Nanotechnology and sustainability**

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The sustainability of our present civilization and, ultimately, of human life itself is challenged on many fronts. The most prominent of the challenges are climate change, extreme food and water shortages, rising chronic diseases, and rampant obesity. They are all of great significance in terms of death and morbidity, and at the same time seemingly intractable. This paper looks at the technical dimension of overcoming these challenges, contrasting the apparent impotence of conventional technologies with the potential of nanotechnology. Attention is paid to the scalability of any proposed nanotechnology-based solutions, as well as the related aspect of realizable timescales. The paper concludes by examining the problems of implementing solutions projected to be successful.

1. Introduction

A recent book by Daniel Callahan calls attention to five major challenges to humanity:[1] (adverse) climate change; extreme food shortages; extreme water shortages; rising chronic diseases; and rampant obesity (which could be considered a kind of chronic disease). The choice of these five is uncontroversial, although food and water are not the only resources that may experience shortages, and environmental degradation, especially through anthropogenic pollution, should also be taken into consideration. Note that the food and water shortages are a foreseeable consequence of adverse climate change (global warming). It is implied that the *net* effect is adverse—clearly global warming will enable some lands to be brought (back) into cultivation, but it is estimated that a significantly larger area will be rendered less productive. The cause of rising chronic disease is more difficult to link directly to global warming. These diseases are widely considered to be driven by lifestyle choices. Hot summery days do indeed tend to promote

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[1] D. Callahan, *The Five Horsemen of the Modern World*. New York: Columbia University Press (2016).

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indolence, hence a lack of exercise, which is considered to be one of the factors contributing to obesity and other diseases following from that, such as coronary insufficiency and diabetes (hence "diabesity"). On the other hand, most people eat less in summer—there is less body heating requirement, and more opportunities for outdoor activity, hence less time for comfort eating.

Food and water shortages are themselves linked, agriculture being a major consumer of fresh (nonsaline) water. "Shortage" means an imbalance of demand and supply; hence, they are driven by a large and possibly still growing population as much as by any diminution of output.

The primary driver of climate change is considered to be global warming. That is incontrovertible enough, and indeed objectively measurable, albeit with some difficulty.[2] What is disputed is the cause of the change—anthropogenic or not.[2] The two extreme proposals are fluctuations—increases—in solar output, or at any rate the amount of solar energy received by the Earth, and excessive emission of "greenhouse" gases (especially carbon dioxide) due to anthropogenic activity, which of course is also incontrovertibly increasing. The "truth" regarding the origin of the warming doubtless lies somewhere in between. It is important to try to establish the cause because that will determine the most effective action that can be taken. With our present level of technological achievement, we are able to do very little to influence solar output and the Sun–Earth distance; hence, useful efforts can only be directed towards mitigation. On the other hand, we can do a great deal about anthropogenic activity, and it is fairly clear which kinds of activity make the greatest contributions to carbon dioxide emissions—deforestation, burning fossil fuels, cement manufacture and pyrometallurgy.[2] Carbon dioxide levels in the atmosphere are well correlated with human population and human activity;[2,3] the simplest way of countering the trend of rising carbon dioxide levels would therefore be to reduce human population and human activity. At a stroke, this would also eliminate food and water shortages, and possibly lifestyle diseases as well, since their growth is well correlated with the growing population, especially urban population.

Nevertheless, reducing population and activity is easier said than done. Although it is possible that the system as a whole corrects itself (for example, food shortage might lead to mass starvation),[4] in this paper we shall focus on possible interventions favouring sustainability, especially those involving nanotechnology.

Before proceeding to the main part of this paper, let us briefly look at what is already happening in this regard. There have been various international agreements (Kyoto, Copenhagen, Paris) seeking above all to limit carbon dioxide emissions. Most countries are more or less active in finding ways to implement such limitations. Initially much criticism came from the perception that such limiting measures dampened the economy, making it more difficult to finance other mitigation measures. More recently, the United Kingdom has led the way with a "green growth" strategy, in which a "low-carbon economy" is seen as an opportunity for expansion, rather than retrenchment.[5]

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[2] G.C. Holt and J.J. Ramsden, Introduction to global warming. In: *Complexity and Security* (eds J.J. Ramsden & P.J. Kervalishvili), pp. 147–184. Amsterdam: IOS Press (2008).

[3] J.J. Ramsden, Doomsday scenarios: an appraisal. *Nanotechnol. Perceptions* **12** (2016) 35–46.

[4] J.J. Ramsden, Nanotechnology and Gaia. *Nanotechnol. Perceptions* **10** (2014) 173–189.

[5] *The Clean Growth Strategy. Leading the Way to a Low Carbon Future*. London: Department for Business, Energy and Industrial Strategy (amended April 2018 from the original version dated October 2017).

2. How can nanotechnology contribute to the five challenges?[6]

2.1 Climate change—limiting carbon emissions

The goal can be achieved by "prevention" or by "cure" (or some combination of the two).

2.1.1 Prevention

Nanotechnology—in other words engineering with atomic precision—can achieve more with less. Equivalent or better functionality can be obtained from using less materials. Norio Taniguchi, the father of nanotechnology, has demonstrated that engineering precision has improved exponentially since the start of the Industrial Revolution. This in turn implies that the efficiency of industrial processes has improved—think of the progressive diminution in the size of steam engines and the concomitant increase in their efficiency expressed as power density or specific power. From this viewpoint, nanotechnology does not represent a qualitative leap, but is simply the culmination (engineering at subatomic scale is scarcely conceivable) of a long trend.

Perhaps it is in the realm of information technologies where progress has been the most striking (Moore's law). Here we have the advantage that the physical embodiment of one bit of information has, essentially, no lower limit.[8] Interestingly, although the feature sizes of contemporary very large-scale integrated circuits are well within the nanoscale, the electronic components still operate in classical mode, making no use of the single electron phenomena that are often associated with nanoelectronics.[9] That may, of course, soon change if a practical quantum computer is developed. Landauer established the theoretical lower limit for the amount of energy required to undertake computation;[10] even now we are still far above that limit with the smallest available devices.

From the viewpoint of limiting carbon emissions, the interest in nanification lies in (a) the diminished energy requirement for carrying out a given process, and (b) the diminished amounts of material required to accomplish the process. The diminution in the quantity of materials used to create a given product, or accomplish a given service, is nowadays called dematerialization;[12] nanotechnology is its apotheosis. The motivation for dematerialization can be aesthetic,[13]

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6 For an earlier view, see ref. 7.

7 A.G. Mamalis, J.J. Ramsden, G.C. Holt, A.K.Vortselas and A.A. Mamali, The effect of nanotechnology on mitigation and adaptation strategies in response to climate change. *Nanotechnol. Perceptions* **7** (2011) 159–179.

8 The limit may be one baryon, well below the nanoscale. See A.A. Berezin, Information storage based on isotopic combinations. *Speculations Sci. Technol.* **7** (1984) 317–319.

9 J.J. Ramsden, *Nanotechnology: An Introduction* (2nd edn). Amsterdam: Elsevier (2016).

10 R. Landauer, Dissipation and heat generation in the computing process. *IBM J.* **5** (1961) 183–191; see also ref. 11.

11 C.H. Bennett, Notes on Landauer's principle, reversible computation, and Maxwell's Demon. *Studies History Philos. Mod. Phys.* **34** (2003) 501–510.

12 In the financial world, "dematerialization" refers specifically to the replacement of paper certificates by electronic records of share transactions.

13 "The less material used per function, the closer the design is to pure principle"—J. Baldwin, quoted by Hawken et al.[14]

14 P. Hawken, A.B. Lovins and L.H. Lovins, *Natural Capitalism. The Next Industrial Revolution*, p. 77. New York: Back Bay (Little, Brown) (2000).

economic (reducing manufacturing and/or delivery costs), or for promoting sustainability. Some examples of dematerialization preceding the nanotechnology era are: Leclanché dry cells (diminishing the mass of zinc in the anode); cans (especially for drinks); and the roof beams (trussed rafters) of houses. In each case, the dematerialization was the result of theoretical work to predict the minimum amount of material necessary, alongside the means to quantitatively assess the quality of the raw material.[15,16]

2.1.2 Cure

Nanotechnology can be useful for mitigating emissions from conventional processes. Nanoengineered porous solids can be used for carbon capture at point emission sources (such as the flues of combustion-powered electricity generating plants). It has proved difficult to implement a cost-effective capture technology at the scale required.[17] A novel approach is to use metal–organic frameworks, highly porous materials that can be nano-engineered to provide cooperative adsorption (i.e., hysteretic adsorption–desorption, like haemoglobin for oxygen).[18]

2.1.3 Critique

The very success of nanotechnology in doing more with less has meant that it has become more difficult to recover precious materials from discarded objects, such as mobile phones, because those materials are so intimately commingled with what is in effect gangue (e.g., organic polymer packaging) that conventional recovery techniques have become less effective. There are, however, rapid advances in extracting gold and other valuable metals from such waste (e.g., the development of supercritical water-driven extraction) and it looks as though we shall eventually be able to overcome this problem with the same technological advances that will allow pyrometallurgy to be replaced.

A very different potential problem arises through Jevons' paradox,[19] which asserts that increasing the efficiency with which a resource is used tends to increase the rate of consumption of that resource. This implies that the progressive introduction of nanotechnology into the economy will not result in a net saving of material and energy; its very success will cause consumption to increase.

It is, however, striking that although commodity consumption has undoubtedly increased during the past few decades, commodity prices have tended to remain rather stable or even decrease.[20,21] In this context, it is highly revealing that reserves (e.g., of unmined ore) have tended to remain stable or even increase.[20] This may be a consequence of the constantly

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[15] W.T. Curry, *Mechanical Stress Grading of Timber*. Princes Risborough: Forest Products Research Laboratory (PRL) (1969).

[16] A.R. Fewell, Machine stress trading of timber in the United Kingdom. *Holz Roh-Werkstoff* **40** (1982) 455–459.

[17] K.Z. House, A.C. Baclig, M. Ranjan, E.A. van Nierop, J. Wilcox and H.J. Herzog, Economic and energetic analysis of capturing CO_2 from ambient air. *Proc. Natl Acad. Sci. USA* **108** (2011) 20428–20433.

[18] T.M. McDonald et al., Cooperative insertion of CO_2 in diamine-appended metal–organic frameworks. *Nature* **590** (2015) 303–308.

[19] W.S. Jevons, *The Coal Question*. London and Cambridge: Macmillan (1865).

[20] A.G. Tvalchrelidze, *Economics of Commodities and Commodity Markets*. New York: Nova Science (2011).

[21] The price question is fraught with difficulties, not least the change in value of the currency units in

(accumulatively) increasing knowledge and expertise of humanity, a view championed by J.L. Simon;[22] nanotechnology is just a part of this constantly increasing knowledge and expertise.

2.2 Food and water shortages

(Fresh) water shortages are already a very real feature of some parts of the world. Perhaps the most visually striking occurrence is around the Dead Sea, the level of which has fallen about 40 m during the last half-century and continues to fall at about 1 m per annum,[23] creating a ghastly landscape of sinkholes and shoreline infrastructure stranded high above the water. The primary cause is excessive diversion of water from the River Jordan for agriculture and human consumption.

Many countries, especially mountainous ones like Georgia and Switzerland, still have abundant supplies of fresh water. Excess in one place is not, however, practicably transferable to places with a deficit. The challenge is to make up the shortfall with methods adapted to local conditions. For example, nanoporous metal–organic framework materials (some of which, as already mentioned, are candidates for CO_2 capture) can also be exploited for water capture in localities that are hot and dry during the day, but cold and humid at night (e.g., the Red Sea coast in the vicinity of Jeddah). Given a suitably engineered material,[24] it is merely necessary to let it be exposed to the atmosphere at night, during which it will collect abundant water, to be released as the temperature rises during the day.

Not many places can take advantage of such conditions, however. Most commonly, seawater is used as the feedstock for the production of potable water. Distillation is the simplest method, and half a century ago there was much interest in using surplus heat from nuclear reactors to power it. Nowadays some form of osmosis is most commonly employed, using either electricity or pressure to drive the salty water through a membrane. We already have *nano*porous membranes used for ultrafiltration and reverse osmosis (an elegant approach is to use self-assembly), to create potable from salty water, albeit that the gains compared with conventional membranes (which may anyway have a degree of nanoporosity) tend to be minor. The procurement of the membrane is only part of the problem, however—both distillation and osmosis are irreducibly energy-expensive. Given abundant energy, the problem of fresh water shortage can be solved using existing knowledge. In the long term, kidney-inspired nanoscale devices might be developed—operating at room temperature and pressure. There is an overabundance of saline water, hence all that is needed is a cost-effective way of desalination.

If technological mastery of atomic-scale engineering is achieved to the extent that the personal nanofactory becomes a reality, then even food will be manufacturable from common hydrocarbon feedstocks,[25] hence in principle eliminating shortages.

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which the price is expressed. But it can be asserted with considerable confidence that soaring prices implied by the imminent depletion of resources suggested by some authors (see references in ref. 3) have not occurred.

[22] J.L. Simon, *The Ultimate Resource 2*. Princeton: University Press (1996).

[23] The Aral Sea constitutes an even more striking example, having almost completely dried up, but this was a deliberate sacrifice in favour of vast cotton plantations created *de novo* in the deserts of Turkmenistan and Uzbekistan in the Soviet era.

[24] H. Furukawa et al., Water adsorption in porous metal–organic frameworks and related materials. *J. Am. Chem. Soc.* **156** (2014) 4369–4381.

[25] R.A. Freitas, Jr, Economic impact of the personal nanofactory. *Nanotechnol. Perceptions* **2** (2006) 111–126.

2.3 Obesity and other diseases

Various causes have been proposed for obesity. They are not mutually exclusive, and it may be a multifactorial affliction. At any rate, if overeating is reckoned to be one possible cause, any mass dietary restriction resulting from acute food and water shortages should rapidly eliminate obesity.

Another possible cause is inadequate activity to dissipate the energy derived from metabolizing ingested food. This includes spending time in overheated interior rooms and using motorized transport. If the desire to at least attempt to halt climate change by restricting carbon dioxide emissions becomes strong enough, efforts will be made to reduce energy consumption, efforts which could include less heating (which global warming will anyway tend to make unnecessary) and less use of motorized transport.

Regarding "lifestyle" diseases (which may include obesity), it is difficult to see how nanotechnology can contribute directly to overcoming them. Possibly large, nano-enabled, animated screens set up in major cities, urging the "right" behaviour, may achieve something. In essence this is already happening in the People's Republic of China. Even the UK government has shown some inclination to pursue that direction, having set up the Behavioural Insights Team. But in China, it seems that the (nano-enabled) ability to collect and process vast quantities of data have allowed detailed surveillance of citizens to be exploited to a far greater extent, such that actions deemed (by the government—and the answer to *quis custodiet ipsos custodes?* is therefore "no one") to be laudable are rewarded, and those deemed to be reprehensible are penalized (the so-called "social credit" system). Perhaps this is nothing more than microlaw or even nanolaw, if law is perceived as the codification of social behaviour essential for survival.[26]

One interesting potential contribution of nanotechnology to combating infectious disease is the deployment of nanostructured photocatalytic antimicrobial coatings for surfaces within hospitals, convalescent homes, care homes, schools, railway carriages, aircraft cabins, trams and so forth—wherever people are gathered in close proximity and are potentially able to infect each other. Upon illumination, these coatings generate highly oxidative radicals that are lethal to bacteria (and viruses), for which the coated surfaces are therefore sinks. Resistance cannot be developed against these radicals,[27] hence the need for using powerful antibiotics is obviated. This provides a powerful weapon against the dangerous increase of antimicrobial-resistant pathogens in the world.

3. Discussion

Summarizing the above, with respect to overcoming Callahan's "five horsemen", nanotechnology should be seen as forming just a part of humanity's constantly increasing knowledge and expertise, rather than offering "magic bullets" to shoot down the horsemen.

Wherever a nano solution to a problem does become available—that is, proof of principle has been demonstrated in the laboratory and field trials are promising—the question arises whether the nanomaterials and nanodevices can be produced at the scale required. The semiconductor industry has successfully solved this problem—so great is the capital cost of

[26] P.R. Wood, *The Fall of the Priests and the Rise of the Lawyers*. Oxford, UK and Portland, Oregon: Hart Publishing (2016).

[27] J.J. Ramsden, Can bacteria develop resistance to photocatalytically generated reactive oxygen species? *J. Biol. Phys. Chem.* **17** (2017) 47–51.

manufacturing very large-scale integrated circuits with nanoscale features that it can only be done for a very high rate of production, satisfying a very high degree of demand, a condition that is fulfilled by the globally sought after highly desirable products containing such circuits, such as cellphones, data-processing servers, personal computers, "tablets" etc.

On the other hand, true nanomaterial production still seems to be dominated by university laboratories and private companies spun out of universities, nanofacturing at a small-scale, each one to its own specification. Commoditization, the key to large-scale availability of a uniform product, is only just beginning.[28]

Of general concern to the public-at-large is the safety of nano products, especially nano-objects released, or potentially able to be released, into the environment. It has proved to be extraordinarily difficult to achieve expert consensus on this matter.[29] Risk is the product of hazard and exposure; the latter can be quantified,[30] and the hazard of nano-objects is not an especially new subject. A common source of nanoparticles in the human body is the wear of prostheses, which has been extensively studied.[31]

The widespread availability of funding for nanotechnology research has (presumably) being the reason for the enormous growth in studies into the toxicity of nanomaterials. Sadly, the quality of many of these studies is low, with numerous deficiencies in experimental design, execution and interpretation.[29] No result of this kind of study should be quoted without a critical scrutiny of every aspect of the work that led to the result.

Relatively little attention has been paid to the inhalation of nanoparticles, or aerosols containing nanoparticles. Hence, in the absence of specific studies, one must look at the wider field and the biological plausibility of any proposed effects. Undoubtedly, *rigid, insoluble nanofibres*, however they are introduced into the body, are the most dangerous type of nanoobject. Like asbestos, they engender chronic inflammation and, in the long term, mesothelioma. Very likely carbon nanofibres fall into this category.[32] It is highly likely that urban air containing carbon nanoparticles from the exhausts of internal combustion engines, especially Diesel motors, is the most dangerous common source of nanoparticles, and masks should be worn on the streets to protect the lungs from these particles. For some reason this is rarely done in Europe, although common in China and Japan. Nevertheless, the types of masks seen in those countries are usually simple sheets of textiles and may not be especially effective in preventing the inhalation of nanoparticles.

4. Conclusions

Nanotechnology as an advanced technology can potentially make many contributions to sustaining human existence on Earth. These contributions can be characterized as generic or specific.

Generic contributions consist of generally improving efficiency, "doing more with less" (dematerialization), hence allowing existing levels of comfort and convenience to maintained

[28] C. McGovern, Commoditization of nanomaterials. *Nanotechnol. Perceptions* **6** (2010) 155–178.
[29] G. Hunt and M. Riediker, Building expert consensus on problems of uncertainty and complexity in nanomaterials safety. *Nanotechnol. Perceptions* **7** (2011) 82–98.
[30] J.J. Ramsden, Assessing the toxic risks of the nanotechnology industry. *Nanotechnol. Perceptions* **9** (2013) 119–134.
[31] P.A. Revell, The biological effects of nanoparticles. *Nanotechnol. Perceptions* **2** (2006) 283–298.
[32] C.J. van Oss and R.F. Giese, Properties of two species of deadly nano-needles. *Nanotechnol. Perceptions* **5** (2009) 147–150.

while consuming fewer resources. For example, nanoparticles added to fuel can increase internal combustion efficiency.

Specific contributions tackle known problems using nanotechnology. For example, novel nanostructured materials can be used for cost-effective carbon capture from flues, and nanoscale artificial kidneys can be used to desalinate water. Most of these applications still require research and development to provide a prototype working under field conditions at affordable cost.

An important question concerns the mode of introducing such innovations. In a free market economy, they must offer some benefit for the same or reduced cost, otherwise they simply will not be adopted, and such adoption must be anticipatable, otherwise it will not be possible to finance research and development. In a planned economy, if the planning bureaucrats deem that the innovation should be adopted, then its adoption can be forced. Note that many countries operate a mixed type of economy, where the government invests more or less significantly in research and development, in the hope that worthwhile innovation will emerge. The benefit of this approach is somewhat dubious, however;[28] the danger is that much of the allocated funds will be used to support work with no commercial prospects and will crowd out support for innovations that are able to stand on their own feet.[33]

The potential of such innovations to make an enduring contribution to sustainability may, however, be limited because of Jevons' paradox: Those innovations that are truly excellent will tend to increase consumption. Hence, the overall challenge of achieving sustainability also has a behavioural component, if that sustainability-vitiating increase is to be diminished.

The root of the sustainability crisis is the growing human population and the growing consumption *per capita*. If Jevons' paradox could somehow be overcome, it is conceivable that nanotechnology could decrease effective consumption; in other words, the same level of comfort and convenience could be achieved while consuming fewer resources. But this would do nothing to limit population. At first sight it is difficult to see how nanotechnology can contribute to reducing the human population. At best, behavioural aspects might be influenced by nano-enabled information technologies.

The question of population is an extremely tricky one that transcends merely objective, scientific considerations. The dilemma of humanism is that it seeks to maximize human welfare, and the welfare function has two extremes, a very large population living in abject poverty and generally uncivilized conditions, and a small, prosperous population enjoying the acme of civilization. It is a classic problem of multiobjective optimization and it may well be that there is a particular combination of level of material prosperity and number of individuals that optimizes the overall quality of civilization. This is a problem that does not yet appear to have been tackled, hence we leave it as a research challenge to be taken up. Once a model has been set up, one can then see how the Pareto front moves with the introduction of nanotechnology.

The fundamental hope placed in nanotechnology—or, indeed, in any new, advanced technology—is that it enables the hitherto seemingly inevitable cyclical progression of history—rise, zenith, decline; followed by a new rise &c.—to be evaded and replaced by a linear progression: in other words, a sustainable, endless rise to ever more glorious levels of civilization. If atomic scale engineering allows humanity to manipulate the material world exactly how it wants, will that suffice to usher in this new, linear history?

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[33] T. Kealey, *Sex, Science and Profits*. London: Vintage Books (2009).