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Buying Time – Using Nanotechnologies and Other Emerging Technologies For a Sustainable Future

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Abstract: Science and emerging technologies should not be predominantly tasked with furnishing us with more sustainable societies. Continuous short-term technological bail outs without taking into account the longer socio-cultural incubation times required to transition to 'weakly sustainable' economies squander valuable resources and time. Emerging technologies need to be deployed strategically to buy time in order to have extended political, social and ethical discussions about the root-causes of unsustainable economies and minimize social disruptions on the path towards global sustainability.

Keywords: Nanoscience; nanotechnology; expanded materials design space; dematerialization; sustainability; permanent resource crises

Introduction

Since the beginning of the industrial revolution, economic growth has been continuously challenged by a series of energy and resource crises. Such crises have been mitigated by technological innovations that subsequently led to a supply-side shift, prompting further growth of our energy needs. Many of these technological innovations are the result of scientific and engineering revolutions (e.g. the steam engine, microelectronics, the internal combustion engine, biotechnology) which have dramatically changed our working, political, cultural, ecological and living environments. The emergence of global issues and challenges in the past decades as well as the concomitant realization of global commons and finite resource limits has focused our attention on sustainability. During its rapid initial development capitalism largely ignored concerns about sustainability. However, in the last 40 years or so we started to acknowledge the existence of certain strategic global resources and ecological limits. However, at the same time we continue to insist on the prospect that technological efficiencies spurred on by shorter and shorter research and innovation cycles will allow us to grow our economies, increase our personal and global wealth, and increase global population while at the same time minimizing environmental impacts as well as social and economic inequalities. The early discussions and questioning of economic growth as a conditio sine qua non triggered by the publication of 'The Limits to Growth' in 1972 subsided for nearly a quarter of a century, but references to it have recently re-emerged as a consequence of discussions on global climate change and global environmental pressures such as deforestation, loss of biodiversity and concerns regarding ecological, economical and societal sustainability (Meadows et al. 1972). New arguments as well as critical re-evaluations of ‘The Limits to Growth’ are now much more sympathetic. Many of the original predictions have turned out to describe characteristics qualitatively in agreement with currently observed trends in bio- and geophysical metrics (e.g. land and global freshwater use, pollution, reduction in biodiversity) (Tuner 2008; Rockstrom et al. 2009). Existing and emerging technologies such as nano- and green technologies will in the short term continue to spur economic growth and provide opportunities to advance solutions to some of the world’s intractable global problems, such as the existence of eternal ‘poverty traps’ in sub-Saharan Africa (Sachs 2008), limited water resources and extended draughts, local and global agricultural crises, global climate change and the constant threat of world-wide pandemics. I will use simple macroeconomic concepts to argue in this paper that (1) science and technology should not be predominantly tasked with building a path towards sustainable societies and (2) that in the long term, global policies must acknowledge and accept global resource and economic growth limits and redirect money gained from ever increasing technological efficiencies to develop strategies and global political frameworks to meet weak sustainability standards. The longer science and emerging technologies continue to be predominantly burdened with achieving increasingly ambitious goals, the shorter the time span will be to transition our societies from a growth to a sustainable mode without encountering major social disruptions. Additionally, we will then have to rely progressively more on serendipitous technological ‘aces up our sleeves’, calling upon historical precedents and selective past successes of transformational technological achievements to avert consecutive resource and supply crises. The time available for the development and implementation of technologies is key to being able to confront global challenges such as climate change, long term environmental sustainability and the eradication of poverty in the poorest regions of the world. These crises also require significant socio-cultural incubation times which we are squandering by predominantly relying on science and emerging technologies to continuously bail us out in the short term. These technological bail outs, however, might even shorten the time span until the next resource or implementation crisis appears and subsequently call for even more challenging technological feats. We risk being caught in a prolonged series of resource crises with respect to specific strategic materials such as rare earth elements, Helium-3 and Lithium that will further paralyze and derail the long-term technological implementation of mature technologies with low environmental impact. Science cannot continuously and at an accelerating pace produce ‘transformational’ answers to more and more complex problems. By speeding up this resource crisis-technology spiral, we will at the same time curtail valuable time needed for cultural, moral and political change required to implement economies which can adhere to principles of weak sustainability. Nanotechnologies and other emerging technologies need to be deployed strategically so as to buy us time to gradually allow us to transition into sustainable economies and thereby minimize inevitable inequities during this process.

Nanoscience – A Different Science

Nanotechnologies (in particular those that address energy-related technologies, such as catalysis, fuel cells, batteries, and solar cells) have been enlisted to "unveil a realm of functional materials for fueling the challenge of low-carbon, sustainable energy" (Schoegl 2008, p. 772). In a commentary Schloegl argues that "…there remains an enormous need for fundamental research into understanding nanoscale effects and hence realizing the rational design of materials for energy applications" (Schoegl 2008, p. 772). In such claims and projections nanoscience and technology are always tethered, emphasizing that the quest to discover and design specific and technologically applicable functionalities of materials and devices is at the core of nanoscience. This claim, made by scientists and politicians, is similarly promoted by governmental and private funding agencies as well as companies, all of whom display a considerable amount of optimism that appropriate technologies can and will be developed to meet these very high expectations. In many cases this optimism lacks any professional modesty and realism, and represents a rhetorical overselling of technologies which raises expectations to naive levels. The traditional academic Mertonian ideal of the disinterested scientist enlarging public knowledge has been in part superseded in most research institutions by a partisan and authoritarian expert concerned with protecting private or public intellectual property rights (Merton 1942). The value of public intellectual property has morphed from benefiting the public at large to advancing and supplementing the financial needs of universities and/or governmental laboratories[1]. The aforementioned focus on the applicability of nanoscience is not relegated to a later phase in the knowledge production chain, but is present in the very early stages of basic research. We have previously argued that nanoscience represents the first full embodiment of a post-academic or mode-2 science, which coexists with mode-1 practices at academic, industrial and governmental institutions (Vogt et al. 2007). Besides the dispassionate behavior of scientists being partially displaced by authoritarian managerial authority, Ziman adds as a further example of the mode-1 to mode-2 transition changes in the notion of originality relating to individual investigators' choices of the problems they decide to take on (Ziman 2000). Within the context of the 'linear model' of science and technology progression – put forward by Vannevar Bush – a 'random walk' approach to problem-choice was justified by arguments mainly based on historical precedence, which in many cases elevated serendipity to a convenient myth (Bush 1945). Recently the formulation of 'Grand Challenges' and a broad push for mission-oriented research and technology development reveal a significant shift from individual research to the collective action of multidisciplinary teams. This (at least partial) change of the operational philosophy of the US Department of Energy (DOE) corroborates the thesis that nanoscience represents a different way to do science.

In a recent DOE Basic Energy Sciences Division document, a transformation 'from observational to control science' is suggested: a contrast is set up between the 20th century's observational tools (electron microscopes, scanning tunneling microscopes) and materials discovery with the emergence of notions of directing matter

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[1] The currently observed 'forced privatization' of public universities in the US by many state governments who are abandoning their fiscal responsibilities regarding higher education while insisting on continued governance and imposition of inefficient regulatory rules will only accelerate 'mission creep' and increase the pressure on commercialization to provide alternative streams of revenue.

and energy through exploring chemical changes, charge, spin and light interactions in materials design (Basic Energy Sciences Advisory Committee 2007). What is emphasized and called for is directed 'bottom-up' self-assembly of materials, 'top-down' fabrication at the nanoscale, and theory, modeling and simulation being used to guide materials design[2]. The latter concept had already surfaced in traditional materials science and chemistry as the concept of 'rational design'. However, in nanoscience the challenge of how to pursue rational materials design becomes center stage with an enormous expansion of the materials design space, enabling the design of new materials with new or significantly improved functionalities. The size and shape of materials becomes relevant due to the emergence of unique and new functionalities at the nanoscale between 1 and 100nm. The size- and shape-dependence of particles of matter alters physical (e.g. melting point, color) and chemical (e.g. reactivity) properties, allowing us to escape the two dimensional functional periodicity underlying the periodic table of chemical elements and thereby significantly enlarging our material design space [3] . Traditional investigations into structure-composition-property relationships no longer suffice at the nanoscale, and need to be expanded to probe structure-composition-size/shape-property relationships. We know the structures of all hundred or so chemical elements of the periodic table that are relevant as material building blocks. Adding on size-dependent functionalities in the nanoscale expands our parameter space for materials design substantially. For example, gold is chemically inert and nonmagnetic at the macroscale but becomes highly reactive and magnetic at the nanoscale.

The Rational Exuberance of Nanoscience and Dematerialization

Using chemical knowledge and an approximate combinatorial approach to estimate the number of distinct materials composed of different chemical elements (A,B,C,D…), we anticipate about 4.950 different binary compounds A_xB_y (such as NaCl and H_2O) (Rodgers and Cebon 2006, p. 976). Chemists and materials scientists have made and partially investigated the structures and properties of about 80% of these materials. In the cases of materials composed of three elements (ternary compounds, $A_xB_yC_z$, such as $BaTiO_3$ or $CaCO_3$), we have made and characterized only about 5% of over 160,000 possible compounds. Of the approximately 3,9 million potential materials composed of four elements (quartenary compounds, $A_xB_yC_zD_w$) we have explored less than 1% of the possible compositions (stoichiometries). Quartenary compounds contain important

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[2] Materials design space: The entire set of parameters (i.e. atoms, chemical compositions, structures) which determine the functionalities of a chemical compound or composite.

[3] The expansion of this concept to a 'multi-dimensional periodic table of the elements' is an appealing one as it allows the use of economic parameters such as price (which scales to a first approximation with the relative abundance of a chemical element in the earth's upper continental crust), ecological parameters such as toxicity and non-degradability, manufacturing and recycling costs and even political factors such as for example the need to minimize the amount of tantalum used in consumer electronics due to the fact that the mining of Tantalum and Niobium is fueling conflicts in sub-Saharan Africa to be taken into account when looking at elemental compositions of prospective new materials and devices. Such an upstream analysis and the imposition of non-scientific constraints on the materials availability for photovoltaic devices reveals that iron pyrite (FeS2) is a very attractive material with respect to cost and availability and that some of the currently leading technologies such as those based on CdTe will not be able to meet the quantities needed to be scaled up globally (see Wadia et al. 2009).

materials such as heterogeneous catalysts, high-temperature superconductors (e.g. $YBa_2Cu_3O_{7-\delta}$) and dielectric materials used for telecommunication (e.g. $Pb_{1-x}Zr_xTiO_3$, $CaCu_3Ti_4O_{12}$). In organic chemistry alone it was recently estimated that the total number of molecules even with the relatively small molecular weight of 160 Daltons is about 13,9 million (Fink et al. 2005).

In our quest for the exploration of distinct chemical compounds with particular physical (e.g. electrical, magnetic, optical) and chemical (e.g. reactivity and stability) properties we have thus barely scratched the surface within 'conventional' materials science, let alone in nanoscience, in which – besides the composition and structure of a material – we can now vary the size and shape of the particles to create unique properties. While the manner in which a particular functionality will change with size and shape at the nanoscale depends strongly on the element and chemical compound, we will be able to radically expand our materials design space for the synthesis and design of new materials and their associated functionalities by adding size and shape to our materials engineering toolbox. This creates a 'rational exuberance' for a quest to optimize and create new materials and properties. This transformative potential of nanoscience is constantly being called upon. An article in Physics Today addressing the ^3He resource crisis is a representative illustration of the expectations raised by nanoscience: "And for the longer term, the hope is that nanotechnology will provide solutions" (Feder 2009, p 22).

However, the sheer size of this expanded materials design space challenges and ultimately renders impossible so-called 'Edisonian' and other traditional approaches to experimentally explore, sequentially and individually, the functionalities of all of these possible elemental combinations. The opportunities that nanoscience offers for the exploration of new materials and properties have, as a consequence, a trade off in inevitably calling for a screening process that relies heavily on 'in-silico-experiments'; namely the use of theory, modeling and simulation (TM&S) to tease out prospective 'hints and hits' from millions of candidate compounds[4]. TM&S at the nanoscale has received much attention and is being promoted as an 'alternative experimental tool' with which to explore novel functionalities in nanoscale structured materials. One example of such game-changing expectations is nanoscience research efforts in heterogeneous catalysis, which have raised expectations that (1) science will be able to mimic the catalytic reactivities and selectivities of expensive and rare noble metals such as gold, platinum or rhodium by combining cheaper elements at the nanoscale (LeGoff et al. 2009), and (2) it will become possible to deposit only a very thin layer of required noble metals on a cheap substrate.

The latter research efforts bring up a second game-changing claim that nanoscience has nurtured and revived; namely, the prospect of dematerialization, in which by using highly optimized composites (e.g. Pt coatings on Al_2O_3 substrates) one is able to do more with less material. Dematerialization, broadly defined as the decline over time of the quantitative usage of materials in industrial and consumer products, has been suggested as the hallmark of advanced economies in which material needs are largely satisfied (cf. Herman et al. 1990). Frequently cited examples include nuclear

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[4] This approach brings up the interesting question of what we miss at the nanoscale using such high-throughput screening processes which by their nature will use a 'fingerprint' that might be very weak and/or masked or even miss a 'hit' completely by a too coarse step used in varying the stochiometric coefficients i.e. xyz in $A_xB_yC_z$. Could the publishing of such screening processes prevent a scientist from re-investigating these now chartered territories in materials parameter space?

fuels such as uranium, where one kilogram can produce the same amount of energy as 13 tons of oil or 19 tons of coal, or telecommunications hardware, where 25 kilogram of fiberglass wire replaces about 1 ton of copper and is produced using only 5% of the energy.

Dematerialization is being put forward as the solution to being able to have continued economic growth as well as increasing the affluence (A) of the global population (P), without this necessarily triggering a commensurate negative environmental impact (Im). Commoner (1972) and Ehrlich and Holdren (1972) introduced a macroeconomic dimensionless ‘ImPAT’ measure relating population size (P), affluence (A) and technology efficiency (T) to impact (Im). Waggoner and Ausubel (2002) recently expanded ImPAT to what they called the macroeconomic ImPACT identity, where the environmental impact (Im) in units of emissions is the product of 4 parameters: population P in capita, affluence A in units of GDP/capita, consumer intensity of use C in units of energy/GDP, and the efficiency T of technologies in units of emissions/energy:

$$\mathrm{Im}[\mathrm{emissions}] = P[\mathrm{capita}] \times A[\mathrm{GDP/capita}] \times C[\mathrm{energy/GDP}] \times T[\mathrm{emissions/energy}].$$

Environmental impact Im implies emitting something into the environment in the broadest sense of the meaning. Affluence A in units of GDP/capita can be called income. The consumer’s intensity of use C in energy/GDP quantifies how much of the income will be used to impact the environment. Thus one form of dematerialization is achieved by reducing the consumer’s intensity of use C. This consumer driven dematerialization is distinct from the technology efficiency factor T, which measures the ratio of environmental impact to goods demanded and manufactured. Thus an advanced and more efficient technology minimizes this factor by reducing the ratio of goods/environmental impact.

Reducing and/or maintaining environmental impacts, which have both global and local consequences, can be achieved by tackling different factors: P is essentially dependent on the total fertility factor and life expectancies driven by disease, war, conflicts, imposed family planning restrictions such as those practiced in China, or the increase of affluence and education which reduces birth rates in developed societies. The latter indicates that the four parameters P,A,C and T are not independent. Affluence depends on the speed of innovation and efficiency of manufacturing and can be influenced by work force quality, efficiency of bureaucracies and various institutional practices (e.g. corruption, incentives). Binary products such as P x A [GDP] represent the challenge of sustainability, whose impact one might be able to offset by using the sustainability levers C x T [emissions/GDP], challenging both consumers and technologists to reduce the environmental impact. Reducing C is referred to as dematerialization; reducing T is called increasing the technological efficiency which is in many cases achieved, as outlined above, by dematerialization.

A simple but important conclusion which will be relevant in a latter section of this paper is that the more factors involved in reducing Im, the less disruptive individual reductions and/or constraints will be for the various actors involved (families, workforce, consumers and producers). To be successful, this shared but distributed burden will require coordination and trade-offs amongst all the actors involved. The nature of this highly political process reveals that forging the path towards sustainable economies by using predominantly scientific and technological progress is a flawed strategy. Both sustainability levers C and T need to be employed to reduce environmental impacts, and declaring the sustainability challengers P and A off limits to reductions severely limits the response tools available and might need to be challenged in the long run. A reduction of the consumer's intensity of use C can concomitantly free up technological efficiencies which can then be used further to reduce environmental impact. Price policies, market incentives and other governmental regulatory policies as well as cultural and behavioral changes can, in the long run, be envisioned to initiate this type of behavior and thereby relieve the pressures on technological innovation and implementation so as to reduce the environmental footprint. This early coordination and integration of policies and research to address local and global crises are again cultural hallmarks of mode-2 science, and will become important attributes in our attempts to navigate our societies towards more sustainable economies.

Technological and Behavioral Wedges

An important tool in addressing how to practically implement significant reductions of greenhouse gas emissions was put forward by Pacala and Socolow (2004). A triangular area of emissions (the 'stabilization triangle') with a total area of 175 Giga tons (Gt) of carbon emitted between 2004 and 2054 will need to be avoided in order to stabilize CO_2 emissions at 7 Gt of carbon per year. This triangle is divided into seven 'wedges' allowing the examination of efficacy of technologies employed to stabilize CO_2 concentrations at 500ppm (Figure 1). Under the assumption of linear growth of fossil fuel emissions, the emission reductions by implementing low carbon emission technologies per wedge are 25 GtC, and the total area of the stabilization triangle is 175

fuel emissions, the emission reductions by implementing low carbon emission techno

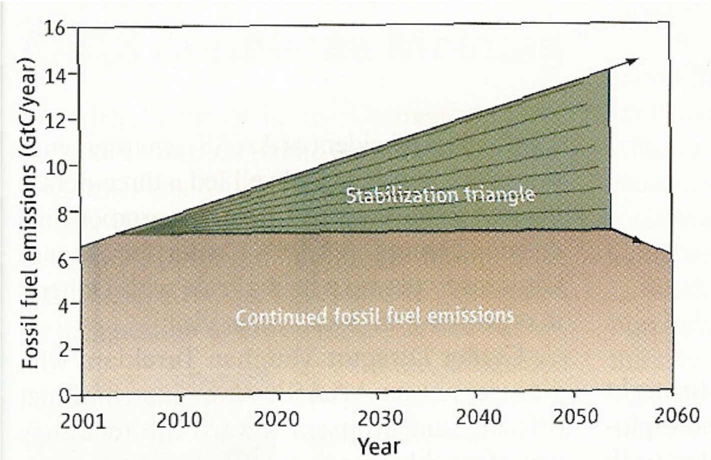

Figure 1: Seven stabilization wedges of an energy portfolio to reduce fossil fuel emissions by employing various technological solutions (taken from Pacala and Socolow 2004, p. 969)

logies per wedge are 25 GtC, and the total area of the stabilization triangle is 175 GtC. The list of potential technology wedges based on currently available technologies includes the use of more efficient vehicles, increasing the efficiency of buildings, the use of wind power and nuclear power, biomass power and others (see Waggoner and Ausubel (2002) for details).

In an intriguing recent study Dietz and his group propose the implementation of a behavioral wedge which could "….potentially help and avoid an 'overshoot' of Greenhouse gas concentration targets; provide a demonstration effect; reduce emissions at lower costs; and buy time to develop new technologies, policies, and institutions to reach long-term greenhouse gas emission targets and to develop adoption strategies. Household emissions represent ~38% of overall CO_2 emissions in the US in 2005" (Dietz et al. 2009, p. 18452) By focusing on US households and targeting weatherization, maintenance and adoption of energy-efficient appliances and a number of low-barrier behavioral changes such as reducing operating temperatures of devices (i.e. dryers, water heaters) and eliminating stand-by electricity, nearly 20% of household direct emissions – or 7,4% of US national emissions – can be eliminated. Such a behavioral wedge could reduce the scientific and technological challenges technologies face in the remaining technology wedges and possibly transform some of the required progress from being transformative to incremental. This will lower the risk of failure of individual technological wedges and increase the probability of meeting the overall goal of stabilizing CO_2 concentration in the atmosphere at 500ppm.

Weak Sustainability and Permanent Resource Crises.

While at least in the short- to mid-term dematerialization has been shown to provide a path towards sustainability, the decline of consumption per GDP and lower intensity production of goods will ultimately level off and we will approach a series of recurring sustainability limits and crises. Even if some radically transformational technology goals could be cost-effectively implemented (e.g. nuclear fusion, hydrogen economies fueled by solar energy), the long term use of dematerialization strategies – in which more will continuously be produced from less, and sustainability will be achieved on the basis of sustained dematerialization through the persistent flow of transformational new technologies – is most likely to be elusive. While we will be able to transform certain processes in our currently 'linear economies' running on non-renewable fossil fuels (and other non-renewable strategic materials) into ones in partially 'closed economies', in which raw materials and products are converted into each other by manufacturing and subsequently recycling to reduce environmental impacts, we will not be able to achieve sustainable economies in the strong sense (as put forward by Constanza and Daly 1992) without drastic population reduction (-P) and austere consumer behavior (-A). Strong sustainability mandates that natural capital stocks are to be kept constant. This is in contrast to weak sustainability, in which natural capital stocks can be replaced by human-made capital, and only the aggregate needs to stay constant (as put forward by Rees and Wackernagel 1995). Reijnders (1998) states that 'dematerialization' of the economy by a factor of ~10 indicates 'remarkable technological optimism'. It took 25 years (1959-1984) to reduce the energy intensity (energy use/unit of GDP) of the US economy by 50% (Graedel and Allenby 1995). Again, the time spans needed for such increases in technological efficiency are decades and require sustained political and technological efforts if they are to come to fruition.

However, even economies based on weak sustainability will be continuously confronted with (1) permanent resource crises due to the limited availability of strategic materials (i.e. rare earths, lithium); and (2) the fact that complete and cost-effective recycling will not be possible.

The amount and types of materials needed to implement low- or zero carbon based technologies for a weakly sustainable economy already point to the beginning of a series of resource crisis ('permanent resource crises'). The rare earth metals have abundances on the order of parts-per-million in the earth's crust. While the elements of this group of 15 metals are not as rare as their name indicates, their 2007 world demand of 110,000 tons, of which 90% comes from China, is used in many high-tech products and processes, including ceramics and pigments (7%), catalysis, including automotive catalytic converters (20%), phosphors for compact fluorescent and solid state lighting (LEDs) (7%), the glass and polishing industry (25%), permanent magnets such as Nd-Fe-B and $SmCo_5$ (35%) and other applications such as the newly identified need for neodymium (Nd) for wind turbine systems and as unrefined mixtures called 'mischmetal' in nickel hydride batteries (6%) (Cuif 2008). Many of these uses are center stage in green technologies and their demand is likely to outpace supply within a very short time. The price of rare earth metals has been going up in the last decade, due to the limited supply (controlled by the Chinese government) and the growing demand for phosphors for lighting applications. The anticipated ban of incandescent lamps in Australia and Europe, and the push for compact fluorescent lamps in the short term has already put enormous pressure on rare earth supplies and prices. A full 'green lighting switch' will double the required volume of phosphors containing rare earth metals. We also anticipate a continued demand for flat plate TV screens: a continuous growth rate of 15-20% for large size flat displays is projected over the next few years. There is already a shortage of Terbium (Tb), needed for green phosphors, and Europium (Eu), used for red and blue phosphors. At most about 40% of additional Tb (~50 tons) and 75% of Eu (~130 tons) will be available by 2015. Recycling 10-15% of the current world supply of Tb and Eu is an absolute must for addressing this materials shortage in the short to mid-term – but there is currently no agreed upon process for efficiently collecting and recycling rare earth metals from lighting phosphors.

Other strategic materials needed to implement green and nanotechnologies which are currently resource limited are silver, tellurium and indium (for thin film photovoltaic devices), platinum (needed for fuel cells), and lithium (for lithium based batteries). The global lithium production in 2005 was about 20.000 tons, and came from two main sources: (i) an Li,Al silicate, the mineral spodumene (18%) and (ii) LiCl extracted from brine lakes and salt planes. 50% of the 2005 global production came from Chile and Argentine; 75% of global reserves are located in South America, with the largest reserves (~50%) currently lying untapped in the Salar di Uyuni salt lakes in Bolivia. Political tensions regarding Li mining are already manifest in both Chile and Argentine, with major flashpoints being the enormous water use required for the LiCl extraction, as well as ecological and environmental concerns and issues about the rights and economic benefits of local communities. Bolivia's lithium mining options are currently not being exercised due to these political constraints. Total lithium production today would allow about 10% of global vehicle production (60 million cars) to be equipped with a 9MWh lithium ion battery. Again this would result in large market distortions since 1 million hybrid cars equipped with Li ion batteries would use as much Li_2CO_3 as raw lithium is used in the entire electronics sector today (Tahil 2007).

These two examples of permanent resource crises, in which demand is already outpacing the supply, reveal intriguing similarities:

1. Lithium and rare earth metals are strategic materials needed to implement green technologies in order to reduce our dependency on Middle Eastern oil production. However, the regional concentration of these strategic resources in China and South America respectively presents similar geopolitical risks and crisis potential as oil production being predominantly located in the Middle East.
2. Fast emerging and disruptive technologies which need strategic materials will have a strong and rapid impact on global materials demand, which will not allow for ordered development and growth of the resource supply infrastructure. This will lead to financial speculation and short term supply problems, which can hamper the implementation of a particular technology platform[5].

I predict that in the future we will see more of these types of permanent resource crises created by a specific technology relying on a particular strategic material resource which cannot initially – or ever – be scaled up globally or nationally. Upstream analysis in the early stages of technology development must detect such critical material requirements, and trigger immediate exploration of possible alternatives and/or relevant recycling technologies. By envisioning applications of emerging technologies very early in their development - a hallmark of mode-2 knowledge production - we have an opportunity to minimize the risk of ‘stranded technologies’ and provide cautious input for future projections, as well as reducing expectations to realistic levels[6].

3. Recycling of these strategic materials is in its infancy and needs to be developed with utmost urgency. While certain materials such as industrial catalysts and metals can be recycled in an economically efficient way, many highly dematerialized nanotechnology products are multi-phase hybrids containing thin films, minute amounts of additives and solvents, and would cost prohibitive amounts of energy to recycle. In other words, the smaller the

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[5] This type of resource crisis is currently being played out around Helium-3. Due to the enormous and rapid growth of neutron detectors using Helium-3 – driven by safety and non-proliferation programs of the US Department of Homeland Security and the Department of Energy – a severe shortage has developed, which has led to a sharp ten-fold price increase over the last 3 years (2006-2009). According to the DOE, the short-term demand is about 65.000 liters per year, while the current supply is between 10.000 to 20.000 liters per year. 1,7% of the Helium-3 is used in medical imaging while 2,5% is required for the oil and gas industry. Detectors for neutron scattering (~10%) and security (~84,5%) make up the vast majority of Helium-3 demand. New detectors which do not rely on Helium-3 and new supply infrastructure projects take time to develop and implement. As mentioned earlier, nanotechnology is being touted as a game changer to overcome this (and similar) resource crises. Another emerging class of materials shortage reaching crisis level is medical isotopes, in particular Technetium-99m.

[6] It needs to be stressed that innovation and technology development calls for a certain level of risk and ‘irrational exuberance’ in order to mobilize human, financial and other institutional resources. A very fine line exists between hype and stagnation created by a risk adverse culture and an ineffective ‘bubble culture’, as seen for instance towards the end of the Internet boom.

resource concentration becomes within a particular waste stream, the higher the energy required to purify it again will be.

It is thus a daunting task to completely re-engineer and re-design our currently unsustainable economies towards even weakly sustainable ones. Incremental tinkering will not be enough, and – if achievable at all – this transition will be accompanied by major global and local political, social and cultural shifts. Looking at macroeconomic trends over time, one can see that technological efficiency and consumer-based dematerialization will be able to reduce environmental impact. However, even with moderate economic growth rates at or near 2%, and significant technological efficiency gains in the order of 50%, one can show that economic growth will in the long run always outrun C x T (C = consumer intensity of use, T = technology efficiency factor) (Huesemann 2005). After one or two decades environmental impact will increase again, despite all technological efficiency gains. New game-changing technologies will subsequently be required to further reduce the environmental impact, which in many cases require decades of development and incubation time. The increasing speed of technological innovation will create resource calamities, increasing challenges and complexities for materials supply and recycling. One could propose that slowing down technological innovation and progress might postpone the appearance of future crises, which themselves can trigger financial meltdowns and civil unrest. Curbing economic growth using monetary policies has mainly been used as a short-term tool to prevent 'overheating' of markets but not with a long-term goal of prolonging the time until the next resource limit is reached. In matters of innovation and technological development we continuously call on fast-paced and accelerated processes.

Time scales of innovation and the implementation of emerging technologies are important but overlooked parameters. The implementation of technologies reveals time constants similar to diffusion time constants of percolation processes and saturation levels of market penetration, which have great implications for science and technology policies (Ausubel 2004). The implementation of the passenger car as a primary mode of transportation, for example, took about 100 years in the United States and leveled off at a saturation level near 1000cars/1000 persons. In Canada the development took place about 40 years later and required about 60 years to reach a saturation density close to 500 cars/1000 people (Figure 2).

Another important lesson learned when comparing the first with subsequent adoptions of a particular technology is that first adopters take significantly longer and overshoot in their saturation levels. The longer diffusion time is caused by the need to conceive and implement a series of necessary conditions for the technology to be implemented. Catching up with technological developments can be done at a significantly faster pace, as one has the benefit of knowing about the failures and lessons learned by the first adopter and can copy and adapt already proven strategies. This should be taken into consideration when exploring the possible 're-run' of technologies such as nuclear energy production, biofuels[7] and genetically modified organisms (GMO), since shorter diffusion times might allow a more realistic timing within a complex low-carbon energy production portfolio. Public reaction to the first implementation version of the technology has already been tested, and policies as well as technological concerns – such as the long term storage and nuclear non-proliferation

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[7] See the figure representing the global production of primary energy sources between 1960 and 2007 and Shell's Blueprint scenario after 2007 in Kramer and Haigh 2009, p. 569.

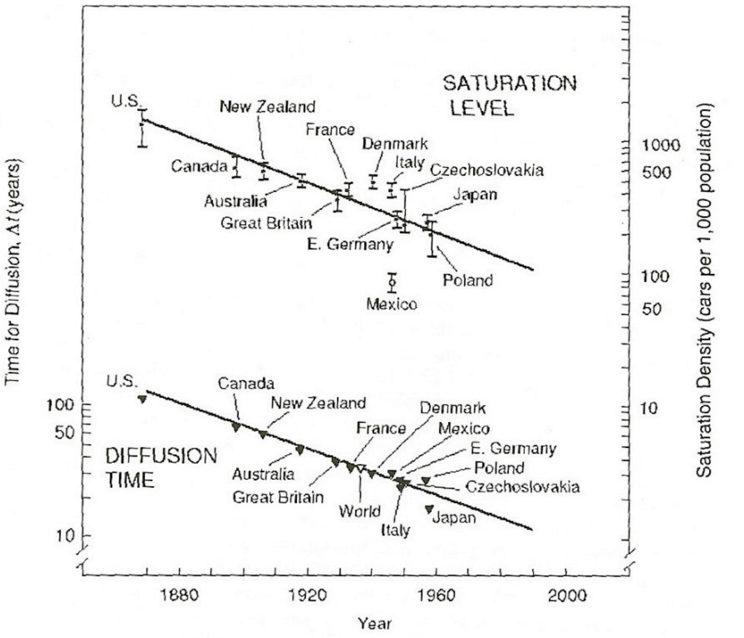

Figure 2: Diffusion time and saturation level of passenger car market penetration in various countries. Taken from J.H. Ausubel (2004, p. 353).

issues – have already been voiced. Thus, as a consequence of earlier public resistance and discussion, nuclear 2.0 might propose small subcritical thorium-based pebble-bed reactors with local storage and advances in transmutation technologies as a nuclear wedge to build a low-carbon based energy supply infrastructure[8]. GMO 2.0 might propose to continue to focus on the local farming of vitamin A and E, zinc and iron enhanced cassava plants in Sub-Saharan Africa, from which about 250 million people obtain about 40% of their daily caloric requirements. In contrast to GMO 1.0 this technology could be implemented with royalty-free licenses and seeds granted by non-governmental organizations such as the Bill and Melinda Gates Foundation to address some of the public concerns voiced earlier.

Timing considerations should be investigated more thoroughly when evaluating the use and impact of emerging technologies. The fact that we are now using billions of dollars for research and development of technologies in order to remediate the confluence of a climate change and multiple sustainability crises begs the question of

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[8] Thorium (Th) is roughly four times more abundant than uranium, requires no complex enrichment process to become a reactor fuel. Th-based reactor waste has radioactivity half life times in the tens of years. ^{232}Th is transmutated into ^{235}U by neutron capture, which is a highly efficient nuclear fuel. The reason Th was not initially pursued as a reactor fuel was that nowhere in its cycle can fuel or waste be converted into nuclear bomb material.

whether science and emerging technologies are not setting themselves up for failure in the public's eye by continuously taking on and rising to this challenge[9].

Kramer and Haigh (2009) argue that the scale of the energy system that needs to be revamped is so immense that we need to be aware of physical limits to the rate at which new technologies can be implemented. They show that energy technologies go through a few decades of exponential growth and incubation until the particular energy source becomes part of the energy portfolio by reaching 'materiality', at a portion of about 1% of the world energy consumption. As shown in Ausubel's study above it takes time to build both industrial and human capacity to reach a materiality level of 1%, after which the growth levels off. This time period cannot be shortened by simply increasing the financing of a technology. The data in Kramer and Haigh (2009) again reiterate that a 're-run' as shown by the deployment of the second generation of biofuel technology is implemented significantly faster than the first generation was.

The expectation, found in large parts of our societies and amongst political establishments in both developed and developing countries, that science will provide the 'magic bullet' to allow us to continue economic growth and elevate ever larger sections of the developing countries to a more affluent life style, without encountering global limits of materials resources, energy or ecological constraints, is not sustainable. We need to redirect our scientific and technological efforts towards research programs with genuine and reasonable deliverables and timetables. Sarewitz' technology criteria are an important consideration in an attempt to maximize the use of scientific efforts and money to assist in tackling complex global issues. Dan Sarewitz and Richard Nelson (2008) discussed the applicability of technological fixes to a variety of technological goals and suggest three rules to assess their usefulness[10]:

1. The technological fix must epitomize a strong cause-effect relationship connecting the problem to the solution as directly as possible. Vaccines might reveal strong cause-effect relationships in laboratory tests which then become weakened during socio-technological implementation. Uncertainties are reduced when we can address a specific cause-effect relationship rather than multiple indirect effects.
2. One must be able to assess the results of the technological fix using agreed metrics which are as unambiguous and uncontroversial as possible. The implementation of various economic stimulus policies by the Obama administration has already shifted the political discussion onto how to assess

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[9] The frustration of the American public with the remediation efforts in the current environmental crisis in the Gulf of Mexico due to a deep-water oil well leak indicates the dangers of continuously raising the technological stakes and coming up short with technological bail outs.

[10] In a 2004 article Sarewitz addressed the question why certain socio-technological problems cannot be solved using technology alone. The three examples, climate change, genetically modified organisms and foods, and long-term nuclear waste disposal are case studies when science becomes politicized and politics becomes 'scientized'. In these cases uncertainties and heterogeneous disciplinary cultures play a major role: in the discussions on global climate change and nuclear waste disposal proposals such as proposed and recently abandoned Yucca Mountain site in Nevada the epistemological and ontological uncertainties are ideologically politicized in contrasting manner: conservatives demand action in Yucca Mountain but oppose action on policies to address global climate change while liberals oppose the construction of a nuclear waste disposal site in Yucca Mountain but demand action to reduce CO_2 emissions to reduce impacts on future climate.

their impact and which metrics to use (e.g. jobless rate during jobless recovery, debt rate, stock market) to gauge their effectiveness.

3. The fix should address a disciplinarily well-rooted homogeneous technological core.

An example given by Sarewitz and Nelson is the approach taken to stabilizing CO_2 concentrations in the atmosphere by radically reducing emissions or CO_2 removal from the atmosphere. While in the first case a plethora of technologies are emerging and being assessed (photovoltaic, wind, sequestration) as well as re-assesed (nuclear), the implementation of a low-emission economy requires an effective coordination of this heterogeneous group of energy producers, suppliers and end users which represents a complex energy management portfolio approach with multiple cause-effect relationships. While rule (3) can be applied to each individual technology proposed to reduce CO_2 concentrations in the atmosphere (e.g. photovoltaics, wind, sequestration), a strong cause-effect relationship is weakened by the implementation, coordination and managerial processes required to succeed. On the other hand, direct removal of CO_2 concentrations from the atmosphere - a technology discussed within the context of certain geo-engineering solutions - satisfies all 3 rules suggested by Sarewitz and Nelson: a strong cause-effect relationship between CO_2 concentrations and global temperature exists (Rule 1), standard measurements and metrics exist and are agreed upon that measure the CO_2 concentrations (Rule 2) and CO_2-capture technologies from air exist and are currently being developed (Rule 3).

A second important consideration is to value science and technology efforts based on the amount of time they provide for society to transform and evolve towards sustainability. The colloquial 'it is not if but when' uncertainty often used in discussions on global climate change, materials resource limitations (e.g. 'peak oil') or global pandemic events suggests that timing is of value in global risk assessments and remediation. To have time to implement changes is of significant value since scientific resources and strategies can be used more effectively and targeted. The convolution of multiple crises ('The perfect storm') creates additional non-linear complexities and entangled issues which make their solutions even much more difficult and uncertain.

Climate change – as well as many other global environmental challenges – has been framed as a tragedy of the commons (Hardin 1968). Each individual user (person, group, state, global region) of a common resource (atmosphere, ecosphere) in using that resource reduces the value of the resource to a smaller degree than the amount of utility he derives from it. However, he thereby reduces the value of that resource to all other users to a degree greater than the amount of utility he receives for its use. Despite their geographical concentrations, material resources such as oil in the Middle East, rare earth metals in China, and Lithium in South America can be argued to be common global resources, and their depletion can therefore be framed as a tragedy of commons. In the absence of enforced or voluntary cooperation, every 'rational actor' has thus an incentive to deplete the common resource and to do so as fast as possible.

Slowing down the depletion of commons appears, at least from a neo-liberal macroeconomic point of view, to be 'not rational' within the context of Mill's and Becker's 'Homo Economicus'. Both behavioral economics and decades of research on human cooperation and the commons by Elinor Ostrom (Nobel Prize in economics 2009) have debunked the 'rational agent' hypothesis of neoliberal economics and replaced it with a more realistic description. Hardin's concept of the 'tragedy of commons' needs to be reinvestigated in light of historical analysis, which indicates that in many cases the commons were not overused by 'rational agents' but taken over by kings and noblemen using the process of enclosure, settlers claiming common land to be terra nullius, and today multinational corporations bottling water from public lakes and springs, and governmental entities dividing up frequency bands for communication purposes[11]. The development of novel cooperative local political structures which value and use commons such as land, lakes, fisheries and forests in new (or not so new) ways are still decoupled and uncoordinated from technological developments (e.g. large scale CO_2 sequestration), despite the fact that they both focus on creating a sustainable environment and promote suitable practices. These and other political changes (such as global CO_2 emission policies) take time to implement. Technologies can provide this time by remediating acute problems, increasing technological efficiencies and reducing environmental impact. However, these political changes need to be pursued with a much longer time horizon than is customary in election cycle-driven politics, and continuously coordinated with policies impacting both consumers' intensity of use (C) and the technology factor (T). It might become necessary to sequester some of the efficiencies gained by the sustainability levers T and C and reinvest them in financial commons. To illustrate this, I will make use of the historical example of Jevons' paradox, sometimes also referred to as the rebound effect. Simply stated it claims that any technological progress which increases the efficiency (T) with which a given resource is used, tends to also increase the rate of consumption of that particular resource. William Stanley Jevons noted in his book 'The Coal Question' (1866) that the consumption of coal sharply rose with the appearance of the coal-fired steam engine built by James Watt, which was more efficient than Thomas Newcomen's design. Improved resource-efficiency tends to lower the cost of a resource and thereby increase the demand, which accelerates economic growth, increasing the demand even further. In a more detailed analysis one has to examine whether the increase in demand outweighs the increased efficiency. Jevons' paradox will manifest itself when the rebound effect is larger than the initial efficiency gains ('backfire'). Whether this occurs or not depends on whether there is an elastic or inelastic demand for the resource. In the elastic case, a doubling of the resource efficiency or halving of the price more than doubles the amount of resource demand, thus Jevons' paradoxical situation is observed. However, in the inelastic demand situation a doubling of resource efficiency or halving of the price does not double the amount of resource demand. In a careful analysis many factors besides just resource costs, such as labor intensity and infrastructure costs, need to be taken into account. This will decrease the effect of resource efficiency and the possibility of the occurrence of a rebound effect. However, naïve calculations on the basis of energy efficiency need to be cautiously examined. In an established market the direct rebound effect is inelastic and quite small and increased resource efficiency tends to reduce resource use. What ultimately outpaces resource conservation is economic growth.

In 1992 Saunders re-examined work by Brookes and Khazzoom and claimed that energy efficiencies increase rather than decrease energy consumption. He argues that this is due to two processes: first, efficiency reduces energy costs resulting in a higher demand (rebound effect), and, second, energy efficiency triggers economic growth which increases the demand for energy even more. If this is correct then energy

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[11] For a historical analysis of the commons see Linebaugh (2008).

conservation can only be achieved by coupling an energy efficiency gain with a tax or another form of governmental intervention. Wackernagel and Rees (1997) argue along these lines and advocate that these efficiency gains need to be removed from further economic circulation and reinvested in natural capital rehabilitation. The ordered political implementation of mandating the reinvestment of technological efficiency gains into financial commons requires decades. This again stresses the common theme of this essay that time is needed to evolve our political structures and societies to a point where aspects of weak sustainability can be achieved. This is primarily an ethical, political, social and cultural struggle, not a technological project.

It is misguided to use the metaphor of demanding an "Apollo Project for our energy future" (R. Smalley), since we did not have to change our societal structures to put a man on the moon. The Apollo project and similar industrial war time efforts span generally less than a decade and are very difficult to sustain in a civil society with no direct external military threat but an 'intergenerational' equity issue, which might well in the future result in military conflict. It is an important and non-trivial realization that emerging technologies can buy societies time to undertake the necessary political, social and ethical discussions and changes to address the root-causes of unsustainable economies and societies. In a certain way, modern societies are using technologies to avoid the necessary political discourse to achieve sustainability. As Allenby put so succinctly: "Consumers and society as a whole must not be left with the impression that simply relying on technology will avoid the need for difficult and complex political decisions. Better technology can buy time, but it cannot by itself buy sustainability" (Allenby 1999, p. 57).

Furthermore, value-based discussions regarding trade-offs between sustainability, economic and population growth need to be initiated. If we fail to do this we may indeed discover that "…all the technical prowess and manipulative cleverness in the world will not solve our problems and, in fact, will make them worse" (Daly 1994, p. 96).

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