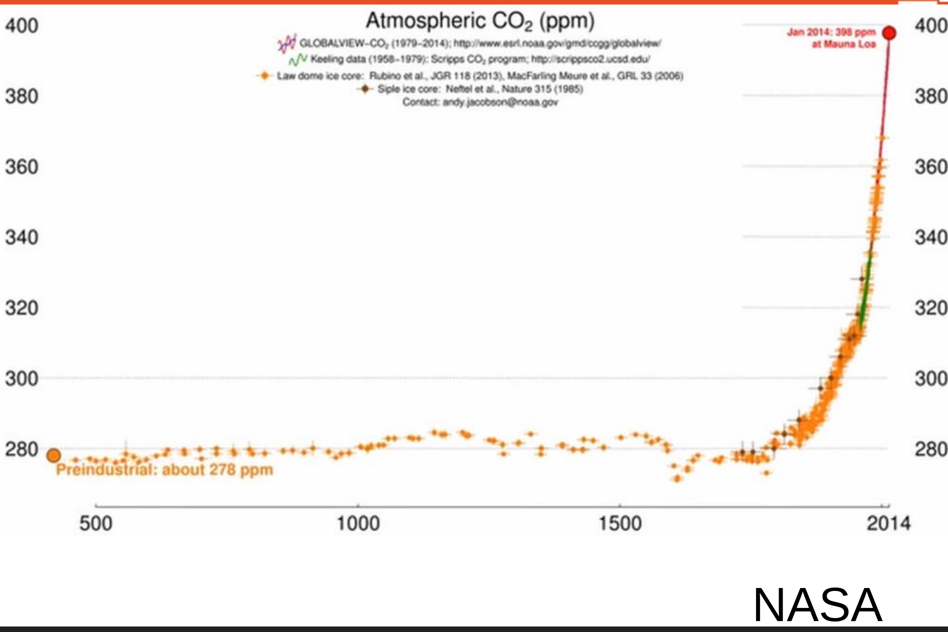
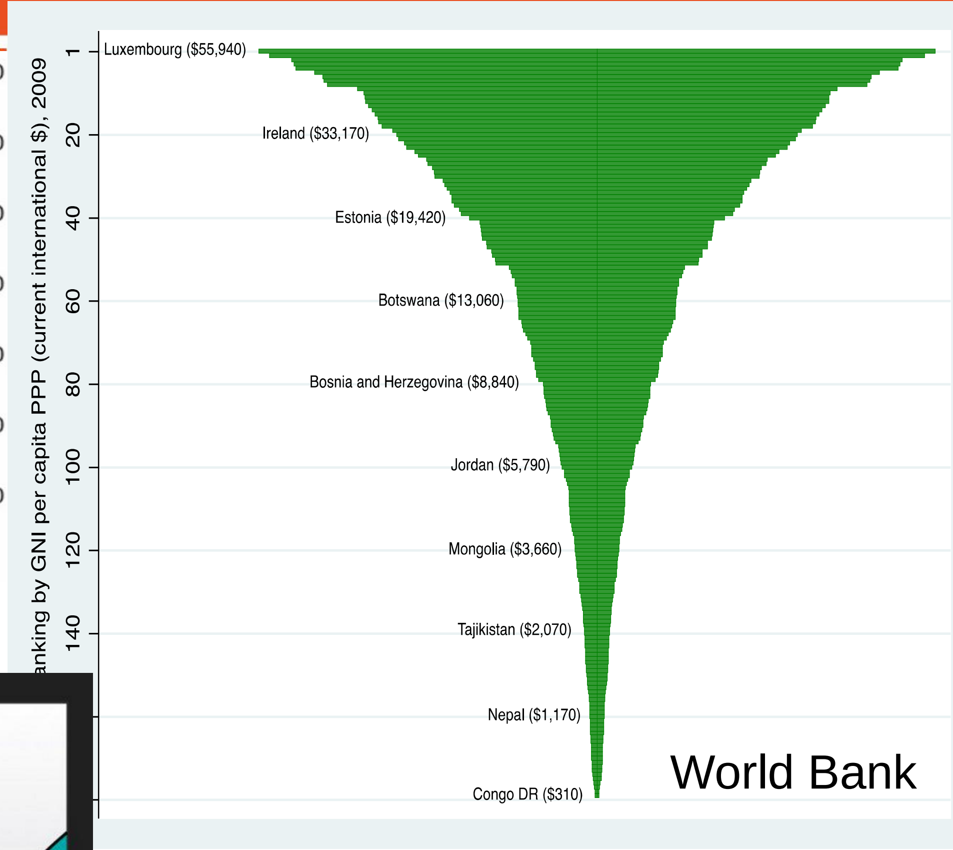
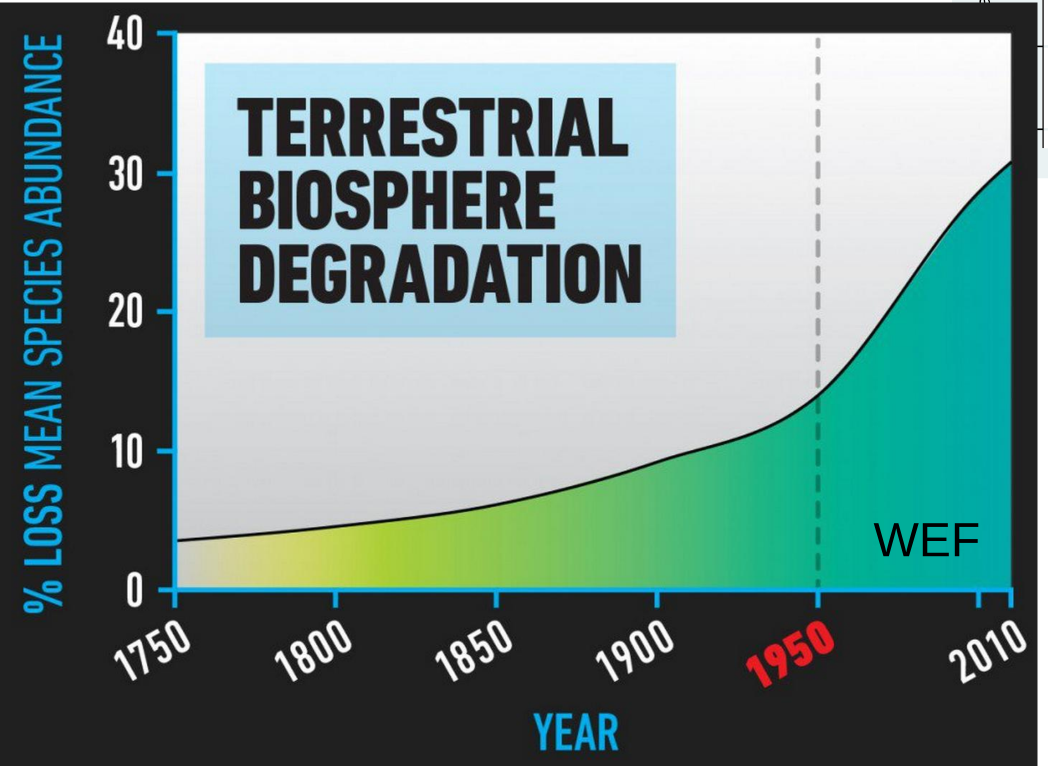
WWF, Rockström et al.





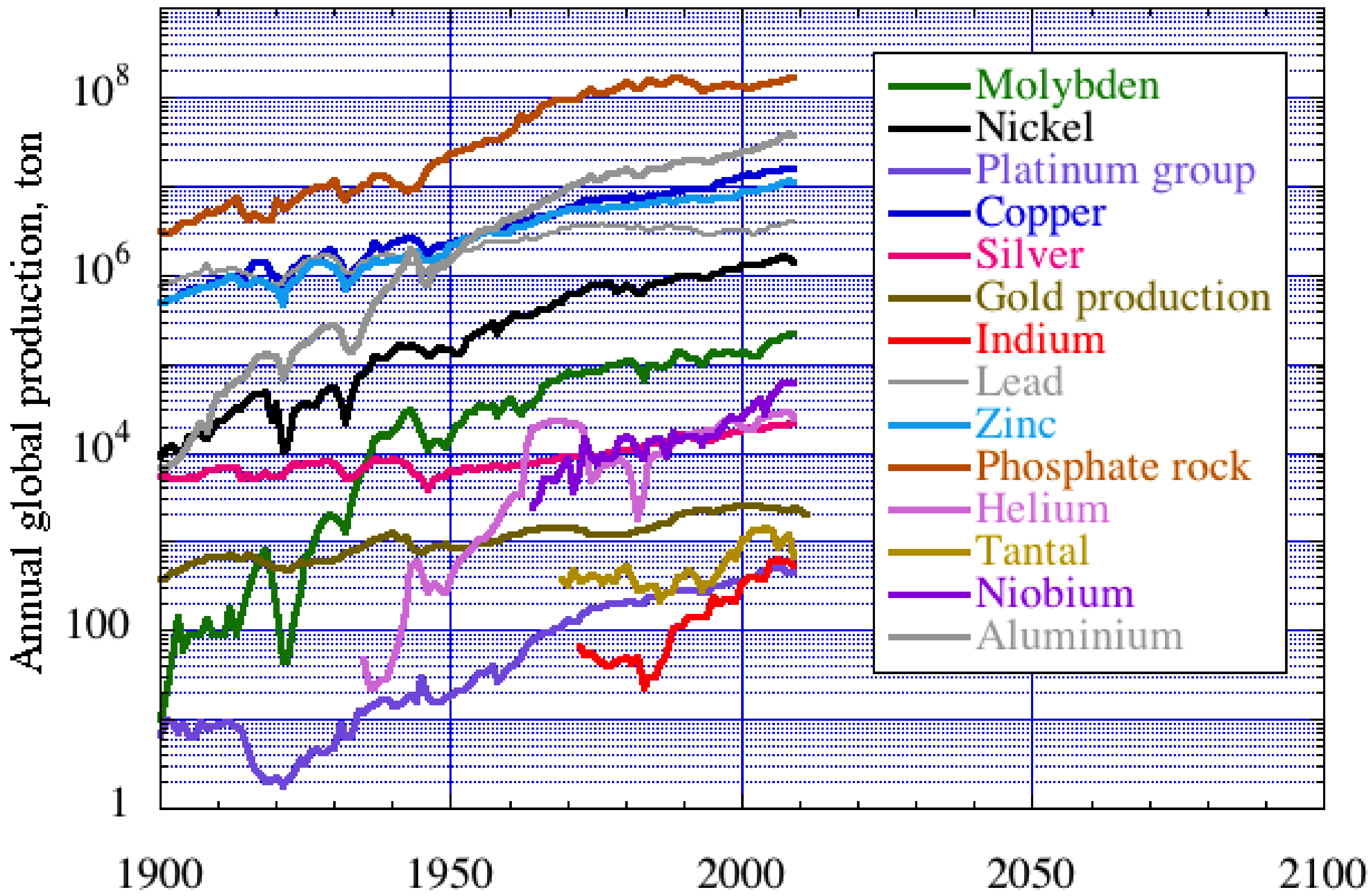


80 individuals have as much wealth as 3.6 billion people!!!

Oxfam

Exponential growth forever?

Doubling time 10 -20 years – 3.5-7% growth



Growth

"Anyone who believes that unlimited growth is possible in a limited world is either a madman or an economist"

Kenneth Boulding

Economist

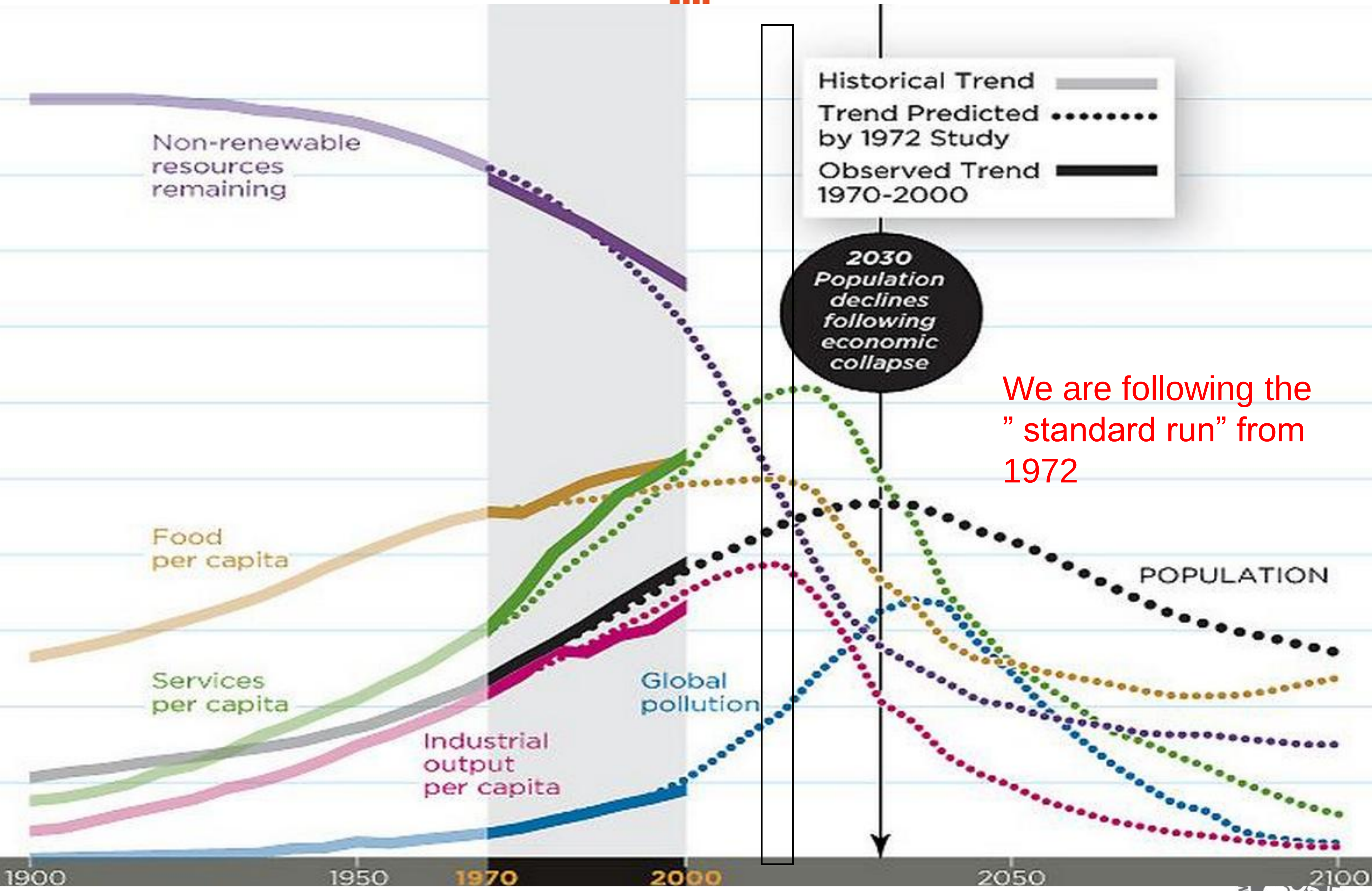
"The greatest imperfection of mankind is that it does not understand the consequences of exponential growth "

Albert Allen Bartlett

Mathematician

Both at University of Colorado, Boulder

We are now here



We are following the ” standard run” from 1972

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Limits to Growth 1972 – Meadows et al.

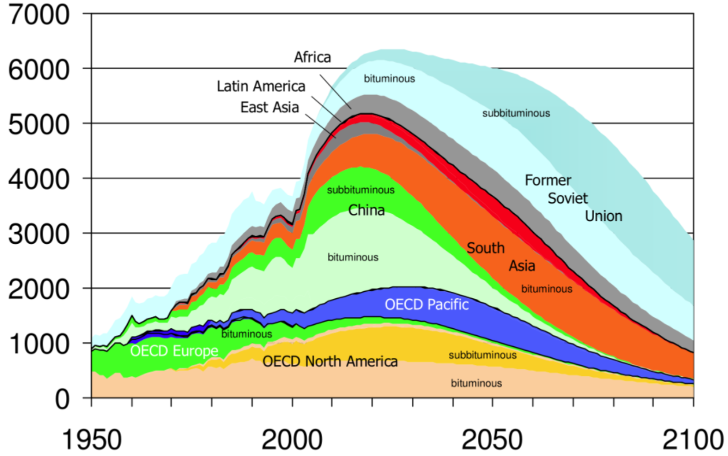
RAW MATERIAL AVAILABILITY

Methods of resource estimation

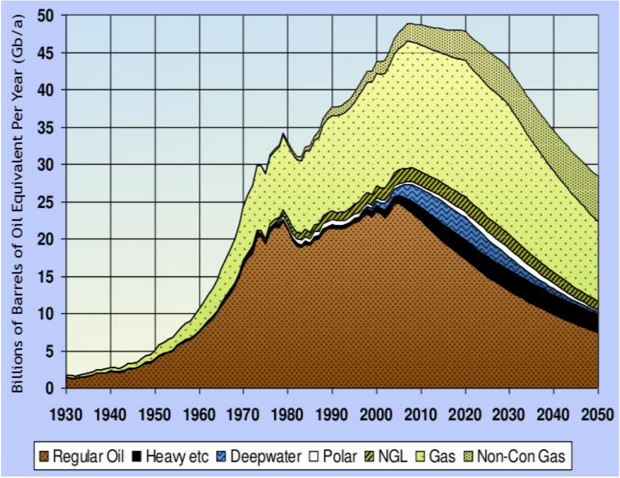
1. Business as usual (BAU)
2. Time between peak discovery and peak production <40 years
3. Hubbert curves
4. WORLD - System dynamics model – with stakeholder group modelling
    1. Integration with econometric model GINFORS
    2. SIMRESS

Peak energy

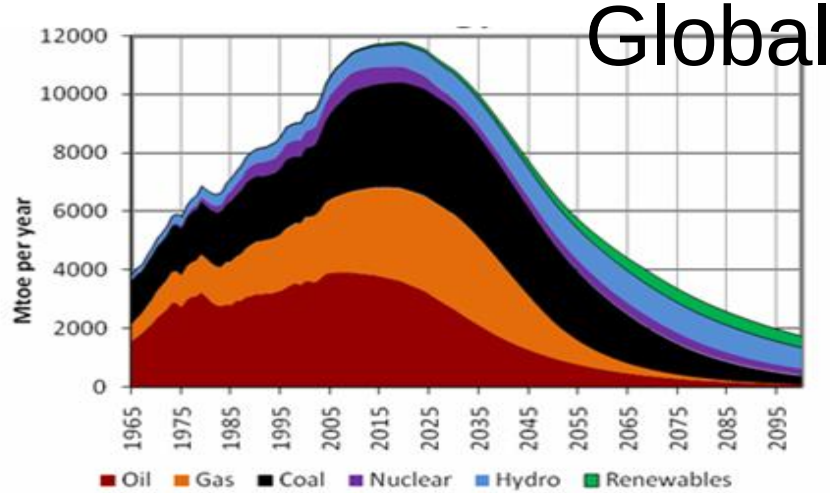
Coal 2015



Oil 2006



Global energy 2020



… but we can only burn 20% of what is left…

ASPO

Colin Campbell
ASPO founder
Peak Oil
Demonstration

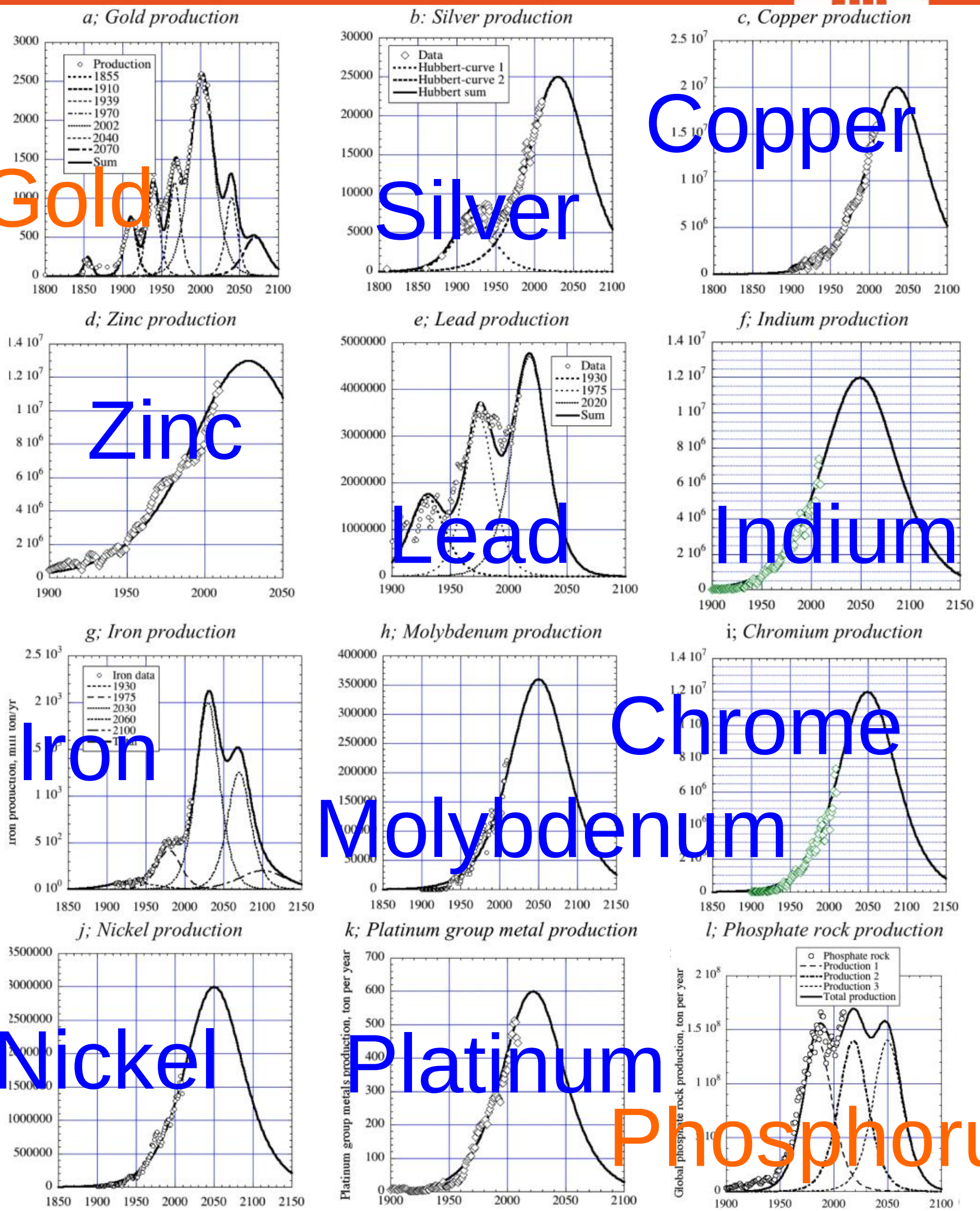
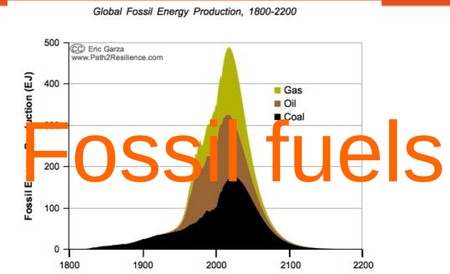
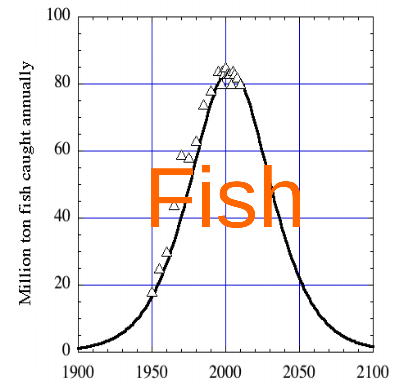
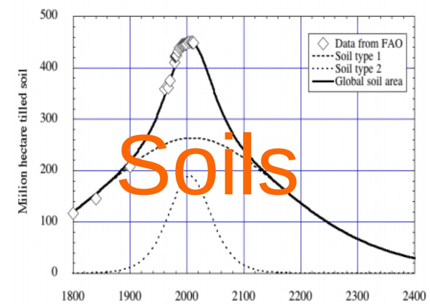


Figure 8. *Hubbert-curve fittings for gold (a) silver (b), copper (c), zinc (d) lead (e), indium (f), iron (g), molybdenum (h), chromium (i), nickel (j), platinum group metals (40% Pt, 43% Pd, 5% Rh, 5% Ru, 5% Ir, 2% Os) (k) and (l) that shows a one-curve phosphorus plot. We can see that the data suggest gold already passed the production peak. The scale on the Y-axis is production in ton per year, the x-axis is the year. Data:* http://minerals.usgs.gov/ds/2005/140/







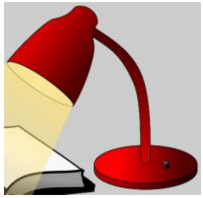
All peak by 2050

Table 2. Estimated **burn-off times** according to the different recycling, materials use and populations scenarios, output estimates of burn-off times are in years. The time to scarcity as estimated with the Hubbert's curve or a systems dynamics model (Sverdrup and Ragnarsdottir 2011) would be the double of this estimate. All values are years counted from 2010 and forwards.

Element	BAU	50%	70%	90%	95%	95%+3bn	95%+3bn+½
The structural metals							
Iron	79	126	316	316	632	1,263	2,526
Aluminium	132	184	461	461	921	1,842	3,684
Nickel	42	42	209	419	838	1,675	3,350
Copper	31	31	157	314	628	1,256	2,512
Zinc	20	37	61	61	123	245	490
Strategic metals and materials							
Manganese	29	46	229	457	914	1,829	3,668
Indium (Zn)	19	38	190	379	759	1,517	3,034
Lithium	25	49	245	490	980	1,960	3,920
Rare Earths	455	864	4,318	8,636	17,273	34,545	69,000
Yttrium	61	121	607	1,213	2,427	4,854	9,708
Zirconium	67	107	533	1,067	2,133	4,267	4,554
Tin	20	30	150	301	602	1,204	2,408
Cobalt	113	135	677	1,355	2,710	5,419	10,838
Molybdenum	48	72	358	717	1,433	2,867	5,734
Rhenium (Mo)	50	50	125	250	500	1,000	2,000
Lead	23	23	90	181	361	722	1,444
Wolfram	32	52	258	516	1,031	2,062	4,124
Tantalum (Nb)	171	274	1,371	2,743	5,486	10,971	22,000
Niobium (Ta)	45	72	360	720	1,440	2,880	5,760
Helium	9	17	87	175	349	698	1,396
Chromium	225	334	1,674	3,348	6,697	13,400	26,800
Gallium	500	700	3,500	7,000	14,000	28,000	56,000
Arsenic	31	62	309	618	1,236	2,473	4,946
Germanium	100	140	700	1,400	2,800	5,600	11,200
Titanium	400	400	2,000	4,000	8,000	16,000	32,000
Tellurium (Cu)	387	387	1,933	3,867	7,733	15,467	30,934
Antimony	25	35	175	350	700	1,400	2,800
Selenium	208	417	5,208	10,417	20,833	41,667	83,000
Precious metals							
Gold (Ag)	48	48	71	357	714	1,429	2,858
Silver (Cu)	14	14	43	214	429	857	1,714
Platinum (Ni)	73	73	218	1,091	2,182	4,364	8,728
Palladium (Ni)	61	61	183	913	1,826	3,652	7,304
Rhodium (Pt)	44	44	132	660	1,320	2,640	5,280
Uranium	61	119	597	5,972	11,944	23,887	47,500
Thorium	187	367	1,837	18,375	36,750	73,500	147,000
The limiting nutrient for all life							
Phosphorus	80	128	640	3,200	6,400	12,800	25,600
Legend, yrs	0-50	50-100	100-500	500-1,000	1,000-5,000	>10,000	

Will run out of 18 out of 43 next 50 years

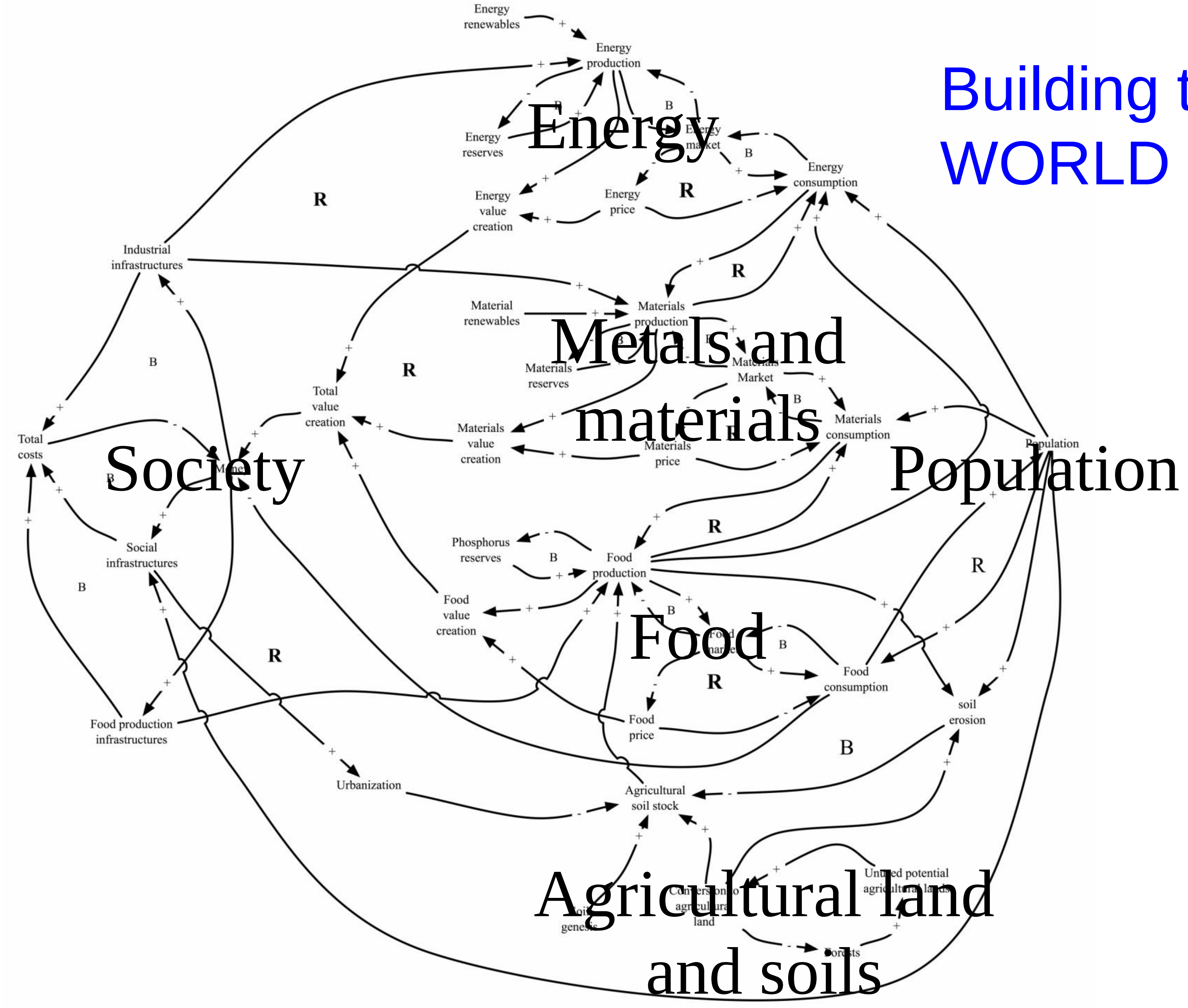
Burn-off time is a useful diagnostic indicator of scarcity risk



Red lamps have come on

Ragnarsdottir et al. 2012

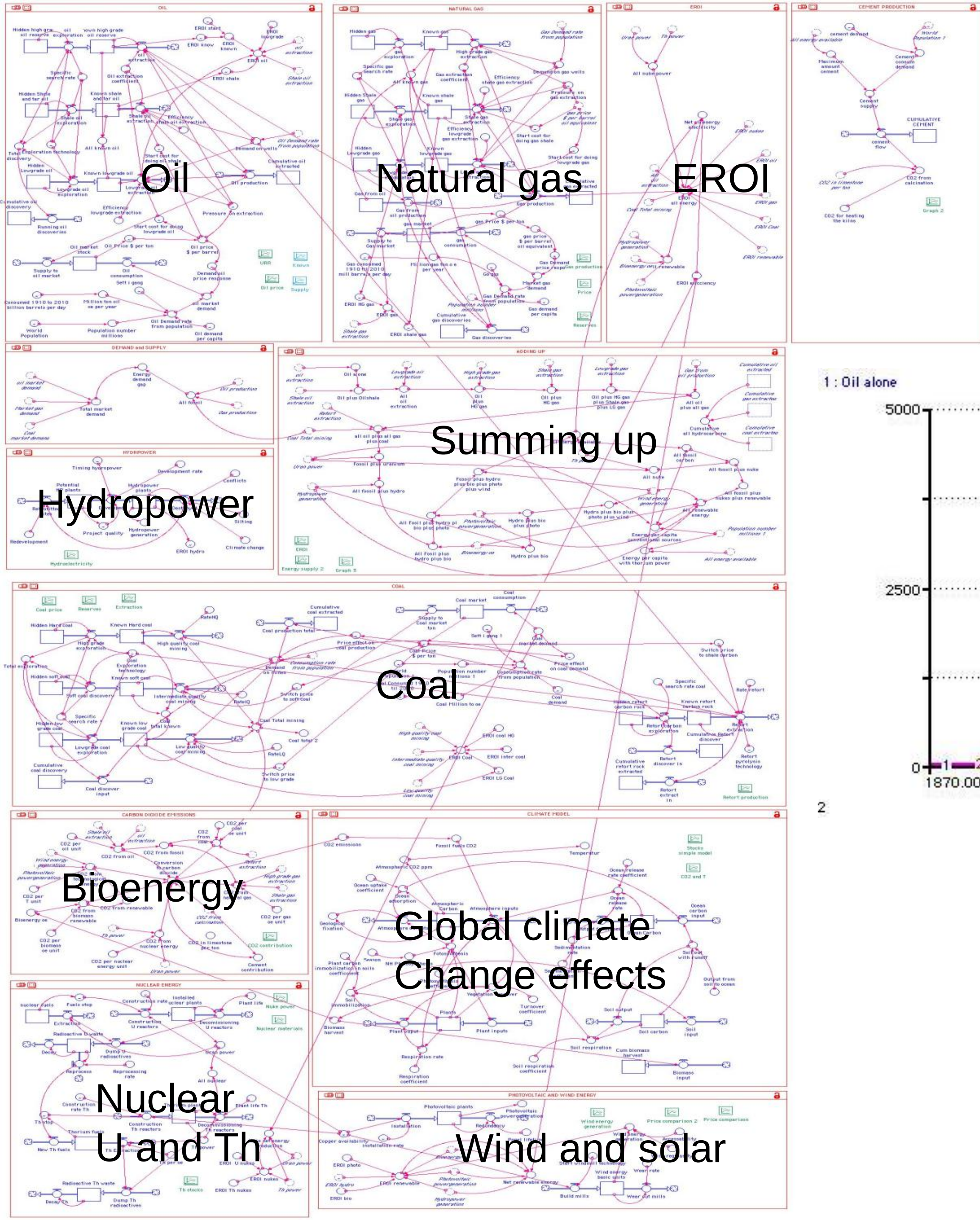
Building the WORLD model

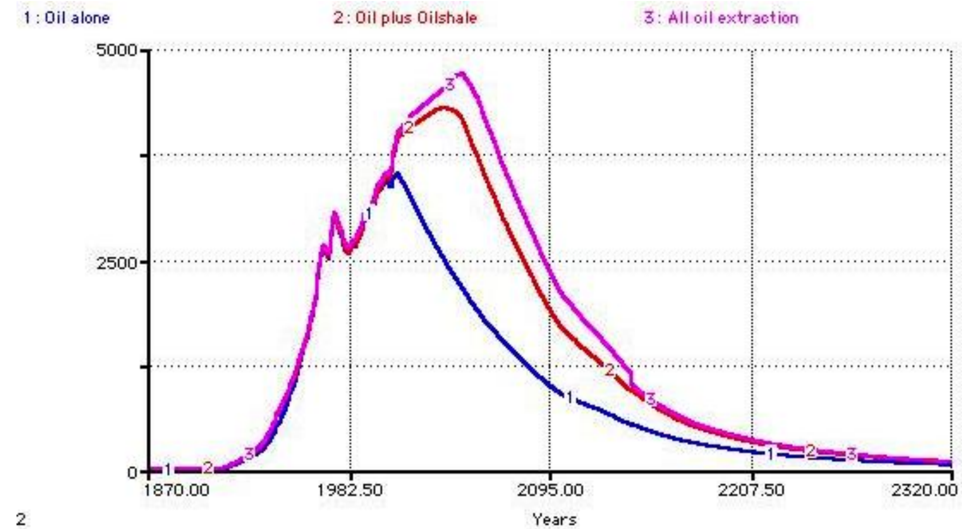


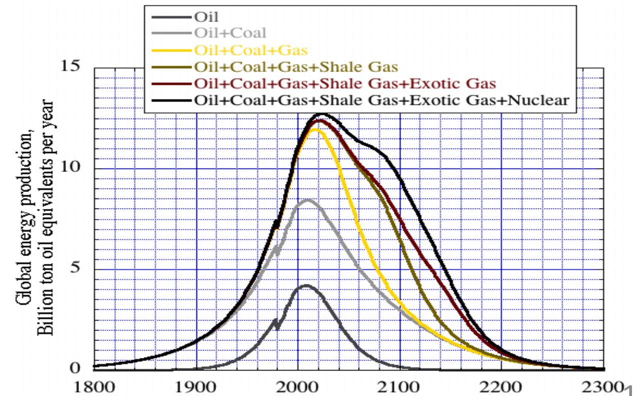
Some of the submodules to WORLD model

- **STEEL**, including the **IRON** model and sub-modules for Cr, Mn, Ni. Huge consumption of fossil fuel, produce large amounts of CO_2
- **ALUMINIUM** for aluminium production and large consumption of energy, potentially large amounts of CO_2
- **BRONZE**, including models for **COPPER** and zinc, and the dependent metals germanium, gallium, indium, cobalt, **SILVER** and tellurium.
- **FoF**, including **phosphorus**, soils, **agricultural lands** and **population** dynamics (demography, numbers, migrations
- **PGMs, SILVER, GOLD** for precious metals
- **ENERGY**, including models for all types of oil, gas and coal extraction, including conventional and unconventional reserves
- **KLIMA**, a very simplified global change model for approximating climate change impacts of resource extraction and use
- **CEMENT**, a submodule for creating building materials out of stone, gravel, sand, limestone and energy. Huge consumption of fossil fuel, produce large amounts of CO_2
- **LAND** for distribution between agricultural land, forest land, urban land and impediment
- **WOOD**, biomass production from forested ecosystems

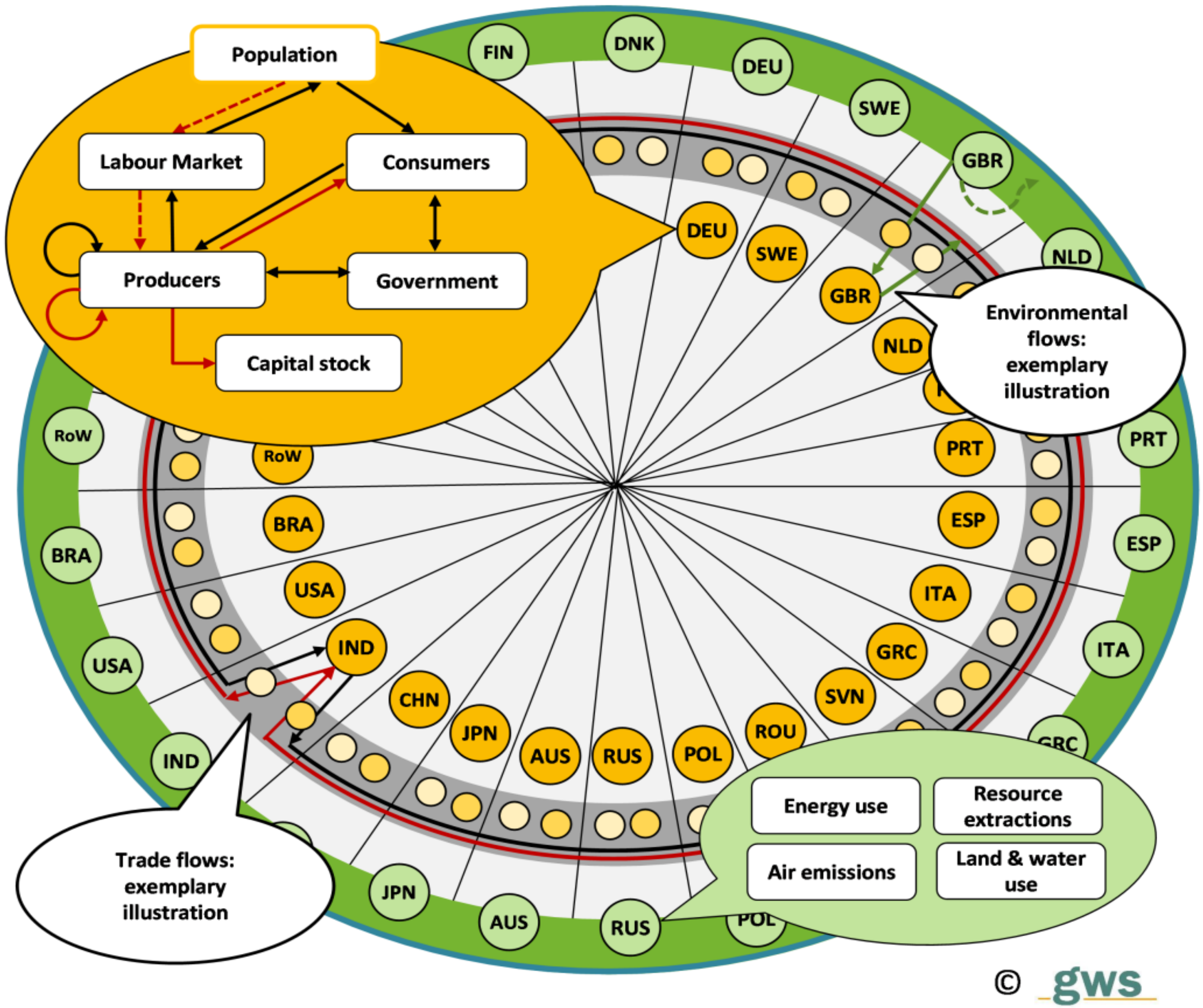
The global ENERGY submodule







GINFORS econometric model



Legend

for 38 countries & Rest of World

- Input-Output, labour market and current account modules (59 goods, 35 industries)
- Imports (59 goods)
- Exports (59 goods)
- Bilateral trade (59 goods)
- Environmental modules
- Earth system and planetary boundaries
- Socio-economic sphere
- Monetary flows

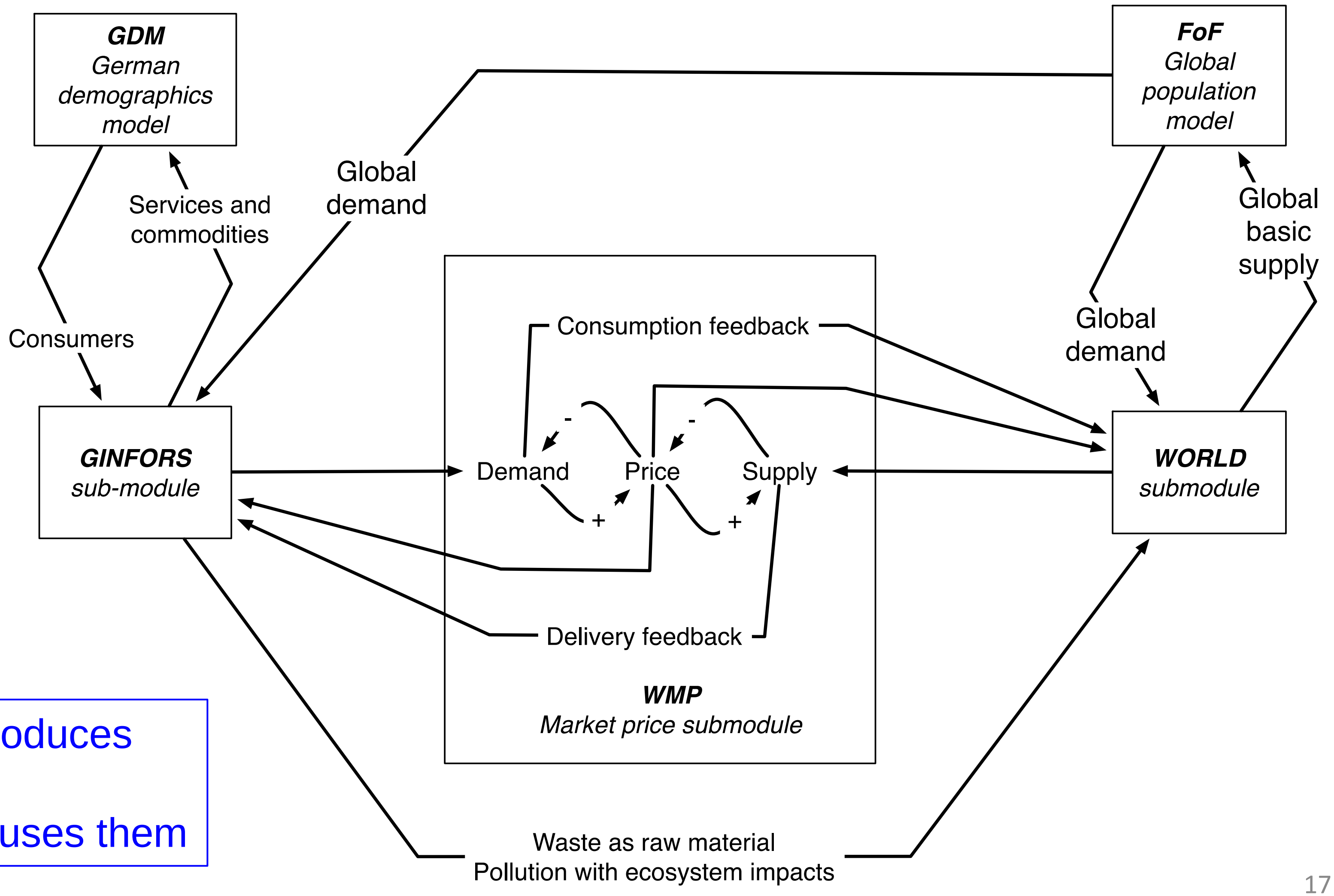
Real flows:

- Goods & services
- Labour force

Physical flows:

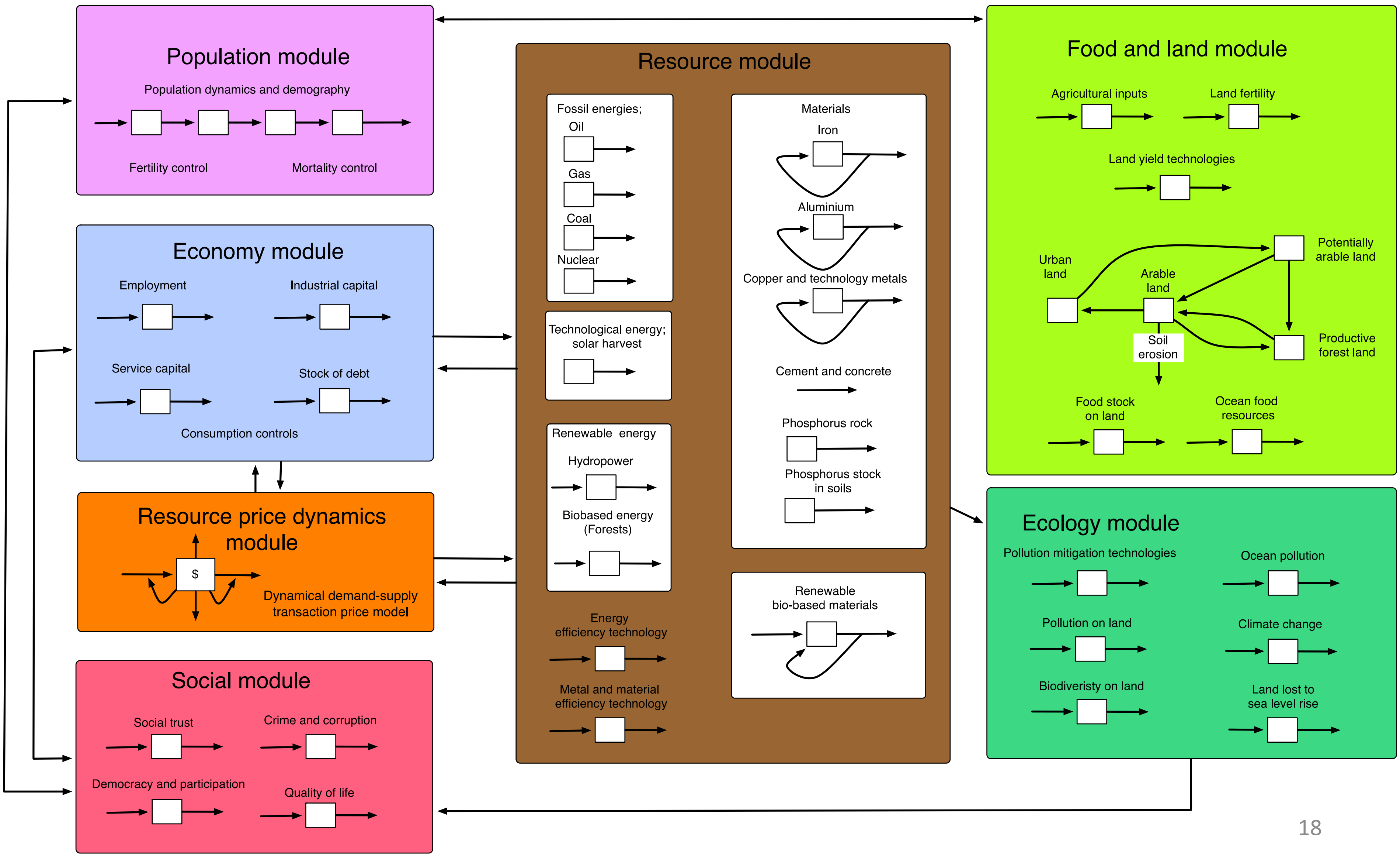
- Energy & resources
- Emissions & degradation

Combining WORLD systems dynamics with GINFORS econometrics: SIMRESS

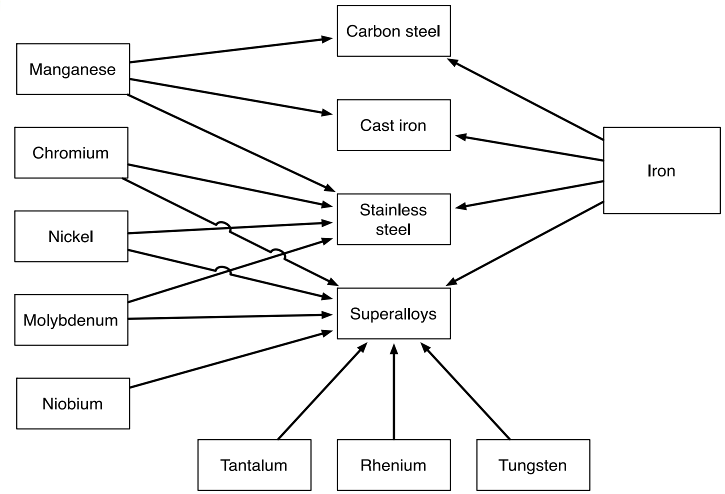


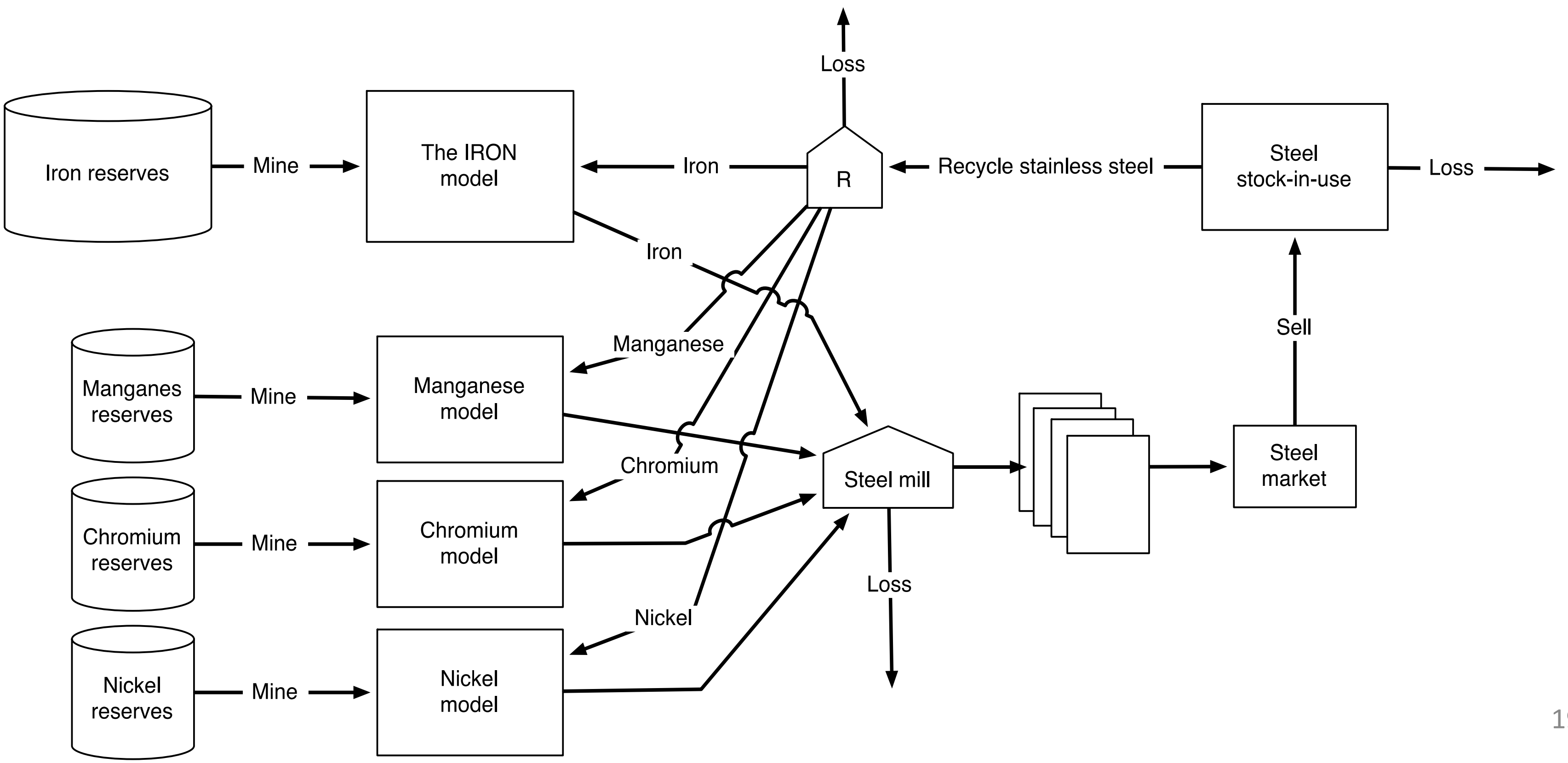
WORLD produces resources
GINFORS uses them

The SIMRESS-WORLD+Ginfors model

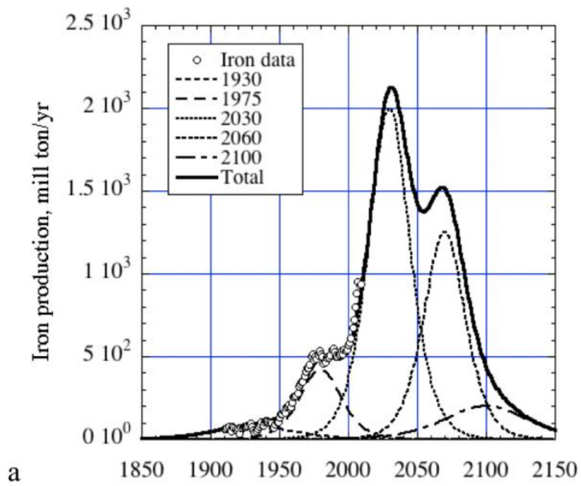


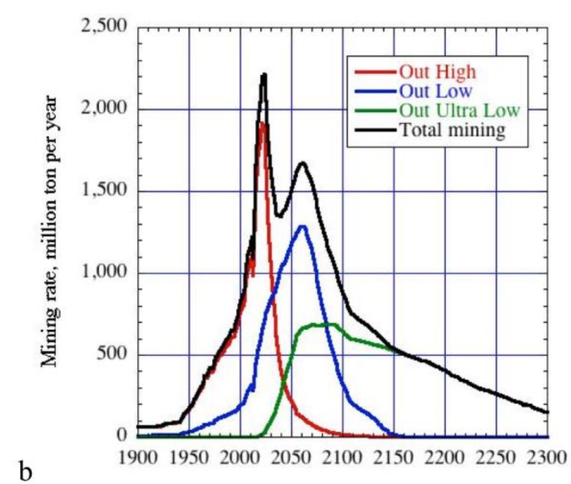
IRON model inside the STEEL module

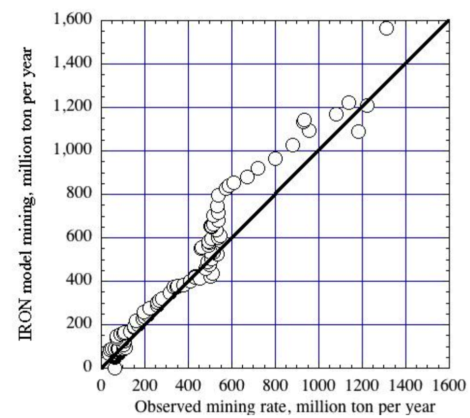




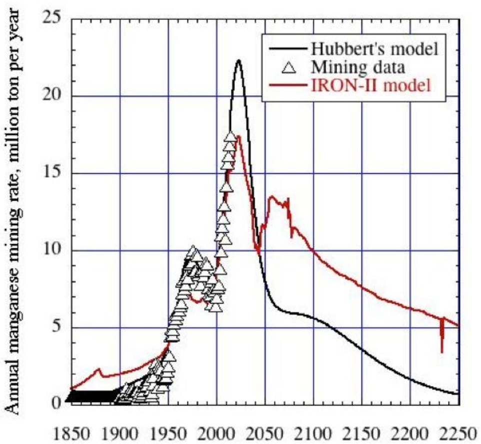
The IRON submodule

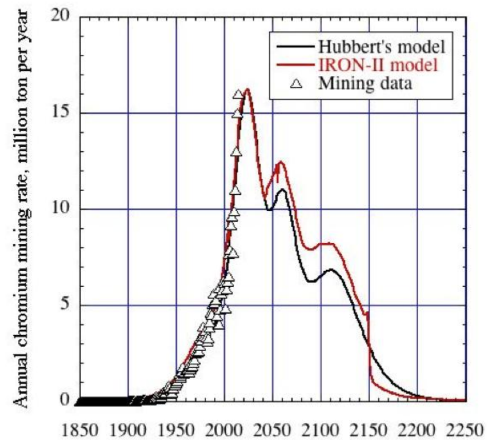


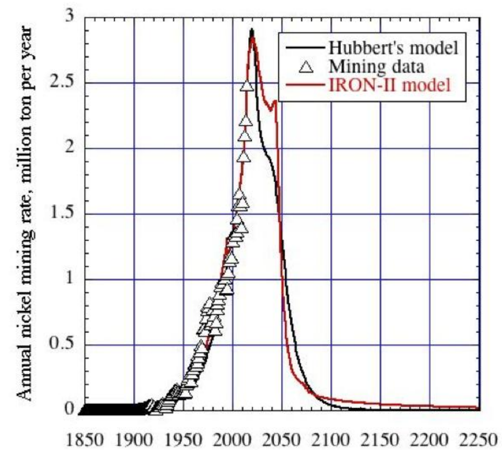


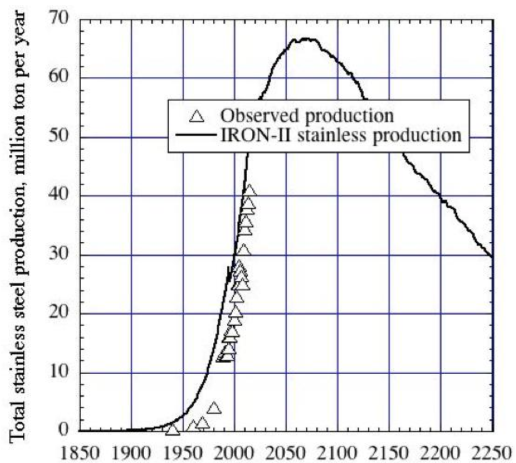


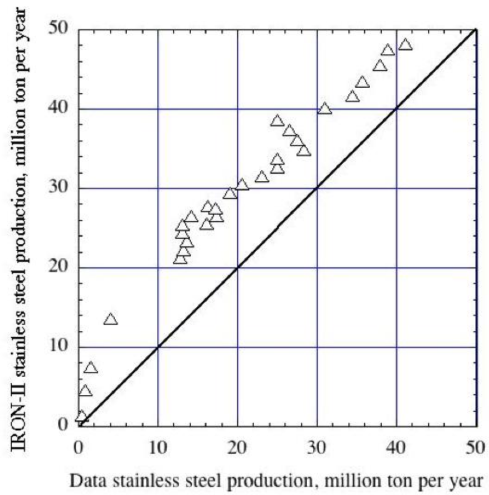
STEEL submodule outputs

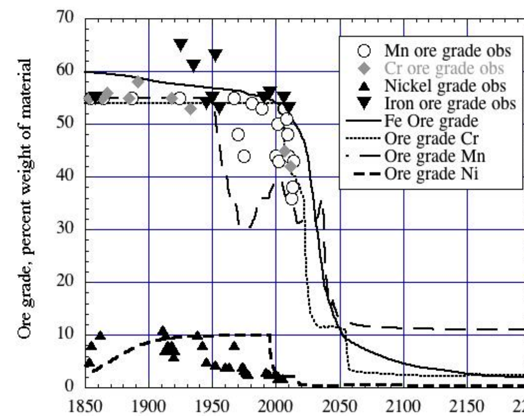






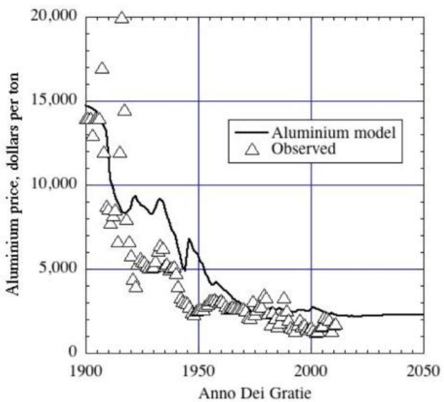


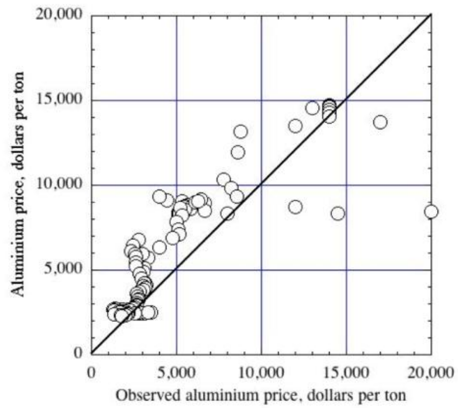


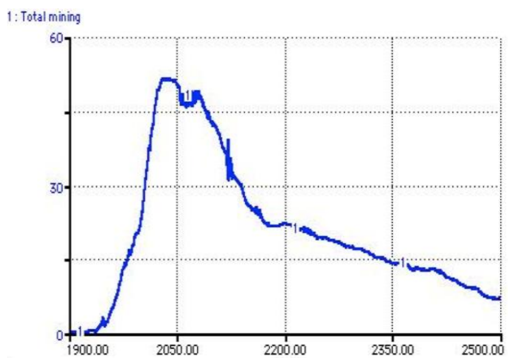


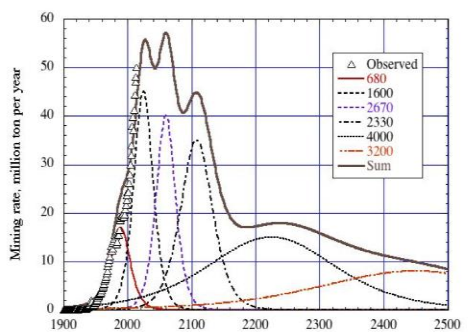
Ore grade cliff

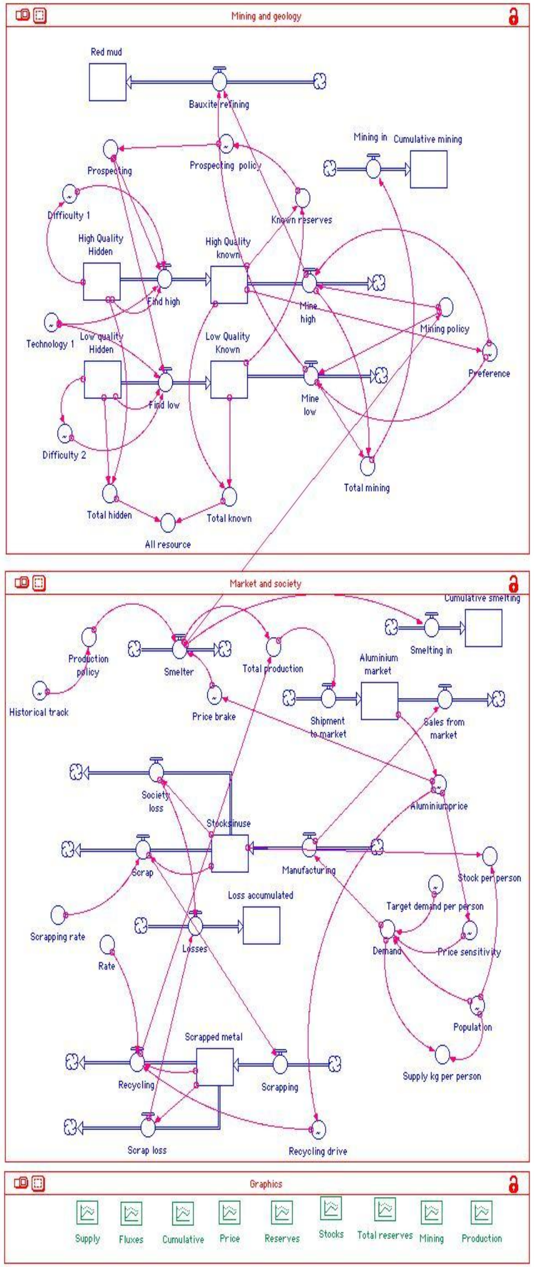
ALUMINIUM submodule











able 28. *Summary of peak estimates, and range of the estimate, considering the lowest nd highest possible reserve estimates still permitted within the data.*

etal	Pessimist	Average	Optimist	Comments
All ready peaked (The problem is here and now)				
ercury		1962		Phased out by political action, target is 2010
ellurium		1984		Dependent on copper and zinc mining
irconium		1994		No good production data is available
admium	1900	1998	2010	Phase out by political action, target is 2010
hallium		1995		Reserve and production data unavailable.
antalum		1995		Partly dependent on mining in Congo.
latinum	2010	2015	2025	Partly dependent on nickel. Serious challenge. Scarcity prevailing
alladium	2010	2015	2025	Partly dependent on nickel. Serious challenge. Scarcity prevailing
hodium	2010	2015	2025	Partly dependent on nickel. Serious challenge. Scarcity prevailing
old	2012	2013	2017	The only real money, well conserved
Coming within the next 10 years (We own the problem, no escapes)				
ead	2013	2018	2023	Limited by political action, target is 2010
iobium	2014	2018	2023	
ndium	2018	2020	2025	Dependent on copper-zinc mining
allium	2018	2020	2022	Dependent on copper-zinc mining
anganese	2018	2021	2025	
From 10 to 20 years from now (We own the problem)				
elenium	2022	2025	2035	Dependent on zinc
hromium	2022	2025	2035	
inc	2018	2025	2028	This is a serious challenge !
obalt	2020	2025	2030	
ickel	2022	2026	2028	
ron	2025	2040	2080	This is a serious challenge !
rom 20 to 30 years from now (Escape possibility; Next generation gets the problem)				
ilver	2028	2034	2040	Partly dependent on copper and zinc
henium	2030	2035	2040	Dependent on molybdenum
opper	2032	2038	2042	This is a challenge !
hosphorus	2025	2040	2100	This is a serious challenge !
From 30 to 50 years from now (next generation gets the problem)				
olybdenum	2048	2057	2065	
>50 years from now (Escape possibility; Our grandchildren get the problem)				
anadium	2055	2076	2096	Dependent on iron
luminium	2030	2130	2230	This is a challenge !

Peak almost every-thing this century

Past peak for 9

5 will peak next 10 years

6 will peak 10-20 years from now

4 will peak 20-30 years from now

Sverdrup and Ragnarsdottir 2014

Scarcity is around the corner

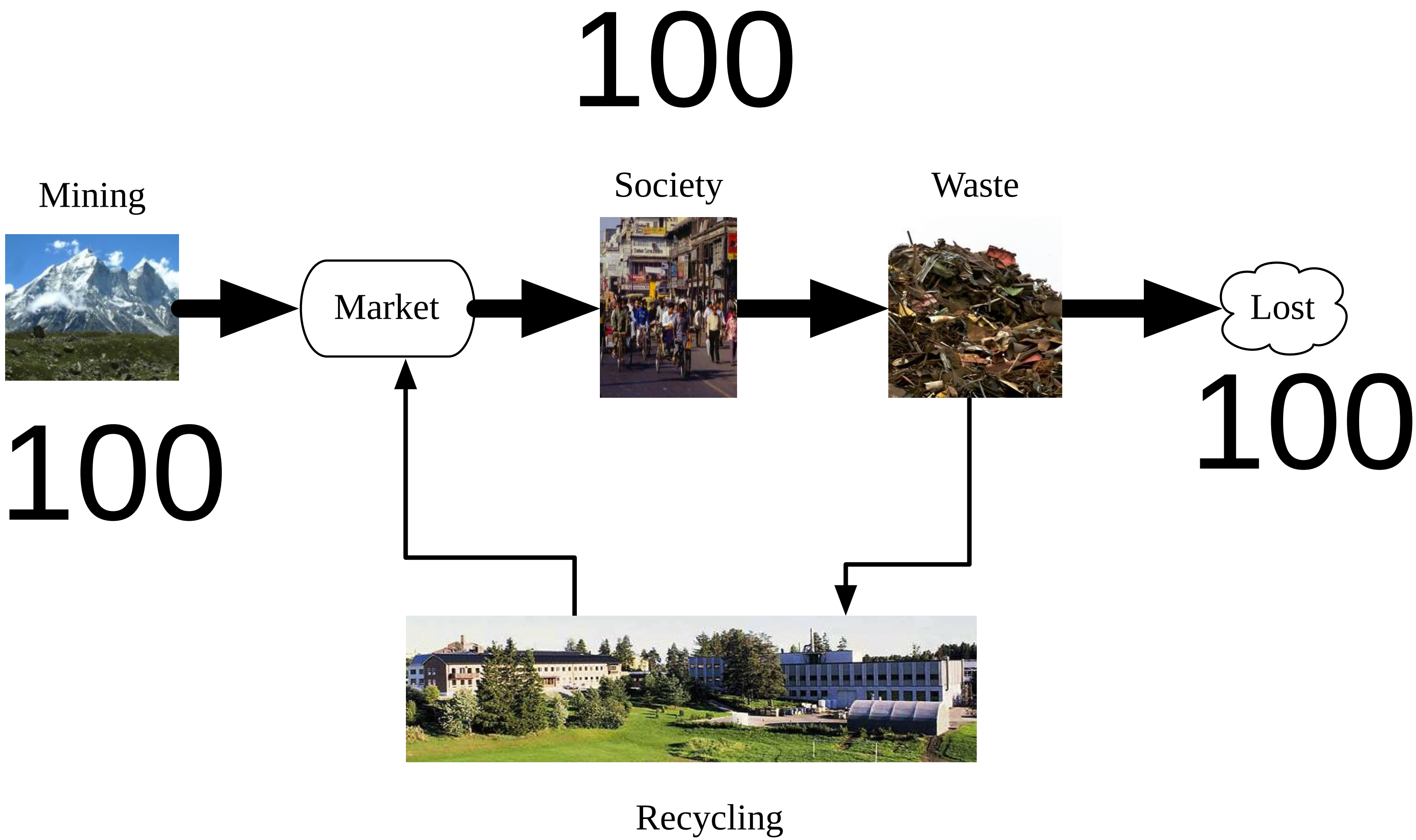
Table 23. Estimated risk of scarcity, using burn-off, Hubbert's estimate and results from dynamic modelling.

Element	Burn-off, years	Hubbert, years	Dynamic model, years	Scarcity		
				2050	2100	2200
Iron	214	176	200	no	no	yes
Aluminium	478	286	300	no	no	no
Copper	31	71	120	yes	yes	yes
Lithium	25	75	330	yes	yes	yes
Rare earths	660	600	1,090	no	yes	yes
Gold	37	37	75	no	yes	yes
Silver	14	44	30	yes	yes	yes
Platinum	73	163	50	no	yes	yes
Palladium	61	134	To be done	no	yes	yes
Oil	44	100	99	yes	yes	yes
Coal	78	174	220	no	yes	yes
Natural gas	64	143	100	no	yes	yes
Uranium	144	To be done	To be done	no	no	yes
Thorium	187	140-470	330	no	no	yes
Phosphorus	161	190	230	no	yes	yes

Sverdrup and Ragnarsdottir, 2014

CAN WE SUBSTITUTE?

Now the world is linear



Substitution ? (ton/year)

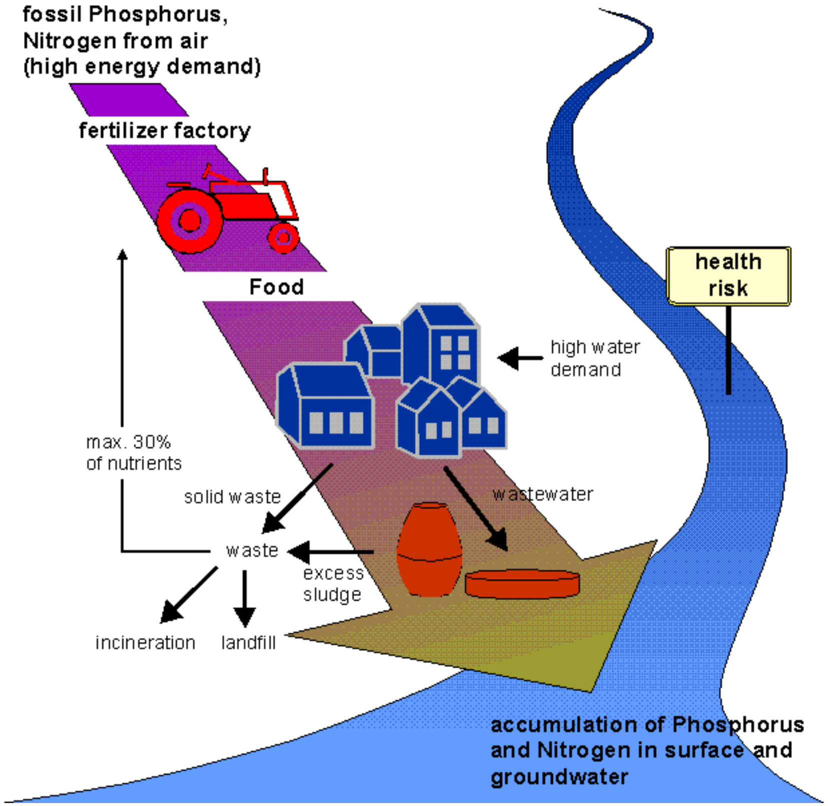
~90x

Table 2. Estimation of sustainable mine extraction of different metals in ton per year. Assessment of the effect of choosing different time horizons.

Metal	Primary production 2012, ton/year	Time horizon applied for sustainability estimate, years from now (t_{DOOM})					
		10,000	5,000	1,000	500	150	60
Iron	1.4 billion tons 1,400,000,000	22,900,000	43,800,000	219,000,000	438,000,000	1,532,000,000	3,831,000,000
Aluminium	44,000,000	1,920,000	3,840,000	19,200,000	38,400,000	128,000,000	320,000,000
Manganese	18,000,000	103,000	206,000	824,000	1,648,000	6,700,000	17,200,000
Chromium	16,000,000	43,700	87,400	437,000	874,000	2,912,000	7,280,000
Copper	16 million tons 16,000,000	55,800	111,600	582,500	1,165,000	3,720,000	9,300,000
Zinc	11,000,000	111,000	222,000	888,000	2,220,000	7,400,000	15,000,000
Lead	4,000,000	69,300	138,600	693,000	1,386,000	4,620,000	11,600,000
Nickel	1,700,000	9,600	19,200	96,000	192,000	640,000	1,600,000
Tin	300,000	7,620	15,300	76,200	153,000	510,000	1,275,000
Titanium	283,000	360,000	720,000	3,600,000	7,200,000	24,000,000	60,000,000
Molybdenum	280,000	2,250	4,500	22,500	45,000	150,000	375,000
Antimony	180,000	700	1,400	7,000	14,000	1,440,000	3,600,000
Rare Earths	120,000	21,600	43,200	216,000	432,000	46,600	117,000
Cobalt	110,000	1,160	2,320	11,600	23,200	77,000	193,000
Tungsten	80,000	750	1,500	7,500	15,000	50,000	125,000
Vanadium	70,000	1,940	3,880	19,400	38,800	129,000	323,000
Niobium	68,000	400	800	4,000	8,000	26,480	66,200
Lithium	37,000	3,500	7,000	35,000	70,000	233,000	583,000
Silver	23 thousand tons 23,000	131	262	1,310	2,620	8,700	21,800
Bismuth	7,000	36	72	360	720	2,400	6,000
Selenium	2,200	17	34	170	340	1,140	2,850
Gold	2,600	14	28	140	280	900	2,260
Indium	670	5	10	50	100	314	785
Tantalum	600	6	12	60	120	390	975
Gallium	280	0.5	1	5	10	35	87
Palladium	220	3.6	7	36	72	240	600
Platinum	180	4.4	9	44	88	294	735
Germanium	150	1.3	2.6	13	26	83	208
Tellurium	120	1.1	2.2	11	22	74	185

700x

From cradle to grave to cradle to cradle



Biomimicry – Cradle to cradle

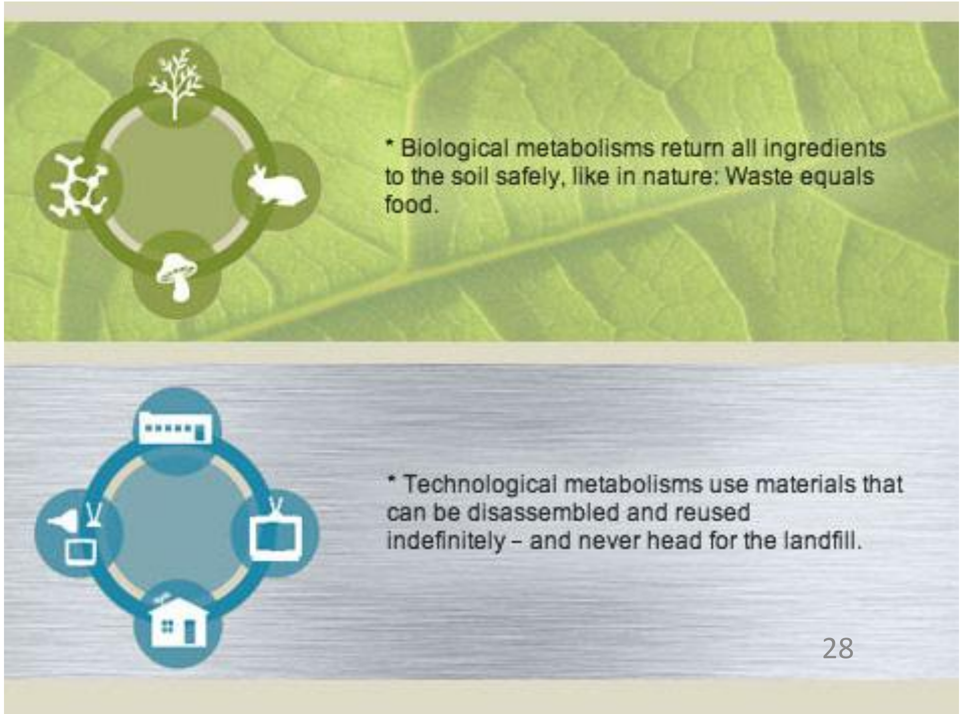


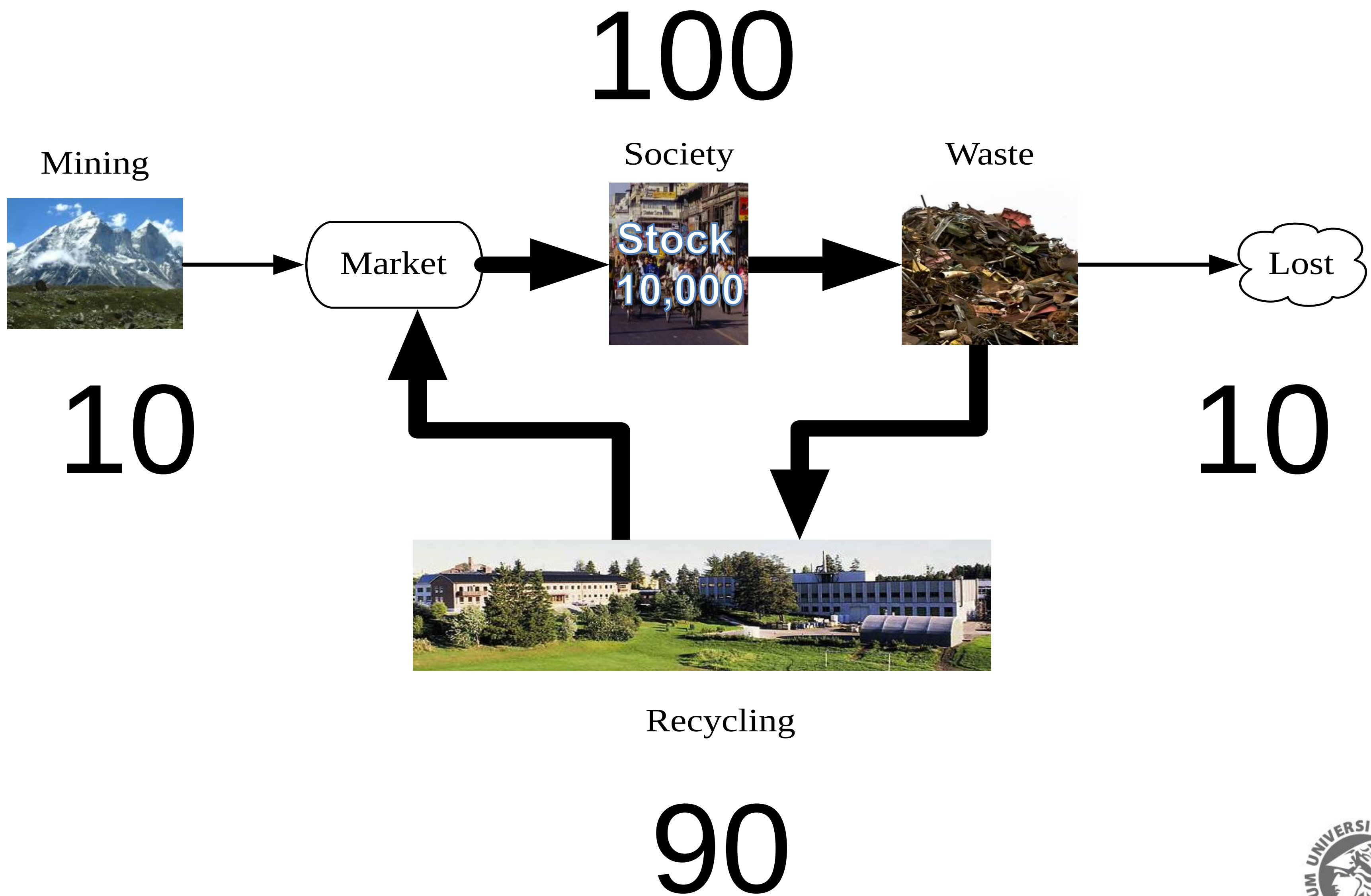
Table 27. Present global production rates, present recoverable reserves, estimated recycling rates and the fraction of total extracted still remaining in the society and available. Metals in italics were not included in Hubbert's estimates here because of problems with reliable data and mining information.

Metal	Production 2012, ton/year	Presently recoverable reserves, ton	Recycling, according Figure 22. %	Present known reserve to production ratio, years	Estimated peak production year
Iron	1,400,000,000	340,000,000,000	60	242	2032
Aluminium	44,000,000	22,400,000,000	75	436	2080
Manganese	18,000,000	1,030,000,000	45	57	2020
Chromium	16,000,000	437,000,000	22	27	2026
Copper	16,000,000	558,000,000	60	35	2034
Zinc	11,000,000	1,110,000,000	20	101	2030
Lead	4,000,000	693,000,000	65	173	2018
Nickel	1,700,000	96,000,000	60	56	2025
Titanium	*1,500,000*	*600,000,000*	*20*	*400*	*n. d.*
Zirconium	*900,000*	*60,000,000*	*10*	*67*	*n. d.*
Magnesium	*750,000*	*200,000,000,000*	*40*	*260,000*	*n. d.*
Strontium	*400,000*	*1,000,000,000*	*0*	*2,500*	*n. d.*
Tin	300,000	76,200,000	20	254	2036
Molybdenum	280,000	22,500,000	40	80	2045
Vanadium	260,000	19,400,000	40	75	2076
Lithium	*200,000*	*4,900,000*	*10*	*25*	*n. d.*
Antimony	180,000	7,000,000	15	39	2018
Rare Earths	*130,000*	*100,000,000*	*15*	*770*	*2060*
Cobalt	110,000	11,600,000	40	105	2026
Tungsten	90,000	2,900,000	40	32	2029
Niobium	68,000	3,972,000	60	58	2025
Silver	23,000	1,308,000	80	57	2034
Yttrium	*8,900*	*540,000*	10	61	*n. d.*
Bismuth	7,000	360,000	15	51	2011
Gold	2,600	135,000	95	52	2012
Selenium	2,200	171,000	5	78	2022
Cesium	*900*	*200,000,000*	0	220,000	*n. d.*
Indium	670	47,100	40	70	2022
Tantalum	600	58,500	25	97	2005
Gallium	280	5,200	15	19	2026
Beryllium	*250*	*80,000*	20	*320*	*n. d.*
Palladium	200	36,000	60	180	2020
Platinum	180	44,100	70	245	2020
Germanium	150	12,500	30	83	2022
Tellurium	120	11,080	0	92	1984
Rhenium	50	4,190	85	84	2038
Rubidium	*22*	*5,000,000*	0	*227,000*	*n. d.*
Thallium	*10*	*380,000*	0	*38,000*	*1995*

Recycling is far too low for most metals and materials!

Sverdrup and Ragnarsdottir 2014

Factor X – importance of recycling



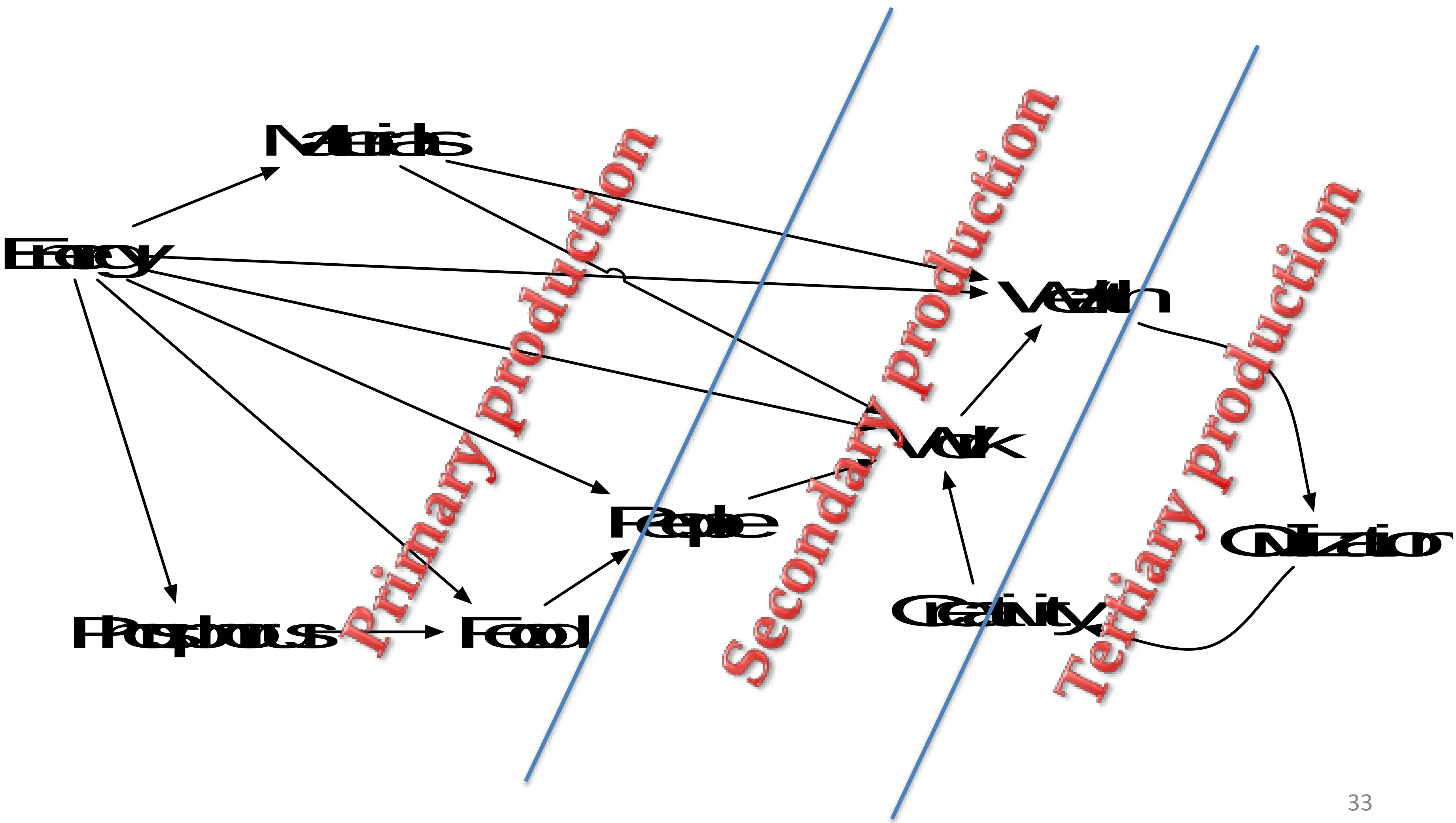
WHAT CAN WE AFFORD?

Economic growth

“Economic growth takes place when people take natural resources and transform them into something more valuable”

Paul Romer,Economist, Stanford

Where does wealth come from?



The Roman Empire

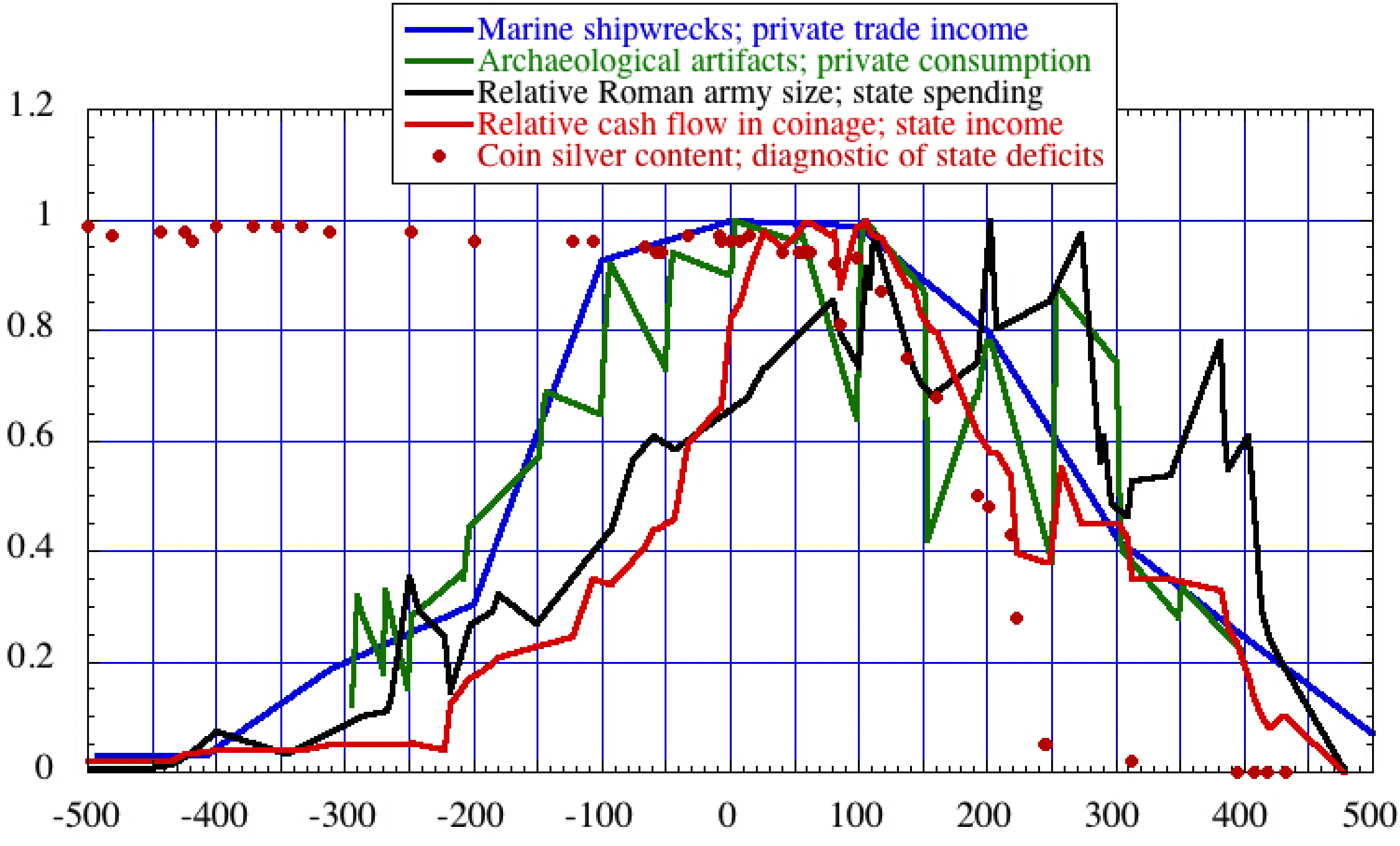
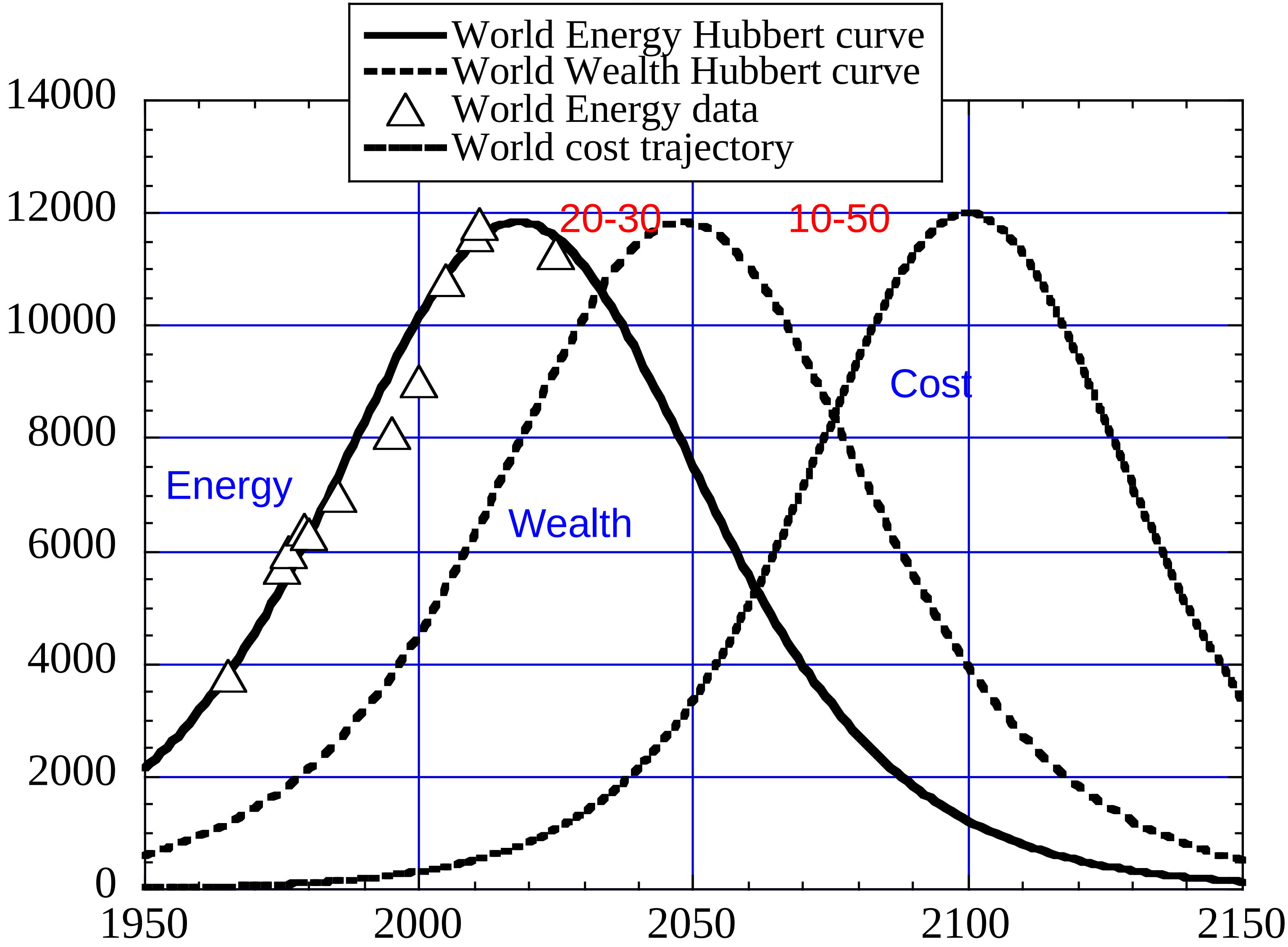


Table 4. *Known resource discovery, resource extraction and wealth creation peaks, cost over wealth overshoots and predicted civilization declines, an attempt at a preliminary prognosis. Red numbers are predicted dates, black dates are the observed based on historical data. The decline dates assume that governance and society continues along the practice of business as usual, without any measures to attain sustainability.*

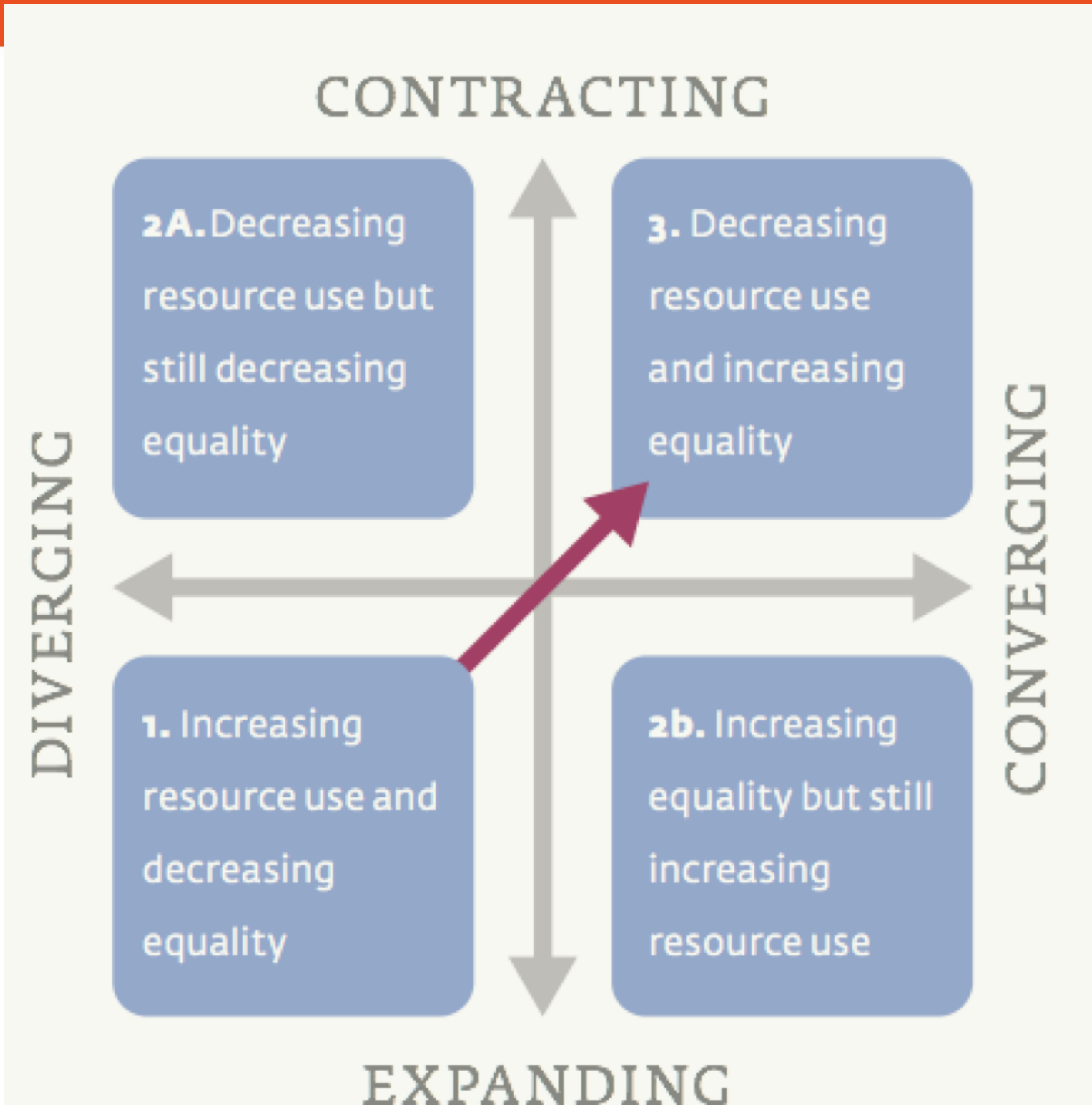
Empire	Predicted with meta-model prototype based on the WORLD-model, outputs in calendar year					Observed decline
	Discovery peak	Resource peak	Wealth peak	Cost larger than wealth	Predicted decline	
Roman	14 AD	80-120	120-160	180-220	240-280	First 287 Final 370
British Empire	1888	1928	1938-1943	1958-1963	1978-1981	Dismantled 1947-1965
Spanish	1520	1550	1565	1580-1600	1620-1660	1700-1750
Soviet	1932	1948	1960	1985-1990	1995-2005	1990-1993
Russian	1880	1993	2005	**2020-2025**	**2035-2045**	n.a.
American	1955	1971	1983-1986	1991-2006	**2010-2030**	2008-2012
Chinese	2000	**2020-2025**	**2035-2040**	**2050-2060**	**2060-2080**	n.a.
Indian	1990	**2030-2040**	**2045-2055**	**2068-2080**	**2077-2090**	n.a.
Global	1975	2007	**2017-2022**	**2040-2060**	**2060-2080**	n.a.

20-40 10-15 20-30 10-50 years



After peak energy, is peak wealth and thereafter peak cost (i.e. decline)

WHO HAS WOKEN UP?

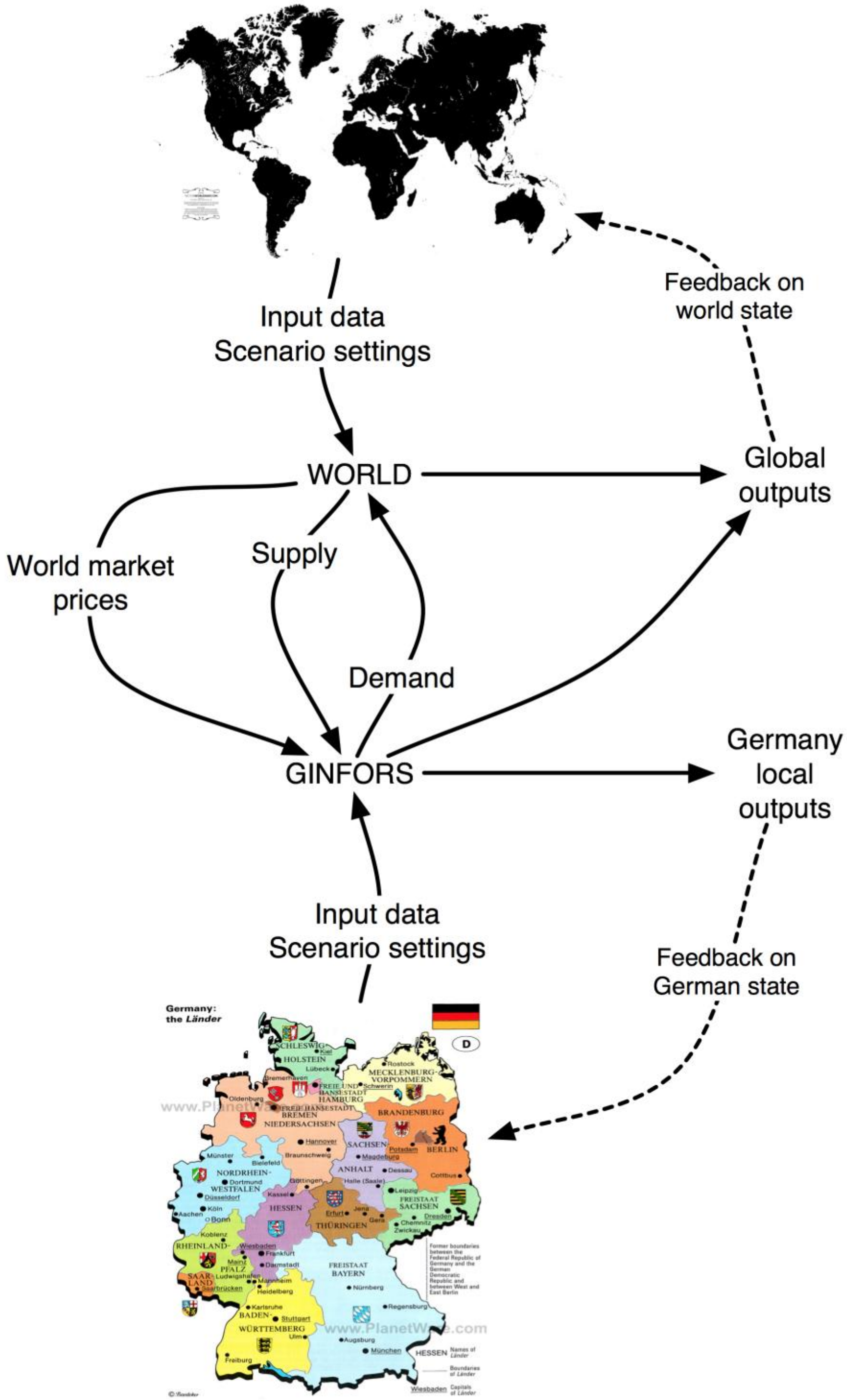


CONVERGE

Many academics know there is a problem

ECs calls fragmented

Vadovics et al. 2012



German SIMRESS integrated modelling project

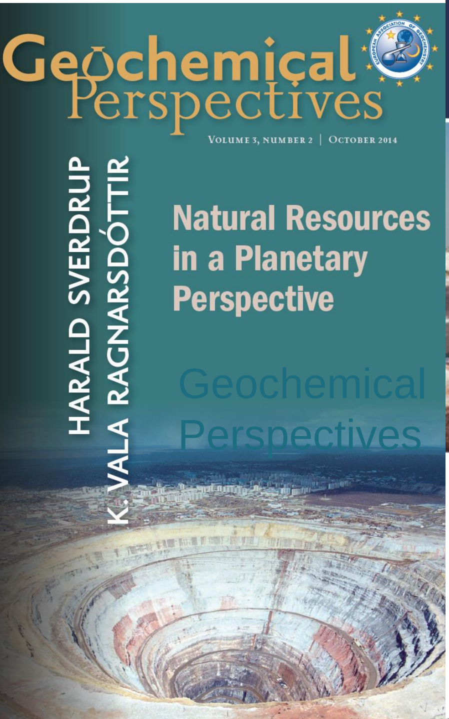
Answers to the questions: Since we live on a limited non-homogenous planet…

- Substitution is a limited option
- We need to recycle metals and materials >90%
  - Economic growth through recycling
  - Oil will no longer fuel economy; energy challenges
- We can **not** afford Business as Usual
  - Social innovation needed; corruption to be tackled
  - New development indicators needed

Thanks to collaborating teams

- CONVERGE: www.convergeproject.org
- SoilTrEC: www.soiltrec.eu
- SIMRESS: http://simress.de/en
- ASAP: www.asap4all.org

Copy of slides available, just ask…



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KRISTÍN VALA RAGNARSDÓTTIR is Professor at the Institutes of Earth Sciences and Sustainable Development, University of Iceland. Her work was initially on the geochemistry of geothermal systems but then she moved into environmental science, cement chemistry, radioactive waste disposal, biogeochemistry, soil science, natural resources, and sustainability. She has a long-standing interest in the link between environment and health and has undertaken research that is related to response to climate change, ecosystem services, sustainable communities, food security and aquaponics. Her career has taken her to work in USA, UK, Germany, France and Norway. She is elected member of Academia Europaea, Norwegian Academy of Science and Letters, Icelandic Academy of Science, and the Royal Academy of Arts (UK). She has been invited member of international scientific expert groups of UNEP, on Depleted Uranium use in conflict areas, and Government of Bhutan's New Development Paradigm. Vala is associate editor (AE) of Solutions and was AE for Chemical Geology, Geochimica et Cosmochimica Acta, Geochemical Transactions and eEarth. She is the Vice-President of the Balaton Group, Member of the Club of Rome, and Distinguished Fellow of the Schumacher Institute (UK). Vala also sits on the board of a number of environmental and social justice NGOs. When not with her nose in a book, Vala enjoys growing food, cooking and being in the mountain hut with Harald, family and friends.

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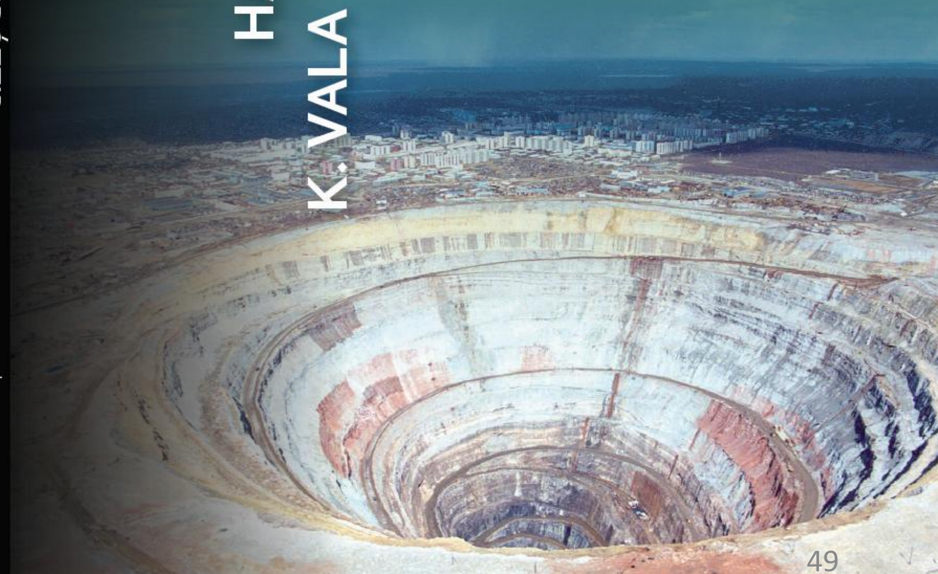
HARALD SVERDRUP
K. VALA RAGNARSDÓTTIR

Natural Resources in a Planetary Perspective



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