A Moore's Law for Chemistry

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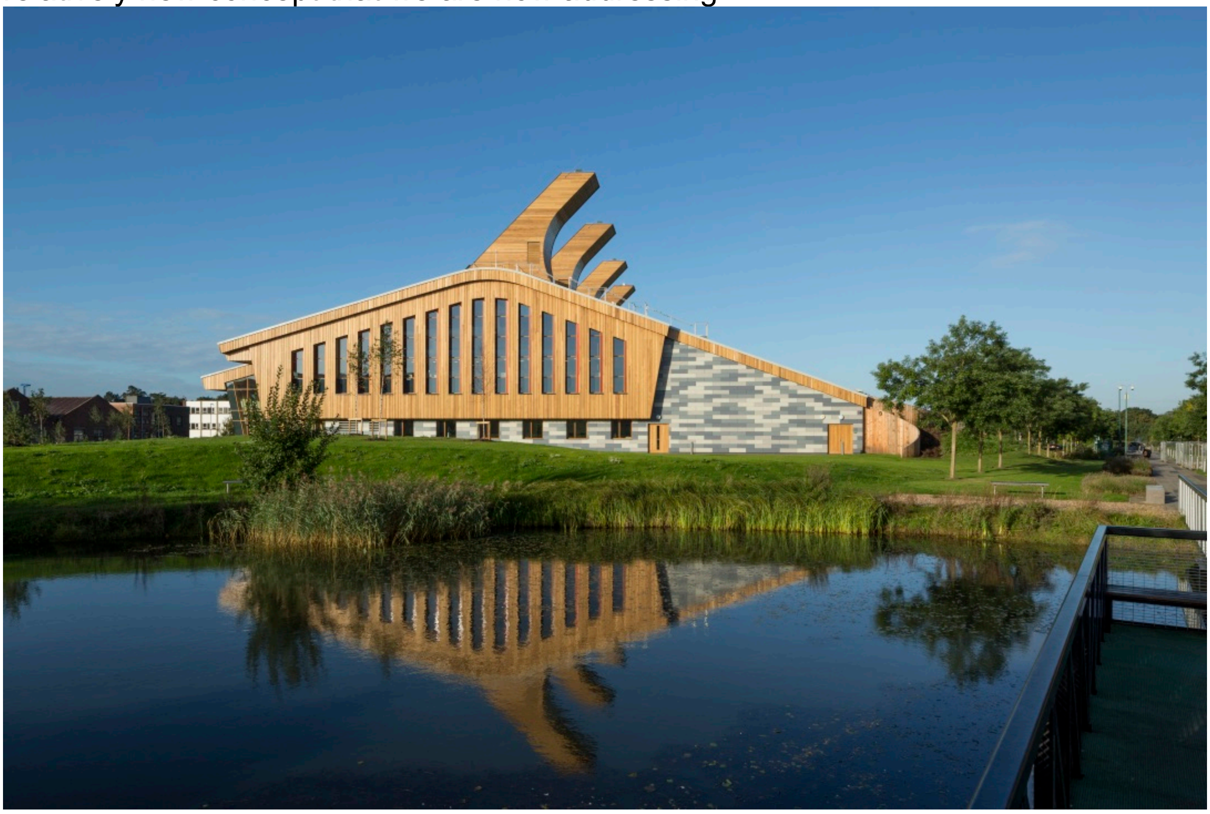
How do we have a major impact on delivering sustainable chemistry? To answer this question clearly requires engagement with a wide range of stakeholders including, academics, industrialists, policymakers, end-users and consumers. Achieving sustainable chemistry involves not only how we conduct the chemical enterprise but also how we use the chemicals that are produced. Here we describe an innovative approach to addressing the challenge of how to do chemistry in the future and then suggest a vision of how we might make our use of chemicals more sustainable.

The questions of what 'Sustainable Chemistry' actually is and how it differs from 'Green Chemistry' are still the subject of some discussion. The human population is rising fast and per capita consumption is also rising; there are now more people and they are consuming more rapidly than ever before. Of course, the level of consumption and the quality of life varies enormously across the world and the UN Sustainable Development Goals have set ambitious targets in an attempt to reduce this inequality. We strongly believe that sustainable chemistry can make a big contribution towards achieving these goals but it is unlikely to do so, if we remain on our present trajectory.

In practice, it is much simpler to see that our current trajectory is unsustainable than to define what is meant by 'Sustainable Chemistry'. For example, unsustainability is perhaps more evident in our use of the less abundant elements (e.g. phosphorus or zinc or rare earth elements) than in our profligate use of fossil hydrocarbons because it is always possible to argue that the hydrocarbons could be replaced by conversion of biomass or atmospheric CO_2. Some of these scarce elements could be replaced by other, more abundant elements but others like phosphorus, essential to the replication of living organisms, cannot. We are not destroying or consuming these elements in the same way that we consume oil but we are plundering a few concentrated sources of these elements and then distributing them so thinly across the planet that they are no longer recoverable at any reasonable economic cost. In effect, we are being defeated by entropy.

In the context of basic research, chemical laboratories are very often the most energy-hungry buildings on university campuses with fume hoods pumping out vast quantities of air and instrumentation that is very demanding in terms of energy. The University of Nottingham in collaboration with GSK have initiated a large-scale science experiment that aims to explore a potentially transformative solution to this problem. The GSK Carbon Neutral Laboratories (CNL) in Nottingham are a demonstration that intelligent design and the application of state-of-the-art construction methods and can drive down the environmental costs of chemistry, whilst providing a safe, modern suite of laboratories that would inspire future generations to think creatively and innovate to deliver smarter, better, more efficient chemical processes.

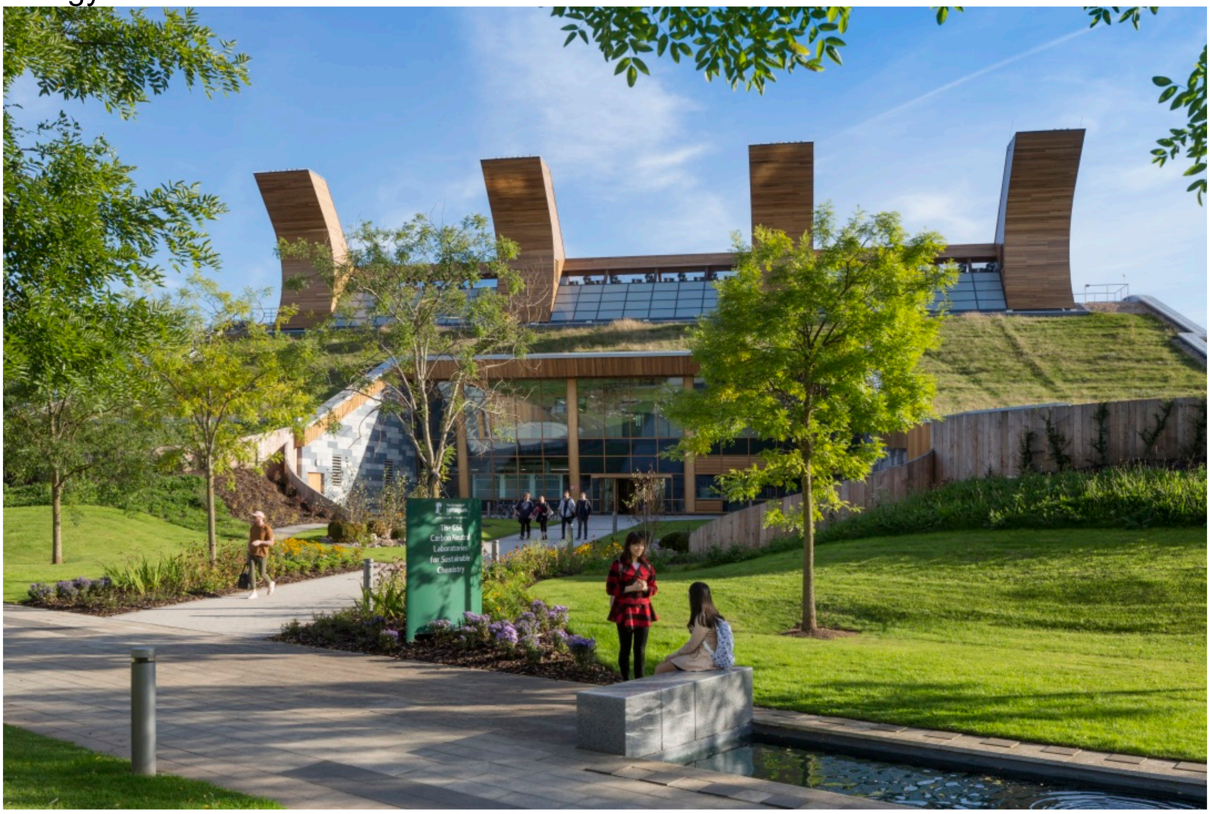
Clearly, the development of any new facility has associated costs, indeed each material, component, fixture or fitting included in construction can be considered to have two costs, a capital cost measured in £,€ and an environmental cost which can be measured in equivalents of CO_2, CO_2e. Of course prudent budgetary control allows us to control capital investment, but we must resort to rigorous certification and professional opinion to evaluate or calculate the amount of carbon invested. To draw on an analogy, the construction of the CNL may be seen like the purchase of a house, we now have to service a mortgage to service the investment of capital, quite amusingly we also have a second mortgage which corresponds to the amount of carbon we have borrowed to complete the build. Repayment of the capital is a concept that we are familiar with, repayment of the carbon mortgage is however a relatively new concept that we are now addressing.



We have deployed a strategy that will enable us to pay-back the invested, or borrowed, carbon in just 25 years. Our strategy has 2 main thrusts, firstly by ensuring that our laboratories are ultra-efficient and constructed from low impact building materials, and secondly by ensuring that all of the energy required to run our laboratories, i.e. electrical power and heat, are drawn from renewable energy systems including a balance portfolio of PV and biomass fired combined heat and power systems. Every day that we operate we are generating sufficient energy to not only maintain a safe and thriving research environment, but we export excess energy to other buildings across our campus, effectively buying back additional carbon credits that we can contribute towards out carbon mortgage.

[Caption]

Our laboratories are exemplars of smart design, we use a fraction of the electricity of a traditional chemistry facility because our systems are optimised and more importantly operate on a demand driven basis, if there are no experiments or occupants in the laboratory, then the intelligent building management system adjusts the flow of air accordingly and starts to put non-critical systems into a rest state. This process ensure that a safe environment is maintained at all times but reduces the energy consumption to non-critical systems accordingly. The CNL is like a complex organism, it responds to needs and demands of users, essentially it learns about how we, as a group of scientists, operate within it. It should be stressed that our laboratories are not at all compromised, in fact they offer state-of-the-art facilities and instrumentation allowing scientists to deliver cutting edge chemistry in a truly energy resilient environment.



So, is the experiment working? well this is a penetrating question that we can now answer with evidence and certainty. 12 months into our experiment, we are delivering high-impact science, and our consumption of electricity within the facility is 32% less than in a traditional laboratory setting. Furthermore our consumption of municipal water, which traditionally is used as process water to manage reaction temperatures is reduced by over 40%. Together these savings cut operational costs and deliver year-on-year savings to the University.

Although the wider implementation of carbon-neutral laboratories could improve the start of the chemical supply chain, major impact in sustainable chemistry also requires radical change at the other end of the chain. In other words, sustainable chemistry must have an emphasis on industrial application and implementation. Much of the new science badged under the banner of “Green Chemistry” has yet to find application in industry. This is surprising because atom efficient processes delivering molecules of impact with lower levels of toxicity and minimal environmental harm should surely be good. However, advances in the optimisation of industrial processes have transformed existing synthetic routes making them more profitable and, as a consequence, less harmful to the environment. It should be noted that currently the prime driver for such developments is almost invariably economic. The rising cost of waste disposal has driven process design towards the reduction of unnecessary costs and promotion of cleaner methodologies.

In principle there should be common goals for both the scientific and business communities, namely working towards satisfying the demands of an increasing global population on a sustainable basis. There is significant complexity in the supply, demand and business models for implementing sustainable chemicals manufacture. Furthermore, achieving even partial sustainability is likely to be a lengthy process, longer than the short-term horizons of much of the chemical using industries. Industrial development over past 100 years has been driven by financial considerations, products deliver a function but they also provide an income. The number of income streams have been reduced as environmental legislation squeezes down and new costs are added to clean up waste. However, things are beginning to change. The wider appreciation of critical materials has led to increased interest in the circular economy which is now being taken up quite widely.

In this editorial we suggest a different strategy for achieving sustainability. We propose that sustainable chemistry requires some overarching goal that can be embraced by everyone involved in the chemical supply chain as well as by the public in general. Our thinking is shaped by the development of the electronics industry which has been truly transformational over our lifetimes. For example, this paper is being typed on a notebook computer which is more powerful and has more memory and storage than major mainframe computer installations of a few decades ago and the notebook cost only a tiny fraction of the price of those mainframes. These developments have been encapsulated by the so-called 'Moore's Law' which broadly stated that the number of transistors per unit area of an integrated circuit would double every 12-18 months with a corresponding drop in unit cost of manufacture, and this has held true since 1965.

Our contention is that the majority of chemicals are only used once and that most users of those chemicals, whether specialist or end-user, are more interested the effect that the chemicals produce rather than the amount of actual chemical that is purchased or used. Thus, they expect a medical condition to be improved by a pharmaceutical, surface tension to be reduced by a surfactant, corrosion to prevented, a reaction to be catalysed and so on. We have previously suggested that chemists should start using the "F-factor", the amount of chemical that is need to create a given effect and we illustrated its use in the context of reducing the weight of the PET bottles used to contain a given volume of drinking water.

Now we propose that this approach should lead to a new concept, a Moore's Law for chemistry (MLFC) namely that over a given period, say five years, sustainable chemists should strive to reduce the amount of a chemical needed to produce a given effect by a factor of two and this process should be repeated for a number of cycles. The key will be to make the whole concept, especially the economics, work for everyone which will require a change in business model for the chemicals market. This change could well be consumer-driven rather than imposed by the suppliers, though legislation might be needed to catalyse the change. In addition, customers will have to accept that they are, in essence buying a service, rather than a quantity of chemicals. This can be thought of as building on the concept of “chemical leasing”, an approach which is gradually gaining ground.

In principle, addressing the challenges of the MLFC will be different from the original Moore’s Law because that was based on ever more precise engineering while the MLFC is based on molecular properties which often differ in size by orders of magnitude. Success will be achieved by a combination of new chemicals and products as well as smarter use of existing ones. A key problem may be benchmarking how much of a chemical is actually used for a given effect because much of this information is likely to be commercially sensitive knowhow. The reduction might be relatively straightforward for use of solvents where increasing the concentration of reactants could reduce the usage of solvents or increase the amount of product made with a given amount of solvent. The case of Viagra manufacture is a striking demonstration of solvent reduction where the volume of solvent per kilo of product was reduced from 1300 to 6.5 litres.

Therefore, the goals of the MLFC might be easier to achieve in some areas than in others but the ultimate reduction would not need to be as dramatic as for integrated circuits. Six cycles of the MLFC, namely a reduction in chemical usage by x64 (i.e. 2^6) might be sufficient to have a major impact on the sustainability of the chemical enterprise. Even less might be required if the MLFC were to be accompanied by a parallel effort to increase the serviceable lifetime of at least some of the chemical-containing products and replacement of single-use items with those that could be used multiple times. The overall usage of chemicals could be further reduced by designing products that are easily recycled or disassembled for reuse, as well as recycling within chemical processes and making better use of unavoidable by-products.

Some customer education and considerable innovation will be required to make people accept longer lifetimes for their possessions. Much of the problem lies in changing human behaviour which is often complex, as exemplified by how frequently people upgrade their smartphones. However, recent developments with vehicles have shown that change is much more possible than we might expect; the unthinkable replacement of the internal combustion engine has become a likely reality in a period of only a few months.

So our message is one of hope. Wider adoption of low carbon research buildings and low energy instrumentation together with appropriate education could have a major effect on future generations of chemists while the MLFC concept could trigger the radical debate needed to unite all stakeholders behind a shared vision of a sustainable chemical future.

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