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Notes

Future Rx: optimism, preparation, acceptance of risk

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Abstract: The world contains the energy and mineral resources needed to sustain 10.5 billion (the level the world population is expected to reach in 2100) at a European standard of living for hundreds of centuries. Using physical and chemical principles to extrapolate from what we know, it is shown that the required resources are present, largely in the world's oceans. The environmental consequences of shifting to ocean supply will be positive, and a transition from fossil fuels to low carbon energy sources is provided by natural gas. The eventual steps required are big (thousands of nuclear reactors, country-size solar facilities in desert areas, large mining operations) and there are risks, but the risks are small compared with failing to meet the expectations of a growing world. The best course is to aim for success (all at European standard by 2113), accept and manage the risks of development, solving unforeseen problems as they arise, accept the transition to gas, and train and engage the best talents to prepare to tap the ocean's resources.



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Generalizations are dangerous, but it is probably fair to say that most people today have come to regard the Earth as a tiny, fragile life raft floating alone in the vastness of space and threatened as never before by a species that has proliferated beyond reason to the point where it is changing the planet itself and threatening its ecological viability. This is a view that plays well to our oldest myths: humans are flawed, the end is nigh, salvation will only come if we repent our evil ways.

Yet how much of this is true, and how should we change? The details are missing. The devil is always in the details. Many books have been written about this situation, but surely one of the most insightful, readable and helpful is a very recent one: *Earth: A Tenant's Manual*, by Frank H. T. Rhodes (2012). He laments that in our busyness we have not taken the time to engage in conversation and hopes that his book can stimulate informed discussion on how to live harmoniously on our venerable planet. I hope this paper can be part of that discussion.

My perception is that what is most lacking is optimism. Rhodes quotes Woody Allen: 'More than any other time in history, mankind faces a crossroads. One path leads to despair and utter hopelessness. The other, to total extinction. Let us pray we have the wisdom to choose correctly.' This short paper gives an optimist's prescription for the future. It argues that our number-one goal over the next century must be to raise all of humanity to a European standard of living, and it argues that the Earth has the resources, in the oceans, to do this and to sustain humanity for hundreds of centuries thereafter. It argues that, if we have the courage to do big things, all of humanity has a fine future.

The first section of the paper describes our current situation, establishes the need for the goal of 'all to an EU standard by 2113', and culls some of the false (too many humans) from real (energy and mineral supply) challenges to reaching this goal.

The second section addresses whether the Earth's energy and mineral resources are adequate to achieve the goal. It is not easy to assess resource adequacy over hundreds of centuries, but it can be estimated by extrapolating forward from fundamental physical and chemical principles. Doing this shows that we have more than adequate energy and mineral supplies, and identifies our soil resource as perhaps the most vulnerable. The discussion is necessarily quantitative (we want to know if the resources are adequate), but here the focus is on the logic of the analysis. Details can be found starting from the references given. The treatment makes no pretence of being exhaustive. The intent is only to show how a more-than-acceptable future might be secured.

The third section discusses the transition from where we are now to where we would like to be 100 years from now, and argues that shifting to unconventional gas on the way to non-fossil energy sources makes great sense, will build confidence and construct a good part of the infrastructure that will be needed for the second half of the 100-year transition.

The fourth section asks why we have found it so hard to chart and take a path forward, or even agree that there is a way forward. It suggests that the main reason may be that we are confused and blinded by specialization, and that we must find ways to deal with this aspect of the modern condition. The fifth section gives my prescription for

what we should do, and the last section provides a short summary.

The current situation, the grand challenge and a way forward

Things are good

At present things are very good. They have probably never been better in all of human history. As documented by Bjorn Lomborg (2001), we have never lived longer and we have never lived better. From 1200 to 1900 the life expectancy of males in England was about 40 years, but in the twentieth century it increased rapidly to almost 80. Mortality has decreased precipitously in this period as inoculations have controlled infectious diseases. As Lomborg states, population is increasing ‘not because we are breeding like rabbits but because we are not dropping like flies’. Life expectancy in Sub-Saharan Africa increased from 35 in 1950 to 48 in 2010, and is expected to rise to 65 in 2050. In 1930 the average Chinese person could expect to live to 24, but can now expect to live to 70. Furthermore, the fraction of life spent with disability is less for those who live longer. Those with a life

expectancy of 45 years spend about 15% of their life with disability, whereas those with a life expectancy of 85 spend 8%. We have never lived longer and we have never lived better. We have never had more to eat, more access to clean water, more energy or more supportive infrastructure. We have never been safer or healthier. Food has never cost less. We have never been better educated. We are working less than ever before (more free time). Inequality is decreasing worldwide. We acquire new things remarkably rapidly (refrigerators, cell phones, cars, etc.) in the poor as well as the rich world. Things are getting better.

But can it last?

The grand challenge

The human population is presently 7.13 billion, and by c. 2113 it is expected to peak at 10.5 billion (Demeny 1984; Fig. 1). Every human rightly aspires to a first-world living standard. If there are the resources to meet this goal in an environmentally acceptable fashion, everyone would surely agree that it should be done. Not to do so would be unthinkable. It would mean not only that a large fraction of humanity has no future, but, more importantly, it would mean that humanity has no

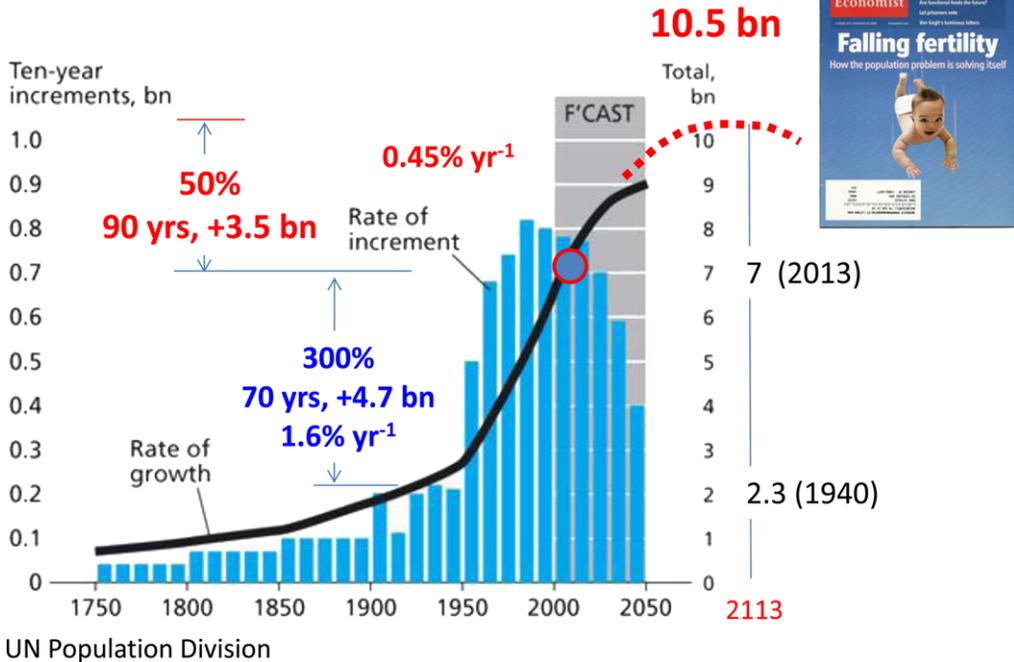


Fig. 1. Population growth peaked in 1980 and the world population is expected to peak in c. 2113 at 10.5 billion. Base figure and insert image are from the 31 October 2009 edition of *The Economist* magazine.

common future. We would be divided forever into competing haves and have-nots.

The grand challenge for the world is to bring everyone to a European standard of living by 2113. The question that I address here is whether this goal is possible to achieve in an environmentally acceptable way and to be sustained for a very long period of time.

Population is not the problem

Figure 1 shows the projected growth and rate of growth of the human population from 1750 to 2050. It shows that the rate of growth has decreased since 1980, and projects that this will continue. The population will peak at about 10.5 billion 100 years from now and then probably decline. The population has tripled over the last 70 years (my lifetime) and will increase by an additional 30% over the next 90 years. The total increase in the number of humans will be similar (3.5 billion v. 4.7 billion in the earlier period), but the rate of increase will be less, and the growth in the population will be slowing rather than accelerating.

We have thrived as the population has tripled, so absent a compelling cause there is no reason per se to be anxious about a further increase of 30%. A declining population (such as is occurring

in Japan and parts of Europe) may, in fact, be more difficult to manage than an increasing population (Longman 2004). The question here is whether the resources needed to raise everyone to an European standard for a very long time are present and can be tapped in an acceptable fashion.

What is required

Energy is the most essential resource. With energy, all else is possible; without it almost nothing is possible. It is no surprise that the per capita gross domestic product is roughly proportional to the per capita power consumption (Fig. 2). The poor world consumes power at <1 kW/person (kilowatt per person). The rich world consumes it at c. 7 kW/person. The per capita power consumption in Bangladesh of c. 250 W/person is equivalent to one-third of a horse working 24 h and 7 days a week for each person, about the same as the horse allocation per soldier in the First World War. A third of a horse is a great deal better than no horse at all. Think of carrying the equipment yourself. However, a third of a dedicated horse is a long way from the luxury of 14 dedicated horses that the average US citizen enjoys. The average Bangladeshi could continuously light two and a half 100 W light bulbs if they dedicated their total yearly energy

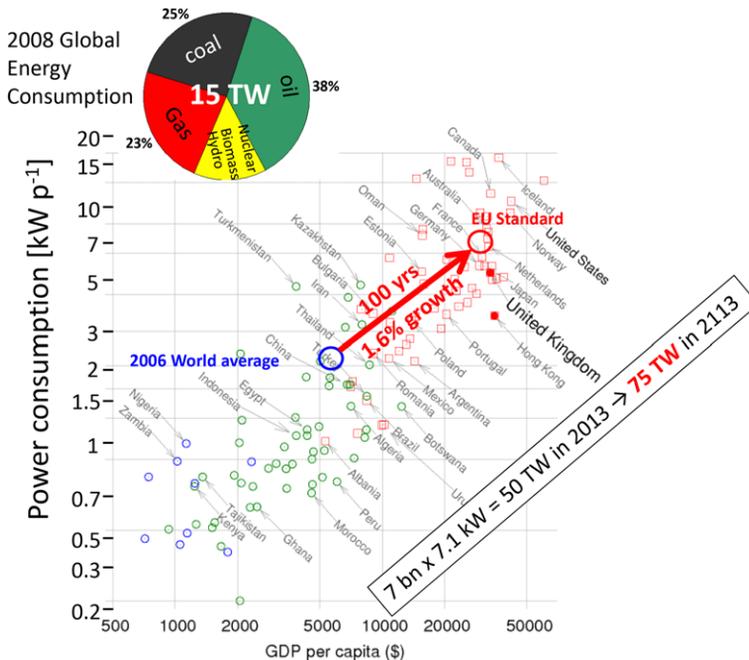


Fig. 2. Relationship between power consumption and gross domestic product per capita (standard of living). Our goal (red arrow) is to provide power at the European standard to each person in the world 100 years from now. Base figure is figure 31.1 in Mackay (2009).

allocation to this task, whereas the average US citizen could shine with over 100 such bulbs.

The world currently consumes 15 TW (terawatts or 10^{12} W) of power for all purposes (e.g. heat, transportation, electricity). Most of the power comes from hydrocarbon sources (Fig. 2). Meeting the challenge of supplying every human with the energy consumed each year by the average French or Australian person of 7 kW would require 50 TW for today's population of 7 billion, and 75 TW in 2113 when the human population is forecast at 10.5 billion. Increasing from 15 to 75 TW over 100 years represents a compound growth rate of 1.6% per year, which is not very daunting. Between 1960 and 2010 US energy consumption increased at *c.* 2.6% per year. Meeting our grand challenge therefore requires only a modest growth in worldwide power delivery.

The energy options

David MacKay (2009), an English physicist, has addressed the question of energy supply with simple back-of-the-envelope calculations. He insists that the plans add up (e.g. that they supply the energy they postulate in a realistic fashion) and emphasizes that 'every big counts'. We will not obtain the energy we need with small measures.

Country-sized steps are needed. He assesses both conservation and renewable production. He shows that the current UK energy consumption could be reduced by 42% from 8.1 to 5.6 kW/person, mainly by electrifying transportation and using heat pumps to heat buildings. He finds that renewables of all kinds (tide, wave, hydro, waste pumped heat, wood, solar, biofuels, photovoltaics and wind) might conceivably contribute 1.4 kW/person, but realistically could contribute only about half this amount.

The challenge with renewables is their huge land area requirements. Table 1 shows the land requirements for MacKay's middle plan (plan M). The largest renewable energy source in MacKay's analysis is pumped heat (e.g. heat extracted from the ground, air or water with heat pumps). Biofuels and wood could supply a significant amount of energy, but at the cost of very high land occupation. Over 36% of the agricultural land area of the UK is dedicated to biofuels and wood in the example in Table 1 and Figure 3. This is so large that MacKay considers it unrealistic. About half the renewable energy supply shown in Table 1, or 700 W/person (43 GW), might be possible, but even so, large amounts of land would be required. Although 43 GW of renewable energy is a lot, it is only *c.* 10% of the 444 GW that is required to supply the 63.5 million current UK citizens with

Table 1. *The possible renewable contribution to the energy consumption in the UK as calculated by methods discussed in MacKay (2009)*

Harvesting method	W m ⁻²	A (km ²)	% Ag	GW	W/person
Geothermal (34.5%)					
Pumped heat				30	472
Plants and refuse (23.5%)					
Biofuels	0.167	30 000	18.1	5	79
Wood	0.417	30 000	18.1	12.5	197
Incinerators (100, 30 MW)				3	47
Wind (21.9%)					
Onshore	2	5200	3.1	10.4	164
Offshore	3	2900		8.7	137
Ocean (11.5%)					
Wave farms (130 km)		550		0.76	12
Severn barrage		800		2	31
Tidal lagoons				1.75	28
Tidal stream (1500 turbines)		2000		5.5	87
Local solar (8.6%)					
PV farms	5	1000	0.6	5	79
Solar hot water	41.7	60	0.0	2.5	39
		Totals	39.9	87	1372

The population of the UK today (2013) is *c.* 63.5 million and the agricultural land area is 166 000 km² (*c.* 70% of the total land area). The first column indicates the category of renewable contribution with the number in parentheses in each category indicating the percentage it contributes to the total. The second column lists the power that can be generated per square metre by the harvesting method listed. The third column gives the land area dedicated, the fourth column the percentage of the agricultural land this area represents, and the last two columns the total power and power per capita. The numbers are from MacKay (2009) with the per capita power consumption in the last column updated to the current UK population of 63.5 million from the 60 million assumed by MacKay.

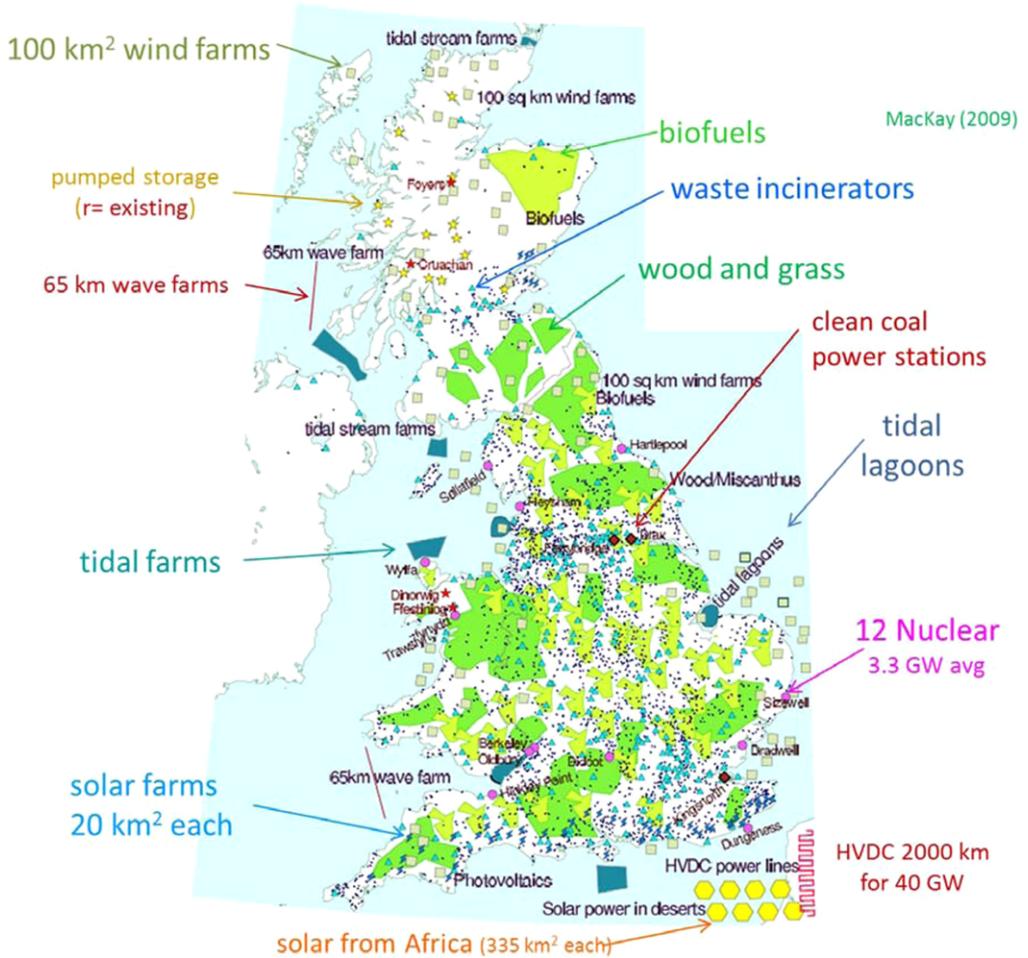


Fig. 3. Land requirements of the energy plan in Table 1. Figure is annotated version of figure 28.2 in Mackay (2009).

7 kW/person, and the percentage will drop as the population grows. Mackay concludes that only nuclear or concentrated solar from (in the UK's case) somebody else's desert could realistically supply 7 kW/person to the UK or any other citizenry.

What amounts of concentrating solar infrastructure in deserts or nuclear stations would be required? To supply 63.5 million UK residents with 7 kW/person power requires 135 3.3 GW nuclear stations or solar mirrors covering a 187×187 km area of the Algerian or Libyan dessert, or some combination of the two. The desert solar calculation assumes 15 W m^{-2} is harvested as electricity and 15% of the electrical energy is lost in the high-voltage DC transmission to the UK (e.g. $7021 \text{ W/person} = 0.85 \times (187 \times 10^3)^2 \text{ m}^2 \times 15 \text{ W m}^{-2} \div 63.5 \times 10^6 \text{ persons}$). Europe, with a population of 1 billion, would require a $750 \times$

750 km area of desert. Poland has dimensions of c. 500×500 km, so the area needed by Europe for concentrating desert power is an area over twice that of Poland. This area would be covered completely with mirrors and would need to be tended and maintained. Water would be required for the steam turbines and perhaps to wash the mirrors. To supply solar power to a global population of 10.5 billion at 7 kW/person would require 30% of the non-polar desert area of the world (30% of $18.6 \times 10^6 \text{ km}^2$ or c. 6% of land area of the Earth). Alternatively, 22 272 nuclear power stations generating 3.3 GW would be required.

In what follows I will consider the nuclear option. Over the next 100 years it seems to me that the solar option will be challenging because it requires long, vulnerable transmission lines, massive infrastructure development and continued

maintenance on other people's land. The offshore wind resources are large (e.g. Schwartz *et al.* 2010; Zayas 2013). If wind farms delivering 3 W m^{-2} were constructed in a 50 nautical mile (92 km) strip along the coasts of the Atlantic, Pacific and Indian oceans (313 000 km), offshore wind could supply 86 TW. Maintenance, power storage and transmission, and protecting such a broadly distributed marine infrastructure from severe storms would be challenging. Nuclear can meet the '75 TW by 2013' challenge with domestic infrastructure and local transmission lines, but requires a large number of power stations to be constructed. All the options mentioned, as well as others, will undoubtedly be pursued, but any viable option that significantly contributes will be of huge numerical or area scale and involve risks. Truly, as MacKay states repeatedly, it is every BIG that counts.

Can we build 22 272 3.3 GW nuclear power stations in 100 years?

Between 1960 and 1990 a US population of *c.* 226 million constructed 110 nuclear power stations with a total power output of *c.* 101 GW. Over the 26 years of the most active construction, *c.* 4.2 plants were built per year. This suggests that a world population of 8 billion could construct *c.* 148 nuclear power stations per year, and 14 800 power stations over 100 years. This is two thirds of the number needed to reach our goal of 'everyone at an European living standard by 2113'. Admittedly the nuclear stations the US constructed in this earlier period were smaller (*c.* 1 GW rather than 3.3 GW), but surely we can build such facilities faster and bigger today. The reactors could be built at factories and installed when all permits were ready and the ground prepared, for example. The 3.3 GW facilities might consist of a collection of Small Modular Reactors.

The scale of construction is not daunting. Never underestimate what large numbers of humans can do. China is in the midst of constructing 221 cities of more than a million people over 25 years, and plans to grow its installed power capability at between 6.6 and 7% per year from 2010 to 2020. In 2008 China's power generation capacity grew at *c.* 12%, so this planned growth is comparatively modest. At 6.6% per year, China will have an installed power capacity of 1.7 TW in 2020. If its expansion were to continue at this rate, its installed capacity 100 years from now would be 1228 TW, more than 16 times our Grand Challenge goal of 75 TW.

Synopsis

The energy infrastructure we need can be constructed. BIG things are required, but humans can

do BIG things at the required, rate. Everyone at an European living standard by 2113 is a feasible goal provided the energy infrastructure can be fuelled and the result is environmentally acceptable. These are geological issues, and I discuss them in the next sections.

The supply of energy, minerals and food

Three planetary-scale wagon trains and a gold-panning operation

Resources are simply materials that nature has concentrated for us. The Earth contains huge amounts of everything we could want, but usually at such low concentrations that it is impossible to recover. Over geological time, natural processes have extracted these materials for us, and transported and deposited them in concentrated form in restricted areas. The key to understanding resources is children with little red wagons.

Consider that on your way home you noticed a number of children pulling little red wagons with a few stones in each wagon – nothing unusual there. When you arrive home, to your surprise, you find your yard piled high with stones. Your reaction is probably not: 'what a nice example of a mineral deposit', but this is precisely the case. The key to mineral deposits is the perfectly natural movement of something (water, magma, air) plus extraction of something (stones) of interest, and the selective unloading of this something at a particular location (your yard).

As illustrated in Figure 4, the world has three planetary size wagon trains: a hydrologic cycle (Berner & Berner 1987) that deposits $37\,400 \text{ km}^3$ of rain on the continents each year, which runs off into the oceans carrying dissolved and suspended material; a haline-driven ocean circulation of 17 Sverdrups or $535\,500 \text{ km}^3$ per year (Rahmstorf 1996), which is driven by thermal and salinity ocean density differences (cold salty water sinks at the poles and circulates at depth around the globe until it warms and freshens by mixing with adjacent less saline and warmer waters); and a hydrothermal circulation cycle of 500 km^3 per year (Cathles 2010a, 2011), operating where the crustal plates pull apart, that circulates seawater to the Moho, heats it to $350 \text{ }^\circ\text{C}$, and discharges it at the ridge axes with enough dissolved minerals to form 'black smokers'. In addition, waves crashing on the shore represent a planetary-scale gold-panning operation that separates fine from coarse material, and heavy from light minerals.

Physically and chemically understanding these planetary-scale circulation systems is what allows us to gauge what resources the Earth has probably

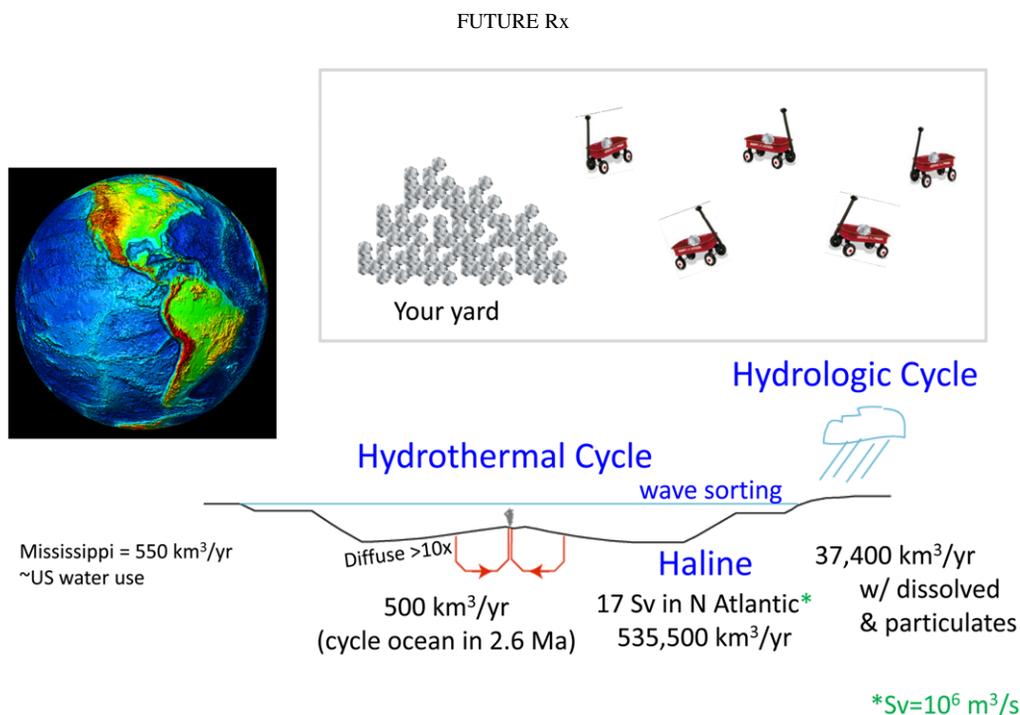


Fig. 4. Illustration of the little red wagon analogy for ore deposit formation and a diagrammatic representation of the planetary-scale wagon trains operating in the world's oceans.

accumulated for us, and to assess the significance of our anticipated demands against this storehouse.

Energy

Uranium for our reactors. In 2005 the global nuclear electric-generating capacity was 369 GW_e (gigawatts of electrical energy from 440 reactors consuming *c.* 67 320 t of uranium (Macfarlane & Miller 2007). At this consumption rate our conventional land reserves of uranium (the U that can be recovered at current prices and technology) of *c.* 5.4 million t will last *c.* 80 years. Land resources of uranium (U that might be recovered if prices were higher or technology better) are conservatively 23 million t, and these could supply our current needs for an additional 341 years. It is expected that nuclear electrical generation will grow to *c.* 860 GW in 2100. If uranium consumption grows concomitantly to 170 000 tonnes of U (t_U) per year, we will need 24.5 million t of uranium between now and 2100. This is about equal to the land resource. Uranium resources are thus considered adequate for the next 100 years, but not much beyond.

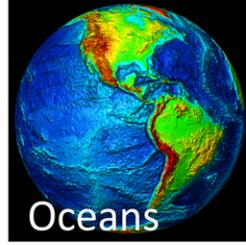
As shown in Figure 5, generating 75 TW_e from conventional nuclear reactors would consume 2.5×10^6 t_U per year and consume half the U

dissolved in the oceans in just 100 years, even though the ocean contains over 200 times the land resource of uranium. On this basis, nuclear reactors might seem a poor option, but with breeder technology nearly 100% of the uranium can be burned, not just the 0.71% that is ²³⁵U. With breeder technology, half of the U in the oceans could supply the world with 75 TW_e for over 100 centuries. We need breeder reactors for long-term sustainable nuclear energy supply from uranium, but these reactors are unlikely to be needed for anywhere near 100 centuries. Long before this period of time has elapsed, fusion power will be available.

Parenthetically, I should comment that this discussion assumes that the electricity generated from nuclear will support all of our energy needs (e.g. transportation and heating as well as electricity). Synergies are not considered. For example, waste heat from a nuclear plant might be used for space heating, but the possibility is not considered. The U fuel requirements estimated are thus maximum requirements.

A drawback to uranium-based breeder reactors is that they convert ²³⁸U to ²³⁹Pu, which can be chemically concentrated to weapons grade. Thorium is an alternative breeder material that is more difficult to weaponize (Macfarlane & Miller 2007). When bombarded by thermal neutrons it produces ²³³U, an isotope of uranium that does not occur in

	U ₃ O ₈ (10 ⁶ t)	U (10 ⁶ t)
Reserves	4.7	3.9
Resources	35	28.7
Dissolved in Ocean (3.3 ppb)		4600



1 tonne uranium supplies 97x10¹² joules of electricity:

$$(1t_U)(0.0071t_{^{235}\text{U}}t_U^{-1})(0.25\text{ conv. to ele})(2/3)(81.7 \times 10^{15} \text{ J } t_{^{235}\text{U}}^{-1}) = 9.7 \times 10^{13} \text{ J}_e$$

burned in reactor

$$1\text{GW}_e = 10^9 \text{ J}_e \times 3.15 \times 10^7 \text{ s } y^{-1}$$

Thus, a 1 GW_e reactor consumes 334 tonnes of U per year:

$$\frac{3.15 \times 10^{16} \text{ J}_e}{9.7 \times 10^{13} \text{ J}_e t_U^{-1}} = 334 t_U$$

50% ocean resource

Assuming population
is steady at 10.5 bn

$$\text{supply} = \frac{2.3 \times 10^9 t_U}{(75 \times 10^3 \text{ GW}_e)(334 t_U \text{ GW}_e^{-1})} = 25 \times 10^6 t_U y^{-1} = 94 \text{ yrs}$$

breeder = 94 yrs × 100 = 94 centuries **Need breeder reactors**

Does not count Th reactors

Or that in a few centuries we will have fusion power

Fig. 5. A little more than 0.2 g per mole is lost in the radioactive decay of ²³⁵U. By Einstein's $E = mc^2$, this liberates 81.7×10^{12} J per kg of ²³⁵U. About 25% of this can be converted to electrical energy; the rest is lost in heat. A conventional reactor consumes about two-thirds of the fuel placed in it. Since 0.71% of uranium is ²³⁵U, a tonne of uranium supplies 9.7×10^{13} J_e, and running a 1 GW_e reactor for 1 year requires c. 334 t of uranium fuel. For 75 TW_e, 25×10^6 t uranium would be required each year. Half of the uranium dissolved in the ocean supply would provide 94 years of supply. With breeder technology, this uranium would last >94 centuries and 2.5×10^5 t of uranium would be required each year.

nature but which is more fissionable (releases more neutrons per neutron absorbed) than either ²³⁵U or ²³⁹Pu. All the thorium burns in a reactor. Thorium is thus a nuclear fuel that needs no breeding. There is c. 20% ²³³U in the running reactor. Centrifuge enrichment to 99% ²³³U would be needed to produce a weapon. Centrifuge facilities are extensive and much easier to spot than chemical laboratories, so the weapons risk will be much easier to manage for thorium reactors than for uranium breeder reactors. This could be important when the reactors are deployed on a large scale.

Thorium reactors have many other advantages over uranium fast breeder reactors: they need c. 1 tonne of ²³³U to start (v. the 5–10 t of Pu needed for a fast breeder), require one-tenth of the fuel per GW_e-y (gigawatts of electrical power for a year) to run (30 t_{Th}/GW_e-y v. 300 t_U/GW_e-y for

a conventional uranium reactor), and generate <4 kg of waste/GWe-y which decays in 500 years (compared with 40 t/GWe-y which decays in 10 000 for a conventional uranium reactor; Thorium Energy Alliance 2012). Reserves of thorium are c. 5×10^6 t (World Nuclear Association 2012), enough to sustain 75 TW_e for 20 centuries. Thorium is four times more abundant in the Earth's crust than uranium and has not been the focus of much exploration activity, so it is likely that the resources of thorium could grow dramatically if and when we pay more attention to it.

More could be discussed, but at this point two things seem clear: (1) the nuclear resources we need are in the oceans (or in thorium deposits); and (2) breeder technology (or a nuclear fuel like Th that fully combusts) is needed if we are to supply energy at 75 TW for more than a few centuries.

Extracting U from the oceans. Nature could do much of the work required to extract the needed uranium from the oceans, and the footprint of the required facilities is tiny! Figure 6 shows a cross section of ocean currents off Cape Hatteras, and illustrates how curtains (e.g. areas of uranium-extracting fabric) hung across a 500 m by 50 km area on the ocean floor would intercept the needed 250 000 t of uranium each year. If the curtains were hung in shallow waters across the Gulf Stream, where the current is 18 times stronger, a 125 m by 10 km long line of curtains would suffice.

A couple of quick points: Bernard Cohen (1983), a University of Pittsburg physicist, pointed out the potential of breeder technology and the ocean uranium resource for supplying nearly endless energy to humanity in a one-page paper. It is elegant, short and worth reading. The Japanese have demonstrated that uranium can be extracted from seawater at a cost of $c. \$300 \text{ kg}_U^{-1}$ (about 2.5 times the current price of $\$130 \text{ kg}^{-1}$). They immersed 0.35 t of fabric in seawater for 240 days and recovered 1 kg_U (kilograms uranium). They confirmed this result in 2006, and estimated that a facility that could recover 1200 $t_U a^{-1}$ (what Japan formerly used each year in their reactors) would cost $\$240 \text{ kg}_U^{-1}$. With eighteen 60-day immersions the fabric loading was

4 g_U per $\text{kg}_{\text{adsorbant}}$. In 2012 the Oak Ridge National Laboratory reported a new adsorptive material called HiCap that can achieve similar loadings much faster (see Wikipedia, uranium mining).

Extraction efficiencies would need to be high for the footprint to be as small as estimated in Figure 6, which assumes 100% extraction of seawater uranium as the water passes through the fabric curtain. To work in deep water, the extraction would have to be effective at low temperatures (Macfarlane & Miller 2007). Nuclear fuel costs very little, however, so doubling its cost will not impact significantly on the cost of electricity generated in nuclear facilities. We could fuel our reactors with uranium from seawater now if the Japanese processes could be scaled up. In 50–100 years we should certainly be able to extract uranium from seawater, and this capability would give most of humanity easy access to this fuel since most of us live near the ocean.

Materials

Copper and zinc. With an energy supply of 75 TW assured, what about the other materials that will be needed for a sustainable future? Copper is a ductile, corrosion-resistant and malleable metal

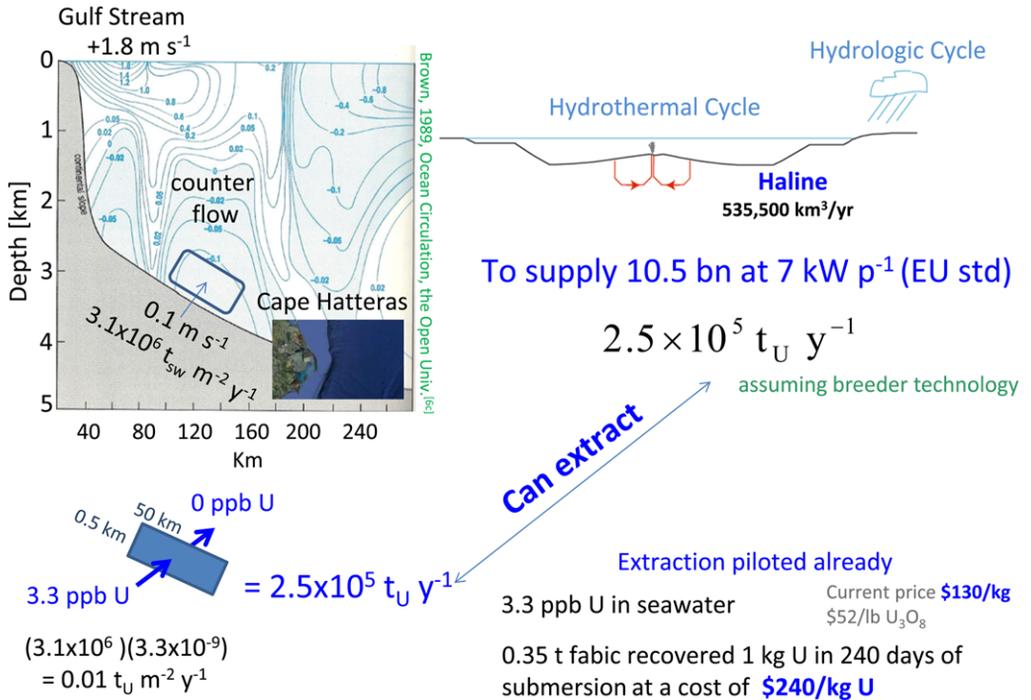


Fig. 6. Ocean currents can be utilized to provide much of the energy need to extract uranium from seawater. Insert figure is modified from Bearman (1989).

that is an excellent conductor of heat and electricity. These properties make it a fundamental part of much of the technology in modern life. It is used in electrical wiring and transmission lines, internet lines, wiring in electric generators and transformers, radiators in cars, and for heat dissipation in electronic equipment. Its antibacterial properties make it desirable in plumbing and building applications such as door knobs. Other materials could substitute for some of these functions, but copper is likely to remain critical for the generators and transformers that we will need in abundance if we are to tap wind or ocean energy in significant amounts.

Each person in the developed world uses *c.* 200 kg of copper over their lifetime. Over a century, about half is dissipated by abrasion and dispersion (e.g. pennies lost and never found). To bring 10.5 billion people to a European standard of living will thus require an initial investment of 2.1 billion t of Cu, and a sustained supply of 1.05 billion t of copper each century thereafter (Gordon *et al.* 2006).

The current land resource of copper is *c.* 1.6 billion t (Gordon *et al.* 2006), which could bring only 8 billion people to the current European level, and they would fall back to zero copper per person in only 150 years at current dissipation rates.

The picture is far rosier if we consider the copper resources on the ocean floor. The oceans have been formed by seafloor and back arc spreading processes that precipitate base metals on the seafloor. From geological observations and inferences we can estimate how much copper has been deposited. Figure 7 shows that, when we do this, we find that the ocean resource should be *c.* 241 billion t of copper. As shown in that figure, this should be enough to last 10.5 billion people for 112 centuries. Of course the supply will last much longer because, in the distant future, we will realize the seriousness of the dissipative losses and take steps to reduce them. We will not make small objects like pennies that are easily lost out of copper, and we will not use copper where it can be dissipated by abrasion.

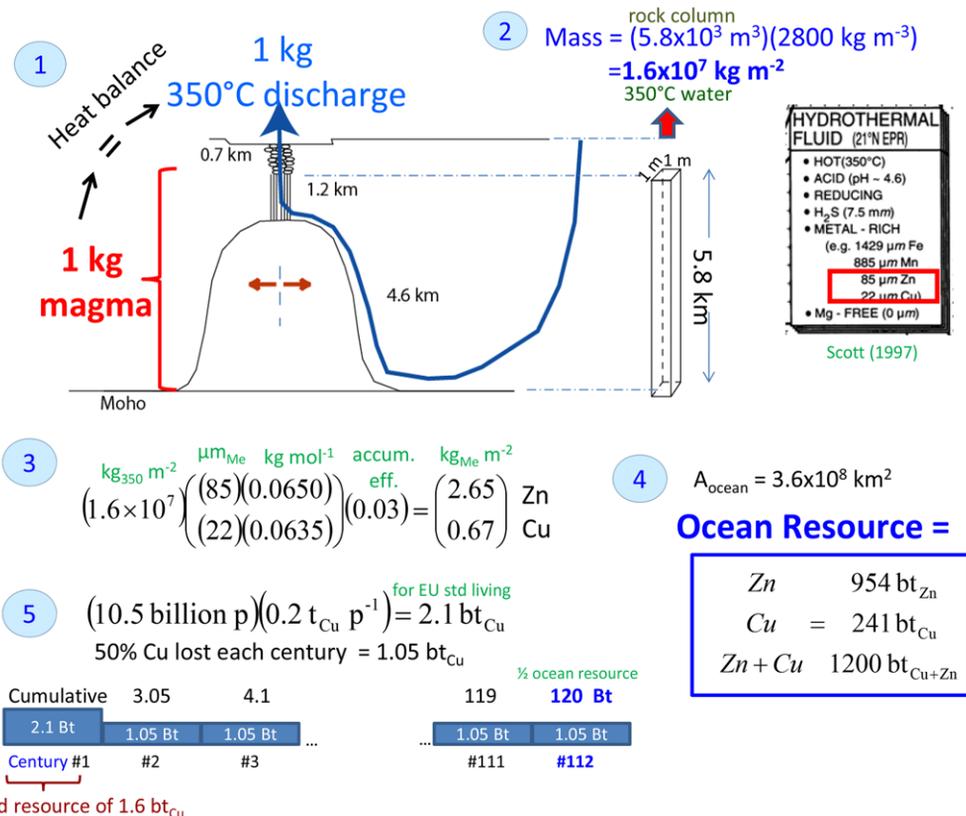


Fig. 7. Estimation of copper and zinc resources on the ocean floor from heat balance, observed Cu and Zn in black smoker vents, and observed and estimated metal accumulation efficiencies (Cathles 2010a, 2011). Vent chemistry in (2) is from Scott (1997).

As illustrated in Figure 7, the ocean copper resource (Cathles 2010a, 2011; Hannington 2010) is estimated from heat balance (1 kg of new crust can heat 1 kg of seawater to 350 °C) and the observation that the ocean crust is cooled by seawater convection at the ridge axis. Heat is extracted from 5.8 km of crust, so on average each square metre of ocean floor has 1.6×10^7 kg of 350 °C mineral-laden seawater pass through it. Of course not every square metre of the seafloor will see this throughput. Some areas will host the discharge, and others will not. However, on average this throughput pertains. We know the concentration of copper and zinc and other metals of the 350 °C waters discharging at the ridge axis today, and can calculate the base metal throughput carried by this hydrothermal discharge. From land deposits, and observations of accumulation at 21°N on the East Pacific Rise, we expect that about 3% of the metal throughput will accumulate in seafloor massive sulphide (SMS) deposits near the vents. Under these conditions the floor of the world's oceans will contain 241 billion t of copper and 954 billion t of zinc. Taking half of this endowment, we find that seafloor copper can supply 10.5 billion humans for 112 centuries at the current copper dissipation rate of 50% lost per century. The longevity of the SMS ocean resource for zinc can be estimated in a similar fashion. A European living standard lifetime consumption of zinc is also 200 kg per person, but 70% is dissipated each century under current practice (galvanizing, etc.). On this basis, half of the 954 billion t of the zinc resource on the seafloor would last humanity 323 centuries. The oceans are obviously and logically the world's largest volcanic massive sulphide district.

Manganese nodules that are rich in Cu, Ni and Co represent an additional seafloor copper resource of potential significance. Early estimates placed the Mn nodule Cu resource at between 2 and 9 billion t. Site-specific mining targets are collectively a much smaller resource (0.16 billion t; Laznika 2010). The best current estimate for the resource between the Clarion and Clipperton fracture zones in the Pacific, one of the richest and best studied Mn nodule areas, is 0.29 billion t Cu, 340 billion t Ni and 58 billion t Co (Morgan 2012).

Economics of recovery. These base metal resources may be on the seafloor but can they be mined? Not only can they be mined, but the first ocean mining operations could begin in the next few years, and the recovery will involve considerably less environmental damage than occurs in the mining of land resources.

The economics (D. Heydon, Deep Green Resources, pers. comm. 2011) can be appreciated by comparing ocean mining with that of a porphyry

copper deposit on land. Porphyry deposits currently supply about 60% of the world's copper. It costs *c.* \$3.50 to mine a tonne of rock and the typical stripping ratio of a porphyry deposit (the tonnes of rock you must mine to uncover and mine a tonne of ore) is 3:1. Thus to mine 1 t of ore you must move 4 t of rock at a cost of \$14 t⁻¹ of ore. Porphyry ore typically has a copper grade of 0.6 wt%. A high-grade SMS deposit such as Solwara I in the Bismark Sea, in comparison, has a copper grade of over 6 wt%, and the stripping ratio is zero because the ore is exposed on the seafloor. Mining an SMS deposit is therefore economically competitive with mining a porphyry copper deposit if the mining cost is <\$140 t⁻¹ of ore. SMS mining costs are expected to be *c.* \$80 t⁻¹. Provided the shipping costs to China are <\$70 t⁻¹, mining SMS deposits similar to Solwara I appears economic. Mn nodules with Cu, Ni, Co and Mn are even more economic because, at an equivalent Cu grade of 14 wt%, they are competitive at mining cost of \$326 t⁻¹. An equivalent Cu grade includes the value of the other metals in the nodules. For example, typical resource nodules containing 1% Cu, 1% Ni, 25% Mn and 0.22% Co, and metal prices of \$7567/t_{Cu}, \$18 149/t_{Ni}, \$2970/t_{Mn} and \$32 100/t_{Co}, would have a combined metal content 14 times the value of their contained Cu, and the equivalent copper grade would be 14 wt% Cu.

Nautilus Minerals (<http://www.nautilusminerals.com/i/pdf/2012-Q2-FactSheet.pdf>) hopes to begin mining the Solwara deposit in the Bismark Sea in the next few years. Mining leases and the necessary environmental permits have been secured, and construction of the various components of the remote-controlled mining system has begun. There have been delays, and funding is being sought to continue this construction in the face of these delays. Copper grades of the deposit have increased with further drilling to more than 7% copper, and a pleasant surprise is that the gold value of the ore (*c.* 5.7 grammes per tonne) is almost half the copper value at current prices (\$630 t⁻¹ at \$4.50/lb Cu and \$312 t⁻¹ at \$1700/ounce Au). Exploration has found attractive deposits with what appears to be remarkable ease, so the future looks bright provided that a current dispute with the Papua New Guinea government can be resolved.

The infrastructure for ocean mining is mobile and small deposits can be mined with surgical precision. There are no mine shafts, mine tunnels or waste piles that produce acid drainage. The mining will be remotely controlled and worker safety will be much greater than on land, and there will also be very little social disturbance. (Scott 2001). Marine life is sparse near inactive massive

sulphide deposits. Unless fertilized by rivers, upwelling or hydrothermal activity, the ocean is a desert.

Initiation of seafloor mining must, of course, be based on proved reserves (i.e. metal accumulations that can be economically recovered at current metal prices and with current technology). Seafloor mining may start with manganese nodules because they appear to be the most economical to recover at present. However, in the long term, as discussed in more detail below, technological innovations can be expected to convert resources (presently un-economic metal accumulations) to reserves up to the point where nearly the full resource is extracted. In the long term, and we are talking in terms of hundreds of centuries, there is every reason to expect that this will be the case with ocean mining. Over the long term, humanity should be able to extract nearly the full resource of nodules and at least half of the SMS resource, even if much of this half is covered with volcanics or sediments.

Lithium resources. MacKay (2009) obtains half his energy savings by electrifying transportation. Electrical motors can convert electrical to mechanical energy with 90% efficiency. Electric cars can provide transport at 15 kW h per 100 km, five times less than current petroleum cars, which require 80 kW h per 100 km. Electricity can be generated from fossil fuels with 30–60% conversion

efficiency, depending whether it is generated in old coal plants or modern combined cycle gas plants. Electric cars could provide surge capacity for wind and local solar energy sources. Cars batteries could be temporarily tapped when they are not in use and are in the process of being recharged, providing a way to store energy from intermittent sources such as wind and solar. Electric vehicles would greatly reduce city air pollution.

Electrifying the car park (the total number of cars in the world) is thus an attractive prospect from many points of view. However, a great deal of lithium (or other battery material) will be needed. Figure 8 shows how much would be required, assuming that every person in a world of 10.5 billion has access to a quarter of an electric car. For a fully loaded vehicle to have a 300 km range, 250 kg of batteries with 7.5 kg contained Li would be required. The car fleet would thus require *c.* 20×10^6 t of lithium metal. This is about equal to the USGS estimate of lithium resources (USGS Minerals Commodity Survey 2012), but it is <0.001% of the Li dissolved in the oceans. A Korean steel company (POSCO), the Korean Ministry of Land, Transport and Maritime affairs, and the Korea Institute of Geoscience and Mineral resources are constructing a pilot facility that they hope will lead to the commercial extraction of 20 000–100 000 t of LiCO_3 per year from seawater (<http://nextbigfuture.com/2011/01/south-korea-commercialization-lithium.html>).

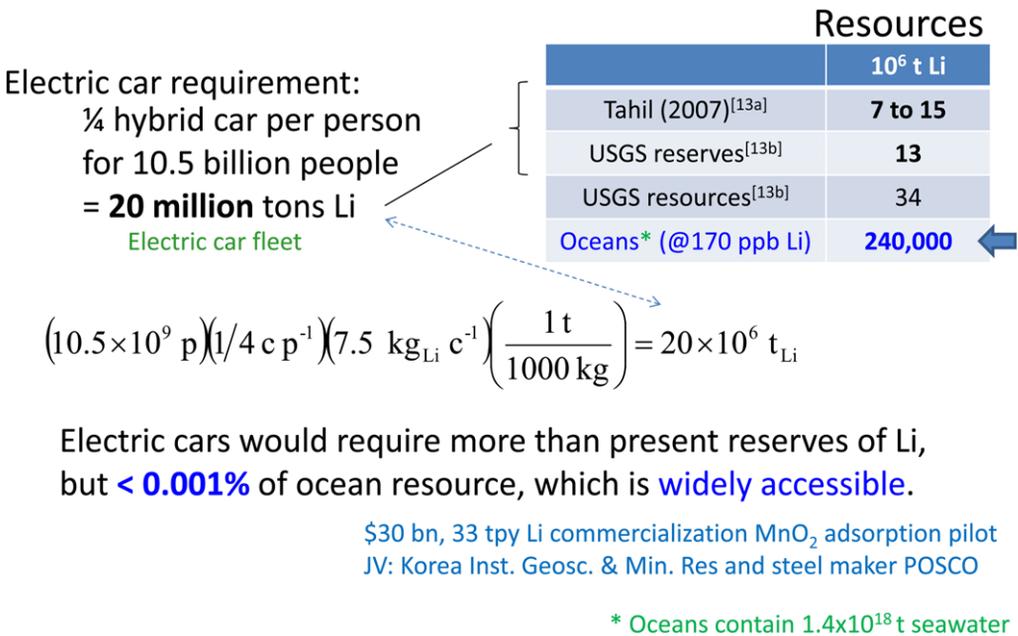


Fig. 8. Ocean resources of lithium are huge compared with the land resources.

Rare earth elements and yttrium. Rare earth elements are important chemical catalysts and vital additives in specialty alloys, permanent magnets and rechargeable batteries, the kinds of things that are needed in electric cars and wind turbines. Yttrium is used in colour television displays, portable media players, X-ray screens and lasers. The recovery of rare earths involves highly toxic chemicals ('Digging in', 4 September 2010 issue of *The Economist*), and, in part for this reason, production from Molycorp's Mountain Pass mine in California, which had been the world's largest source of rare earths, ceased in 2002 ('Rare-earth ills lift US miner', *Wall Street Journal*, 21 October 2010). In 2010 China produced 97% of the world's rare earths (USGS Minerals Commodity Survey 2012).

In late 2010 China scared the world by imposing export quotas on its rare earth production. The stated reason was environmental concerns, but the world suspected a desire to control rare earth processing and encourage a shift from low- to high-value manufacturing. Newspapers quoting Deng Xiaoping's 1992 statement that 'The Middle East has oil, China has rare earths' probably did not help to reduce global anxieties ('China's rare earths gambit', *Wall Street Journal*, 19 October 2010). In any case the political reaction in the West was fierce, as one might expect when one's colour TVs and iPods are threatened.

With about the same crustal abundance as lead, rare earths are not particularly rare, and the ratio of global reserves to present production is 827 years (USGS Minerals Commodity Survey 2012). Sage advice was given and reported. John Kiser stated on a mining web site that was quoted in *The Economist*: 'The problem of [rare earth] supply is easily solved. It just takes three to five years and billions of dollars' ('Digging in', *The Economist*, 4 September 2010). Molycorp is re-opening their Mountain Pass deposit, and rare earth prices are already declining in China.

However, the real shocker in this story was an article published on 3 July 2011 in *Nature Geoscience* by a Japanese group from the University of Tokyo (Kato *et al.* 2011) reporting that rare-earths-and-yttrium (REY)-rich sediments cover the Pacific seafloor, and could constitute a resource 1000 times bigger than land-based reserves, enough to support current production for 827 000 years. Muds containing 0.2 wt% REY that are 24 and 8 m thick cover the central north and southeastern Pacific Ocean, respectively. The muds are similar to those from which the particularly valuable heavy rare earths are being extracted today in southern China, except that U and Th levels are much lower, which makes the muds even more attractive. As in the Chinese clay deposits, the rare earths can be easily extracted by leaching with dilute acid.

The mud distribution is broadly coincident with the helium 3 ocean water anomaly associated with the hydrothermal plumes on the East Pacific Rise. The REY sediments consist of iron oxyhydroxide particles produced at the mid-ocean ridge that scavenge rare earths and yttrium from seawater as they travel from the ridge. The present deposits accumulated from fallout of these particles over the last c. 65 million years, and the REY concentration is greatest where the dilution from land-sourced particulates is minimized (Kato *et al.* 2011). The REY muds of the Pacific are a beautiful example of a resource produced by the mid-ocean hydrothermal wagon train shown in Figure 4.

Fertilizers and soil. Ninety-seven per cent of our food presently comes from the land, so the land will probably supply almost all the food for 10.5 billion people. The other way to look at this is that, properly fertilized, the ocean could supply a huge amount of food, but we will address only land sources here. The 29% of the Earth's surface that is land constitutes 14.8×10^9 ha. Ten per cent, or 1.48×10^9 ha, is cultivated and 22% is pasture. An additional half-billion hectares (c. one-third of the area now under cultivation) might be put under cultivation. This new cultivatable land is mostly in Africa, Latin America and eastern Europe. Cultivated land is being lost to urbanization, soil erosion and other forces, so meeting the challenge of feeding 10.5 billion will depend mainly on bringing best practices to existing areas, using high-density livestock management methods, and developing new breeds of plants with the help of genetic analysis (e.g. marker-assisted plant breeding) and genetic modification ('The 9 billion-people question', *The Economist*, 26 February 2011).

Fertilization is a necessary part of sustainable agriculture. At the very least the nutrients that are removed when crops are harvested and shipped to market must be replaced. The main components that must be replaced are potash, nitrate and phosphate, which are needed for plant electrolytes, making chlorophyll, and constructing DNA respectively. It is desirable to add only what is needed because adding too much can fertilize water runoff and produce anoxic dead zones like those found off the Mississippi Delta in the Gulf of Mexico. Sustainable supplies of potash and nitrate have not been questioned. Potash is hugely abundant in evaporites and seawater. Nitrate can be obtained via the Haber–Bosch process from atmospheric N_2 . However, concerns have been expressed about phosphate, with some suggesting phosphorous production could peak in 2035 owing to depletion of the global phosphorous resource and urging research into methods to conserve and recycle (Schroder *et al.* 2010).

How much phosphorous will be needed in the future and how sustainable is the supply? In 2011 the world produced 2.02×10^9 t of corn, wheat and rice. Assuming that the phosphorous content of these grains is 0.3%, 6×10^9 kg_P (kilograms phosphorous) must be replaced to maintain soil productivity. These cereals consume about 40% of the total agricultural phosphorous (Schroder *et al.* 2010), so the total P that must be replaced is $c. 15 \times 10^9$ kg_P. The population was $c. 7$ billion in 2011, so on a per capita basis, the phosphorous replacement is 2.24 kg_P/person/year. Much of the world is under-nourished, although some parts are over-nourished. Assuming that 50% more P is needed to provide everyone with a first-world diet, the per capita consumption rate in our target world becomes $c. 3.25$ kg_P/person/year, a value similar to what others have estimated (Schroder *et al.* 2010). A world population of 10.5 billion would thus require a phosphorous supply of 34×10^6 t_P a⁻¹.

Phosphorous resource estimates have increased dramatically in the last few years. In 2012 the USGS Mineral Commodity Summaries estimated phosphate rock reserves at 16 billion t, but in 2011 the reserves jumped to 65 billion t as more reserves were reported in Morocco, and in 2012 they jumped to 71 billion t as reserves were reported in Iraq. The 2012 USGS Mineral Commodity Summaries also for the first time stated a figure for the world

resources of phosphate, a massive 300 billion t, commenting that 'large phosphate resources have been identified on the continental shelves and on seamounts in the Atlantic Ocean and Pacific Ocean'. Chatham Rock Phosphate Ltd holds leases and is in the advanced planning stage of supplying phosphate to New Zealand from up to 4 cm diameter nodules on the Chatham Rise (<http://rockphosphate.co.nz/>). Phosphate is needed for New Zealand's largely agrarian society and the Chatham Rise lies 450 km east of Christchurch, much closer than Morocco.

Phosphate rock typically contains 6.5 wt% P. Figure 9 converts the phosphate rock resources just discussed to tonnes of phosphorous using this factor, and shows that the resource indicated by the USGS will supply 10.5 billion for $c. 6$ centuries. In addition there are 90 billion t of phosphorous in the deep ocean (Paytan & McLaughlin 2007) that could be recovered, and this would last 26 centuries. Phosphate eroded from the continents is delivered to the oceans almost all as particulates which settle on the continental shelves at the rate of more than 30×10^{10} mol P a⁻¹ (Payton & McLaughlin 2007). At this rate, $c. 9.3 \times 10^6$ t_P are deposited in just 1 million years, and this would sustain 10.5 billion for 3735 centuries. Since sediments have been depositing on the present-day shelves for hundreds of millions of years, this is a very low estimate of the phosphate present on the shelves. We have

Consumption:	Phosphorous per person $3.256 \text{ kg}_P \text{ p}^{-1} \text{ yr}^{-1}$	Needed steady supply $\times 10.5 \text{ bn p} = 34 \times 10^6 \text{ t}_P \text{ yr}^{-1}$
	Resource	Life [centuries]
USGS	19.5 bt _P	5.7
Dissolved in Deep Ocean	90 bt _P	26
1 myr shelf deposn.	9,300 bt _P	2735
	Paytan and McLaughlin (2007)	

Phosphate rock is also a source of U

Contains 50-200 ppm U or $\sim 1.2 \times 10^{-3}$ kg_U/kg_P

$3.25 \text{ kg}_P \text{ p}^{-1} \text{ yr}^{-1} = 3.85 \text{ g}_U \text{ p}^{-1} \text{ yr}^{-1}$ as byproduct

7 kW p⁻¹ y⁻¹ requires 23 g_U p⁻¹ y⁻¹ (breeder technology)

Could meet 17% of energy needs with fertilizer

Fig. 9. Phosphate resources of the ocean and shelves are more than adequate to support the needs of human agriculture indefinitely.

plenty of phosphorous we could extract. Uranium recovery could be a side benefit of mining phosphate rock. Figure 9 shows that byproduct uranium could supply 17% of the uranium needed to provide a population of 10.5 billion with 7 kW/person of power.

In conventional practice at least, crops require soil. Soil is probably the most threatened food-related resource. In the last 40 years, 40% of the world's arable land has become unproductive as the result of soil erosion. For example, half the fertile topsoil in Iowa and 40% in the Palouse region of the northwestern USA has been lost in the last 150 and 100 years of cultivation, respectively. Millimetres of soil can be lost by sheet flooding in a single winter storm (Pimentel 2006). It is a stealthy loss and easy to miss and therefore to ignore. There is no gullying, just the ubiquitous loss of an almost imperceptibly thin layer of soil. With energy available, it is hard to imagine that humanity would be impacted by diminishing soil cover. Hydroponic methods, even vertical agriculture in skyscraper towers (Despommier 2010), could be used. Nevertheless soil loss may be humanity's greatest future challenge, and the last thing we may want to be doing is taxing our soil resources further by cultivating biofuels ('A dysfunctional system may become more so', *The Economist*, 3 July 2010).

Tensions within the agricultural community parallel the small-and-local v. the BIG-that-counts discussion that underlies the broader resource discussion. One agricultural group fears that mankind can feed itself only at the cost of wrecking the environment (the 'agro-pessimists'). A second group thinks that technology and modern practices can transform agriculture, and supply the food needed. The latter group points to successes like the cerrado of Brazil, where research and technology have combined to produce the first tropical world-class wheat bread basket ('How to feed the world', *The Economist*, 28 August 2010). They might also point out that, as aquifers are depleted, rivers could be diverted to transport water across drainage basins for irrigation (for example, diverting a sustainable amount of the Great Lakes water to irrigate the US Great Plains as the Ogallala aquifer supply declines), which would be a good example of the BIG-that-counts perspective.

Other ocean resources. The ocean hosts many other resources not yet mentioned, and some have been already extracted (Scott *et al.* 2008). Dissolved components being recovered or recovered in the past include salt, bromine and magnesium. Salt has been and is being extracted by evaporation from a great many localities around the world, including San Francisco Bay. The Ethyl-Dow Chemical

Company developed a method for extracting Br from seawater on-board a ship, and in the 1930s constructed and operated a bromine-extraction facility at Kure Beach in North Carolina that eventually extracted up to 20 000 t of bromine per year. In 1940 they opened a 15 000 t a⁻¹ extraction facility in Freeport, Texas. In 1965 the Freeport plant provided 80% of the bromine used in the USA (Mero 1965). Bromine is now produced from underground mines in Arkansas, with two companies producing one-third of the world's bromine (USGS Mineral Commodity Summaries 2012). Seaweed was a significant source of iodine prior to 1959 and remains an important resource (<http://minerals.usgs.gov/minerals/pubs/commodity/iodine/>)

Dow Chemical erected the world's first large-scale plant for extracting Mg from seawater at Freeport, Texas in 1941. The site benefited from easy access to natural gas and calcareous shells. For some period after the second world war the US supply of magnesium was derived entirely from seawater (Mero 1965). Today Mg is recovered from Great Salt Lake brines (USGS Mineral Commodity Summaries 2012).

Sand and gravel, diamonds and minerals such as titanium, tin, gold and lime are currently being extracted from offshore placer sands in various parts of the world. Oil and gas are being extracted from progressively deeper portions of the world's shelves. The proposed sea floor massive sulphide (SMS) mining technology is adapted more or less off-the-shelf from the equipment used for trenching in the deep sea for pipelines and cables and pumping offshore oil. Gas hydrates represent a huge gas resource that several countries are investigating as a potential future gas supply, as we will see in the next section. An interesting footnote is that Fritz Haber dreamed of paying off the German war debt by economically extracting gold from seawater, and devoted about 10 years of his life to this effort, but neither he nor anyone else has ever succeeded (Mero 1965).

The transition

How might a transition from fossil to non-fossil energy resources take place? Figure 10 shows three possible 100-year fuel consumption scenarios starting in 2005. All grow the total global energy supply at 2.1% per year over the first 50 years and at 1.2% per year over the second 50 years. All reach the goal of providing 7 kW/person for 10.5×10^9 persons in 2105 (e.g. $7 \text{ kW/person} \times 10.5 \times 10^9 \text{ persons} = 74 \text{ TW} = 2300 \text{ EJ a}^{-1}$, where $\text{EJ} = 10^{18}$ joules, $\text{TW} = 10^{12}$ watts, $\text{kW} = 10^3$ watts). The business-as-usual scenario continues the current

increase in fossil fuel use for the next 50 years, and then phases them out. The substitute-gas scenario substitutes gas for coal on an equal-electricity-generation basis, and replaces oil in transportation on an equal-fuel-heat-content basis in such a fashion that oil use does not increase over the first 50 years. In the second 50 years gas is phased out by zero-carbon energy sources and oil use further reduced. The low-carbon-fast scenario eliminates coal and holds both gas and oil constant over the first 50 years by immediately bringing in zero-carbon energy sources. Gas then substitutes for oil over the next 50 years as in the previous cases. Additional discussion of these scenarios can be found in Cathles (2012).

Table 2 shows how much fossil fuel is consumed in each of the 100-year scenarios shown in Figure 12. The consumption is shown in conventional units, in billions of tonnes of oil equivalent (Gtoe), and as a percentage of the ultimate quantity of fossil fuels it is thought possible to recover (e.g. the percentage consumption of the resource base as estimated by Rogner (1997)).

Reserves are the quantity of a material that can be economically and technically recovered at the present time. They can be considered stocks that

are continuously replenished from resources as technical and economic changes occur. Historical experience suggests that in the long run technology caps price increases, and converts resources to reserves, right up to the point where almost all the resource it is possible to recover (the so-called *resource base*) has been recovered. As present reserves are depleted, prices rise and encourage and fund technological innovations, which convert resources to reserves, which causes the price to again fall. The price road is bumpy, but Rogner and other economists argue, convincingly I think, that this bumpy price oscillation means that nearly the full resource base will be consumed before prices rise significantly in a prolonged fashion, and recovery is strongly and permanently curtailed.

Rogner's global reserve base estimates for gas, oil and coal are shown in Table 3. Gas hydrates are considered unrecoverable 'occurrences' which lie outside the resource base. However, shale oil and shale gas are included and, apart from not including hydrates, Rogner's estimate of the reserve base is generously large. For example, the world has consumed to date about a trillion barrels of oil (tbo) (134 Gtoe), so Rogner's resource base is about 6 times the oil we have currently consumed. His resource base indicates that 5 tbo remains to be produced. A Hubberts peak analysis (Deffeyes 2005) of conventional production suggests about 1 tbo remains to be produced, and the latest USGS estimate of remaining oil is about 2.3 tbo (<http://pubs.usgs.gov/dds/dds-060/>).

Tables 2 and 3 reveal several important facts about the longevity of our fossil fuel supply and its environmental impact. First, Table 2 shows that a significant fraction of the resource base of oil and gas will be consumed in the fuel use scenarios shown in Figure 10. In the business-as-usual scenario, 59% of the resource base oil and 50% of that of gas will be consumed. In the substitute-gas scenario 41% of the oil and 103% of the gas resource base will be consumed. This means that there must be a transition from these fossil fuels to alternative energy sources on a time frame not too dissimilar to that illustrated in Figure 10. Over a period of about 100 years we will be transitioning away from oil and gas to other energy sources. Only the economic extraction of methane from gas hydrates would significantly change this picture.

Second, Table 2 shows that coal resource base will not be significantly depleted in any of the scenarios considered. This is not surprising for the last two scenarios in which coal is phased out as an energy fuel over the next 50 years. However, even in the business-as-usual scenario, where we continue to increase the use of coal for 50 years, only 15% of the resource base of coal will be consumed in the full 100-year transition.

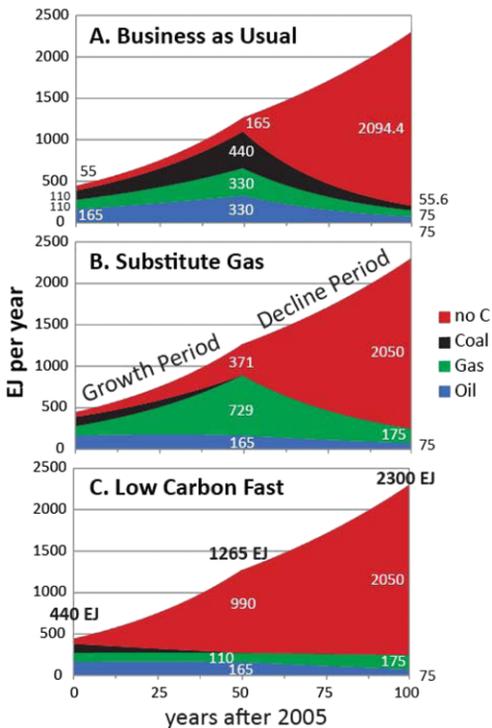


Fig. 10. Fuel consumption scenarios (from Cathles 2012).

Table 2. Fuel consumption over the three fuel use scenarios shown in the insert in Figure 10

Fuel	Business as usual			Swap gas			Low-C-fast		
	Conventional	%RB	Gtoe	Conventional	%RB	Gtoe	Conventional	%RB	Gboe
Gas (tcf)	16 847	50%	433	34 829	103%	896	11 299	33%	291
Oil (Gbbl)	3573	59%	479	2462	41%	330	2462	41%	330
Coal (Gt)	731	15%	497	93	1.9%	63	93	1.9%	63
GtC/PAL	2.13 (1268 GtC)			1.57 (935 GtC)			0.91 (544 GtC)		

%RB is the percentage of the resource base consumed. GtC/PAL is the number of times the pre-industrial carbon content of the atmosphere has been introduced by the burning of fossil fuel in the scenario. The gigatonnes of carbon released to the atmosphere are shown in parentheses. The reduction of GtC carbon introduced into the atmosphere in the swap-gas scenario is 46% of that achieved in the low-C-fast scenario.

Third, Tables 2 and 3 also show how much CO₂ would be released to the atmosphere if the resource base of the fuels was consumed, or if the consumption scenarios shown in Figure 12 were carried out. The CO₂ carbon produced and released is expressed as a ratio to the CO₂ carbon in the atmosphere in pre-industrial times (the PAL). Table 3 shows that the burning of the full resource base of either gas or oil would introduce about 1 PAL to the atmosphere (e.g. each would introduce an amount of carbon that would double the amount of CO₂ in the pre-industrial atmosphere if it was not removed in any fashion), but burning the coal resource base would release 6.6 PAL. The threat to global warming thus comes mainly from coal, and less so from oil or gas.

Finally, the amounts of CO₂ that are released in the three scenarios shown in Figure 10 are shown in Table 2. The business-as-usual scenario would introduce more than 2 PAL, the substitute-gas scenario 1.6 PAL, and the low-carbon-fast scenario 0.9 PAL. Substituting gas for coal and new oil reduces the CO₂ input to the atmosphere by 46% of that which could be achieved by the fast substitution of zero-carbon energy sources (Cathles 2012).

A rule of thumb in global warming is that permanently doubling the pre-industrial atmospheric CO₂ will raise the average global temperature by 3 °C.

The carbon inputs to the atmosphere shown in Table 2 do not translate directly to temperature increases, however, for three reasons: first CO₂ is removed from the atmosphere, and so the increase in atmospheric CO₂ levels will be less than that released; second, if the increases in CO₂ output are temporary, the ocean uptake of the heating pulse slows and diminishes the warming; and third, CO₂ is not the only greenhouse gas involved in the burning of fossil fuels. Methane is released in the mining of coal and in the production and delivery of natural gas, and the global warming impact of methane needs to be taken into account.

Figure 11 shows the warming predicted for the fuel consumption scenarios shown in Figure 10. The CO₂ and methane released in producing and combusting the fuels are added each year to the atmosphere and removed in subsequent years in an appropriate fashion. The ultimate change in global temperature is computed and modified by heat exchange with the oceans. The methods used to calculate the warming are standard and non-controversial, and are described in Cathles (2012), where many additional details can be found. The business-as-usual scenario produces warming that peaks at about 1.8 °C in 2100 and then declines very slowly as the 26% fraction of the introduced CO₂ is removed with a decay constant of 173 years. In the long term, the substitute-gas scenario reduces the warming by about 40% of that achieved in the low-carbon-fast scenario, and achieves this reduction during the transition as well, provided that the leakage rate of methane is between 1 and 3%, as appears to be the case today. Even if the leakage rate were an implausibly high 10% of gas consumption, and the substitute gas scenario provided no reduction in global warming over the 100-year transition period, the 40% reduction would still be realized later because methane leaves the atmosphere quickly (exponential decay time of 12 years) as soon as gas production stops. The warming shown in Figure 11 is of the magnitude one might expect. For example, CO₂ removal

Table 3. Resource base estimates of Rogner (1997)

Commodity	Resource base (PAL = 595 GtC)		
	Conventional units	Gtoe	GtC/PAL
Gas	33 852 tcf	870	0.9
Oil	6066 Gboil	814	1.2
Coal	5041 tonnes	3400	6.6
Total		5209	8.8

PAL is the pre-industrial carbon content of the atmosphere. At 280 ppmv CO₂ the pre-industrial atmosphere contained 595 Gt of carbon.

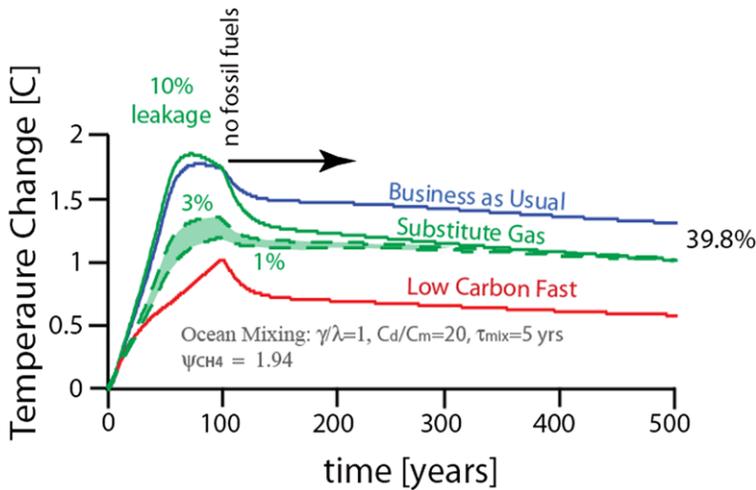


Fig. 11. Global temperature change for scenarios shown in Figure 10. Calculations are described in Cathles (2012).

reduces the 2.13 PAL input in the business-as-usual scenario to *c.* 0.9 PAL, and the bit less than 3 °C warming predicted for this increase in atmospheric CO₂ is reduced by *c.* 1 °C by heat exchange with the ocean.

The 1.2 °C (declining to 1 °C) warming predicted for the substitute-gas scenario for the 100-year transition is not particularly serious. It is less than the average temperature difference between the latitude of New York City and Boston, for example. It is unlikely we can do much better. The low-carbon-fast scenario is not feasible. The world is not ready for massive nuclear power deployment, and it is unlikely that wind and solar facilities of the scale necessary could be built in 50 years. Time will be required to discover the problems with the large-scale deployment of wind and solar facilities, to develop thorium reactors and safer nuclear reactors, and for the public to become comfortable with new solutions. The infrastructure and workforce of no country can be rapidly re-directed, and accelerated re-direction incurs added costs and risks. The Western world would be hard pressed to move along the low-carbon-fast scenario. The world as a whole would find it impossible. We will need to live with a bit of global warming and concentrate on limiting rather than eliminating it.

What will matter is the fuel choices made in the next decade by China, India and in the underdeveloped parts of the world. The Western world has an established energy infrastructure and constitutes *c.* 19% of the world population, and what it does in the future will not count much in absolute terms. China and India have abundant coal, but they also have abundant shale gas. If China and

India build the infrastructure to dramatically increase coal production, it is likely that this production will continue until the coal resource base is depleted. If, on the other hand, the infrastructure for harvesting shale gas were developed instead, coal extraction might be delayed and even avoided if better sources of energy become available soon enough.

There is some hope that the development of shale gas could be accelerated in preference to coal because it is potentially cheaper and it is vastly preferable environmentally. Natural gas is presently a cheaper fuel than coal in many parts of the world, and where this is the case, conversion from coal to gas electricity generation is occurring automatically for economic reasons with no government intervention. Natural gas emits no particulates, mercury or acid rain-producing SO₂ during combustion, burns cleanly, leaving no ash piles behind, and produces no acid mine drainage during mining. Cars and trucks running on natural gas will greatly decrease air pollution in cities. Replacing coal or wood with gas in home kitchens will dramatically improve health. Thus shifting to natural gas would have many immediate benefits to countries like China and India. Developing gas first could also be good strategy because gas-fuelled electricity generation could promote development of an electric car fleet that could help manage the intermittency of solar and wind power and would be ready to receive electricity from other cleaner sources such as nuclear as they are developed.

The West could encourage the development of natural gas in preference to coal by developing and demonstrating the technology to extract and deliver natural gas safely and with low leakage, by

showing how impediments (unnecessary fears, laws, regulations, etc.) can be reduced and the needed infrastructure constructed, and by demonstrating the benefits of a gas transition, including the decreases in greenhouse gas emissions involved in moving along the green substitute–gas trajectory in Figure 11. With an example set, the rest of the world might be more inclined to follow. Since companies would be eager to apply the methods to new areas, the benefits of the gas transition could be replicated quickly across the globe.

Why are we hesitating?

The world has never been better and it is improving. The energy and minerals are available in the oceans to sustain a human population of 10.5 billion for hundreds of centuries. A transition (natural gas and then non-carbon fuels) strategy that is economic and feasible, and manages a major portion of the global warming risk, is at hand. There are many advantages to setting and achieving the goal of bringing 10.5 billion people to a European standard of living: those setting this goal will be seen as contributing to humankind; there will be reduced conflict over resources; and all will be able to see that they have a place in a common future. In progressing toward this goal, we will learn a substantial amount about the Earth, and we will challenge and engage the best and brightest in the most constructive quest imaginable. Prosperity will limit population growth as a higher standard of living seems to be the best birth control measure ever invented. So why are we hesitating?

There are the usual suspects: tapping the oceans is environmentally risky. Only companies will get rich. No one owns the oceans. It is better that no one taps them than the wrong ones. Why should we develop the competition by bringing everyone up to our level? Would it not be better to keep investment at home? We do not like change. The system is dysfunctional (not capitalist enough, not centralized enough, dummies are in control). We have gone soft, and are too worn-out to take on big challenges.

All of these possibilities are tried and true, and all have real appeal. However, unfortunately I think the problem is something new and more difficult to deal with: accelerating specialization.

The world works because it is specialized. A wonderful book (Harford 2011), which I will return to, starts with a parable on ‘how you could spend your whole life building a toaster’. Many graduate students can probably relate to this. I know I could have. You would need to learn to smelt the iron, mine copper and nickel, make wire, get the hydrocarbons and discover how to make

plastic from them for the plug, etc. At the end of your life you might have a toaster and it might work, but the chances are it would not be anything that you could sell or that you yourself would buy. We depend on specialization – furthermore, we like it. We love solving problems to the degree that we complete crossword puzzles when we do not have anything better to do. We are happy to find the small niche where we know what we are doing and can contribute. However, what all this means is that we do not know what others are doing, and when they are doing BIG things that might count, we get nervous. Computers, technology and the speed of change make the situation worse. We can quickly discover some facts, communicate with other worried folk and fan our worst fears. The result is that we are becoming increasingly risk-averse. This risk aversion is why we hesitate. It is a new condition of modern life, and we have not yet discovered how to manage it.

What should we do?

Regulation is not the answer. It is stifling and it will not protect against the unforeseen, such as a crop-killing wheat fungus migrating out of Africa (‘Rust in the bread basket’, *The Economist*, 3 July 2010). Caution, retrenchment and inaction are not the answer. The damage from failure to meet the challenge of raising 10.5 billion to a European level is much greater than the risk of trying. Risk cannot be avoided. Any living entity must accept a healthy amount of risk. Only death removes this imperative. And this goes for economic as well as biological life. Innovation requires risk. This is the point of the book that starts with the toaster parable, entitled *Why Success Always Starts with Failure* (Harford 2011). It points out that many failures always precede success, and reminds us that Gutenberg went bankrupt on his printing press invention. Finally, sustainability requires a flexible system and diffusion of responsibility, which is incompatible with centralized control.

My recommendation is to:

- Accept the challenge of supplying 10.5 billion with the resources needed for a European standard of living.
- Accept that accidents and unknowns will be encountered along the way with the confidence that they can be fixed, and in this process we will learn and improve. Accept that we will constantly be safer but always at risk. The Fukushima Daiichi meltdown would not be possible with pebble bed or thorium reactors. We will not again build reactors without power backup available, or tsunami protection. The Macondo

oil leak would not have been as damaging if we had had caps ready in warehouses as we do now, or had had policies in place to allow us to accept foreign help such as the Dutch oil skimmer that had the capacity to skim all of the oil as it leaked. It was allowed into US waters only 10 days before the vent was contained. Next time we will know whether dispersants, berms and fresh water diversion will help or make the problem worse. There are many examples, in fact it is a general rule, that a new activity, which may be dangerous at first, becomes constantly safer over time (think car and air travel; Lomborg 2001). We cannot afford to be scared away from promising activities.

- Communicate this position and its importance to the public from our geological and resource professional societies.
- Organize university-level training around the commitment to supply resources in as environmentally responsible a fashion as possible. The resource enterprise needs the science and the best and brightest students that universities can provide. Universities need to be perceived as constructive to be supported. Their focus needs to be on achieving a worthy future and fixing problems, not just identifying them.

Summary

Although not exhaustive of all needed materials, the above discussion indicates that the needs of a human population of 10.5 billion, bought to a European standard of living, can be met for hundreds of centuries by the resources the Earth provides, and outlines a feasible *c.* 100-year transition to this condition.

Desert solar, nuclear and perhaps wind could supply the energy needed. With breeder technology the ocean uranium resource can sustain 10.5 billion people for over 100 centuries and the footprint of the required extraction facilities is tiny. Ocean floor copper and zinc resources can bring 10.5 billion people to a European standard of living and maintain them there for hundreds of centuries, and much longer if dissipative losses are controlled, as they surely will be. Ocean mining is starting now. Lithium dissolved in the oceans can supply the batteries needed for each member of a 10.5 billion population to have a quarter of an electric car, and techniques of extraction are already being piloted. Rare earth elements are present in abundance in sea-floor sediments. Phosphate resources in the oceans are adequate for agricultural needs for thousands of centuries.

An orderly 100-year transition from fossil fuels to zero carbon energy sources is feasible if

preceded, starting now, by a transition from coal and new oil to natural gas. Global warming will not be severe for a 100-year transition, and substitution of gas for coal and new oil will reduce greenhouse gas emissions by *c.* 40% of what could be achieved by an immediate substitution of low-carbon energy sources, which is not feasible.

Meeting the goal of 10.5 billion at a European standard by 2113 will require big steps. Little steps can and should, of course, also be taken. We should make buildings more efficient, save energy and water wherever possible, and do all the things that we do more efficiently and with less waste. These steps will be important and nothing stated here should be construed as minimizing the desirability of taking all these steps. However, meeting our ambitious goal of 10.5 billion at a European standard by 2113 requires BIG steps. We will need to harvest resources from the oceans, divert rivers for irrigation, develop country-sized infrastructures in desert areas, develop safer nuclear reactors and deploy them globally, and adapt new agricultural and plant breeding practices on a very large scale. These big changes may seem intimidating, but they will tend to occur naturally. The construction that has occurred since the 1940s would also have seemed intimidating and implausible in 1940.

Science and technology must play a central role. Their advance, already extremely rapid, is accelerating, in part because the internet has increased so dramatically the size of the collaborating talent pool. Manipulating individual molecules to create nano-scale devices that never existed before, printing objects in three dimensions, growing replacement body parts and tailoring drugs and foods with genetic engineering, are scary. It makes us anxious when our highly specialized fellow humans are doing big things the details of which we cannot fully comprehend, and it is easy to fan our worries using the internet.

The current situation is as good as it ever has been, and we have more capabilities than ever before. We have the energy and material resources sufficient to last us for the foreseeable future and beyond. We have a grand challenge that is profoundly positive and a more than worthy goal. Committing to raising 10.5 billion to a European standard by 2113 is not only the smartest choice, but it is also the safest. Failing to try to meet it will be much more risky than trying and failing.

The barriers to meeting the vital challenge of 10.5 billion to a European standard by 2113 are not physical restrictions of resource supply, or the lack of a good way forward. Rather the barriers are related to us. We need to learn how to deal with the modern condition of specialization and our modern forms of instant communication. If we

can do this, with courage and optimism, the human future will continue to be better than the past in all regards, and very bright indeed.

I have been fascinated by resources for years, but began teaching again specifically on the topic only in 2008. My intent was to explore in the class whether there were critical resources whose exhaustion could imperil the future of humanity. Student papers and discussion over the three years I have taught this course contributed greatly to assembling the material discussed here and I am deeply indebted to the students for these contributions. This paper owes its origin to a long-time friend J. Hedenquist, who, as president of the Society of Economic Geologists, invited me to present a Viewpoints article for the SEG newsletter. My contribution there, 'A path forward' (Cathles 2010b), became the basis for a series of talks I delivered as the 2011 Society of Economic Geologists Distinguished Lecturer under titles like: 'Humanity's greatest risk is risk avoidance', 'Future Rx: Optimism, preparation, acceptance of risk' (to the Femor Conference in London), and 'Humanity (all 10.5 bn of us) has a future after all'. The opportunity to give these talks brought suggestions from audience members, and the invitation from G. Jenkin to contribute this paper to the Femor 2011 Special Publication of the Geological Society of London. I would like particularly to recognize important input from D. S. Cronan (for drawing my attention to Mero's book), S. Scott (for many discussions and a very helpful review), D. Heydon (for indirect contributions of economic calculations), J. F. Kasting (for drawing my attention to Rogner's paper) and P. Lusty (for editing). I thank G. Jenkin for encouragement and patience, and F. Rhodes for timely encouragement to publish. Finally, I thank the Wold Family for establishing the Wold Family Professorship in Environmental Balance for Human Sustainability at Cornell with the hopes of bringing the industrial side and a real world perspective to the Cornell academic table. Although this generous act has not impacted this article or me personally, it will promote the kind of future discussion that is needed in the areas this article discusses.

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