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Perspective

Sustainable Chemical Engineering: Dealing with "Wicked" Sustainability Problems

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Introduction

In our office building, a converted old textile mill, at the University of Manchester, UK, there is a display and memorial to George E. Davis (1850–1907). Davis is regarded by many as one of the fathers of Chemical Engineering. The memorial marks the fact that Davis gave a series of 12 lectures in 1888 at Manchester Technical School (which later became the University of Manchester Institute of Science and Technology (UMIST), now the University of Manchester). These lectures, as many historians of our discipline will tell us, were one of the key events that defined Chemical Engineering as a discipline.[1,2]

There is a story, reported in some academic papers,[1,3] that in 1880 Davis overheard a chemical manufacturer in Manchester say "I have heard of civil engineers, electrical engineers…but never of a chemical engineer". This remark prompted Davis to work hard on promoting Chemical Engineering—he later published *A Handbook of Chemical Engineering* and was, for instance, instrumental in the formation of the Society of Chemical Industry (1881), for which incidentally he had unsuccessfully canvassed the name 'Society of Chemical Engineers'.[1]

Some 130 years later, thanks to Davis and other pioneers of our discipline, as well as the work of many generations of chemical engineers that came after, that early ignorance of the discipline has disappeared and we can proudly say that the world has now indeed heard of chemical engineers.

Today, chemical engineering is a well-known and established discipline. Chemical engineering is the backbone of many industries and it helps, directly or indirectly, make all products we use in our daily lives. From the water we drink to the food we eat, from the buildings we live and work in to the ways we travel, from smart phones to beauty products—we can be sure that there will be chemical engineering involved at some point in the life cycle of everyday products and services.

Needless to say, chemical engineering has changed significantly since Davis's times. The discipline has been constantly evolving and responding to challenges that the world has posed to it. Nowadays, chemical engineers need to provide solutions to some new, unprecedented challenges—climate change, resource scarcity, food security, water access, energy demand—these are just some of the issues that pose great challenges for current and future generations of chemical engineers.

With a growing urgency we now recognise that many of the lifestyles and practices of modern industrialised society, to which chemical engineering so significantly contributes, simply cannot be sustained indefinitely. Growing scientific evidence[4,5] shows that we are exceeding the Earth's capacity to provide many of the resources we use and to accommodate our emissions to the environment. It appears that Earth systems are being pushed towards their biophysical limits, with evidence that these limits are close to being or, in some cases, have been exceeded.[5] At the same time many of the planet's inhabitants cannot meet even their most basic needs.

The latest Global Environmental Outlook published by the United Nations Environment Programme (UNEP) warns that the world continues to speed down an unsustainable path, and cautions that "if current trends continue, if current patterns of production and consumption of natural resources prevail and cannot be reversed and '*decoupled*'" then, "several critical thresholds may be exceeded, beyond which abrupt and generally irreversible changes to the life-support functions of the planet could occur."[5]

Population growth and economic development are generally recognised as ubiquitous drivers of these global environmental trends. The human population reached 7 billion in 2011 and is expected to reach 9.6 billion by 2050.[6] However, there are large differences in population numbers and changes between the world's regions. For instance, the population increase is much greater in West Asia (67% since 1992) and Africa (53%), while in Europe, it has grown only slightly (4%). Meanwhile, populations are aging and

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stabilising in many developed countries. The population aged over 65 is growing at a faster rate than other age groups in most regions of the world. This has major implications for economies, the education and health care sectors, and the environment itself.[7]

There is another demographic trend that is highly significant for the world's sustainability: rapid urbanisation. In 1992, 2.4 billion of us lived in urban agglomerations. By 2009, the number had climbed to 3.5 billion, a 45% increase. It is estimated that by 2050 the global urban population will double.[8]

This unprecedented urban growth, projected to continue (although at a decreasing rate) in the coming decades, will require special attention in order to make life in cities more socially, economically and environmentally sustainable.[9] With large and dense metropolises come the associated environmental impacts of urban life. For instance, the population living in urban areas now account for 75% of global energy consumption[10] and 80% of global carbon emissions.[11] Very dense population structures and people living in close quarters bring sanitation, waste management, air quality, pollution and other concerns for residents and the environment.[9] Urbanization and associated livelihood changes are often accompanied by changing patterns of energy use and increased meat and dairy consumption.[5]

It is also important to note that most of the global economic growth will happen in developing or emerging economies where many people will be moving up the economic ladder towards a middle class standard of living, consuming many more resources per capita. This demographic change—the rise of the middle class in emerging economies—has also significant sustainability implications. In new and rising economic powers such as China and India, millions have been lifted out of poverty, but often at a high environmental cost such as depletion of natural resources and widespread ecosystem degradation and loss.[5]

With income growth, urbanisation and associated livelihood changes in developing countries, dietary patterns have also changed,[12] again with significant sustainability implications. As diets shift away from basic foods towards livestock products, there is the ever-increasing demand for meat—for instance, between 1992 and 2007 global average meat consumption grew from 34 kg per person per year to 43 kg.[9] It is estimated that currently meat production accounts for 18–25% of the world's greenhouse gas emissions.[13–15] For example, producing 1 kg of beef emits on average 18 kg CO_2 eq. (our own estimate, which was based on 60 data points found in the literature). This is equivalent to 1.24 Mt CO_2 eq. per year, based on the annual global production of beef of 66.88 Mt.[16] On top of this, 47 kg of feed and 15,400 L of water are also consumed[17] requiring 3 Mt of feed and a staggering 1000 million litres of water.

As societies grow and become wealthier, demand for energy also increases. The global primary energy demand has doubled since the 1970s and is expected to grow by one-third from 2011 to 2035.[18] The global depletion of natural resources is also going up significantly. In the last couple of decades alone, their global use increased by over 40%, from about 42 to nearly 60 billion tonnes; on a per capita basis, this is equivalent to a 27% increase.[5] Among the four major material groups (biomass, fossil fuels, ores and industrial minerals, and construction minerals), there has been a major increase in the extraction of construction minerals of almost 80%, followed by ores and industrial minerals (close to 60%).

The good news is that, while more energy and natural resources are being consumed, the amounts needed per unit of product are declining. We are becoming more efficient in our production, use and disposal of materials, hence there is a general decline in emissions, energy and material use per unit of output.[5,19] However, owing to the increasing population numbers and the need for shelter, food and an improved standard of living, overall energy and material use continue to grow. This ever-increasing demand for resources has raised the issue of scarcity. For example, the known reserves of indium used for display devices, solar cells and semiconductor may be exhausted within the next 13 years, while the reserves of zinc and magnesium may disappear in less than 50 years, followed closely by phosphorous.[20] Emerging energy technologies, such as solar cells and batteries, put a particular strain on rare earth elements – for most, the demand is already exceeding the production.[21] As a result, the IChemE estimates that the number of chemical businesses that expect to be affected by scarcity issues may triple over the next five years.[22]

These are some of the global trends which give a strong indication that the world, despite all publicly stated sustainability commitments and initiatives, appears to be on an unsustainable path. It is obvious, as the growth and development take place, that substantial changes are required in the way we produce and consume in order to stop and reverse these unsustainable trends. In particular, for 10 billion people to live well within the limits of one planet by the end of this century, extensive changes will indeed be required.

Needless to say, chemical engineers cannot tackle all the world's problems, and dealing with some of these unsustainable trends goes well beyond the reach of chemical engineering. But, chemical engineering does have a significant role to play. After all, from Davis's times and its inception in the latter years of the 19th Century, chemical engineering has always been associated with the design and operation of processes that add value to materials which ultimately end up in consumer products. Today, as we know, chemical engineering still plays a fundamental role in delivering products that help people live healthy and fulfilling lives. However, in doing so, we as chemical engineers have also a responsibility to help society move towards a significantly more-sustainable lifestyle. Sustainability challenges require sustainable chemical engineering: meeting human needs through technologies, products and services that are economically viable, environmentally benign and socially beneficial.

Sustainable Chemical Engineering

Unprecedented challenges require novel, innovative responses. Amongst the greatest challenges we face today are those of providing sustainable supplies of food, water and energy. The implementation of innovative engineering solutions is fundamental to addressing these challenges and chemical engineers have a key role to play in delivering such solutions. However, there are two important aspects that we would like to emphasise when considering chemical engineering responses to sustainability challenges.

Firstly, sustainability issues that chemical engineers have to deal with as engineers are not purely 'engineering problems'. In fact, it is often the social complexity of sustainability issues rather than their technical intricacy that make them so challenging and difficult to deal with from an exclusively engineering point of view.

Consider, for instance, biofuels. They are, in essence, an innovative engineering response to the grand sustainability challenge of climate change and the need to decarbonise the economy. As we know, there has been a rapid rise in the production of biofuels for transport, including from maize, sugar cane, palm oil and rapeseed. The global use of ethanol, for instance, accelerated at the end of the 1990s to reach 30 Mt tonnes of oil equivalent (toe) in 2009, while the production of biodiesel has been growing at around 60% per year since the early 2000s, reaching nearly 13 Mt toe in 2009.[9] So, biofuels as an innovative technology, appear to be taking off, providing us with a low-carbon alternative to unsustainable and climate-harming conventional fuels, thus helping us with climate change mitigation. So far so good — or is it?

In addition to the positive aspects, biofuels production has also raised some significant concerns such as the environmental and social impacts of land-use change, the introduction of potentially invasive biological species, the overuse of water and the consequences for the global food market and food security.[23] Could biofuels be regarded as a sustainable alternative to conventional fuels if they raise such serious concerns? We will come back to the this issue in more detail later in the paper, but at this stage we would like to point out that the sustainability assessment of technological options must take into account all relevant sustainability aspects, not just a single issue such as climate change, however important that issue may be. Otherwise, the issue we are trying to address could simply be displaced elsewhere or replaced by another problem. This leads us to the second point we would like to emphasise when considering sustainable chemical engineering:

Most of sustainability issues are not conventional engineering problems – they are "wicked" problems.

Wicked Problems

The idea of "wicked" problems is not new. It was originally formulated in the 1970s by Horst Rittel and Melvin Webber in the arena of urban and regional planning. As urban planners, they noted that that there was a whole realm of difficult challenges facing planners at the end of the 20th century that could not be tackled successfully with traditional linear, analytical approaches. They called these challenges "wicked" and contrasted them with "tame" problems. Unlike the latter that could be defined closely and a solution identified or worked through reasonably readily, "wicked" problems were much more intractable and highly resistant to resolution.[24] The authors originally described a wicked problem as having:

- no definitive formulation;
- no 'stopping rule';
- a solution that is 'good or bad' rather than 'right or wrong';
- no immediate or ultimate test of its resolution;
- no possibility of learning by 'trial and error';
- no well-described set of potential solutions;
- symptoms of another problem;
- causes with no unique explanation; and
- expectations that its 'owner' will find the 'right' answer.

The concept of "wicked" problems has since spread to other areas, including engineering. It has been generally used to denote problems that standard approaches find difficult to define clearly and often impossible to solve owing to their innumerable causes, incomplete or contradictory knowledge, competing interests and opinions, and interdependencies.[25,26]

The list of wicked sustainability problems is potentially extraordinarily long. Climate change, energy generation, water resource management, genetically modified organisms, urban planning, waste disposal, nuclear waste, biodiversity loss—these are just some of the issues that can be characterised as "wicked".

Take climate change, for instance. It is a highly complex issue involving multiple causal factors. There is no agreement about 'the problem' nor there is a universal agreement on the solution. Then, various aspects of climate change interact – potentially extending from individual lifestyles to international government agreements; from innovative technologies to climate change modelling; from education to financial instruments, etc. As our knowledge and perceptions about the climate change develop, so 'the problem' of climate change changes. Local sub-problems differ from place to place. Stakeholders from different industries and interest groups, and from developed and developing countries, have different perspectives and goals. Various strategies to tackle climate change will likely have unintended consequences... and so the list continues.

The same complexity and intractability are present in most of the other issues, some mentioned above, that come under the sustainability umbrella. So, how do we then deal with the "wicked" sustainability problems?

Systems Approach and Life Cycle Thinking

Different approaches and strategies have been proposed for dealing with wicked problems; they come from various disciplines that are "trapped" into the wicked-problem territory; see for instance, Roberts[27] and Brown et al.[26] However, we believe that for chemical engineers the best way for dealing with "wicked" sustainability problems is by employing the whole systems approach and embedding life cycle thinking into chemical engineering practice. It is something that chemical engineers have been doing for quite some time (for an overview, see e.g., ref. 28) but, we would argue, not consistently and not sufficiently.

We believe that there is still far too much of traditional 'linear' thinking in current chemical engineering practice which simply fails to address the interrelationships between the full range of causal factors and to grasp the social complexity of "wicked" sustainability problems. Sustainable chemical engineering, based on the whole systems approach and life cycle thinking, on the other hand, approaches and treats sustainability issues as complex systems, and instead of focusing just on 'cause and effect', recognises their

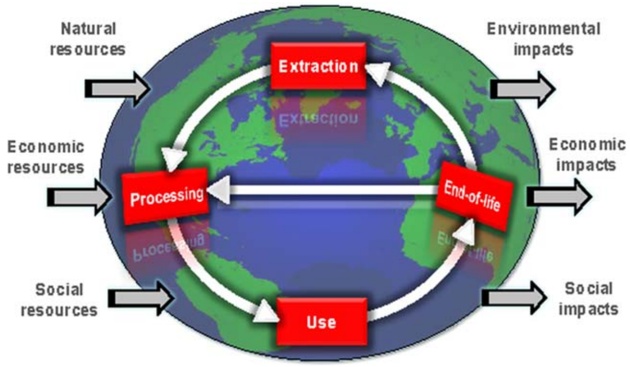

Figure 1. Integrating systems approach, life cycle thinking and sustainability considerations.

Production systems are considered from 'cradle to grave' spanning whole supply chains. Inputs into the system are natural, economic and social resources and outputs are the related environmental, economic and social impacts, both positive and negative. As supply chains become more globalised, the system boundaries expand across the globe.

complexity and interrelationships. It acknowledges that sustainability is not purely an 'engineering problem' and that technological solutions must be considered in a wider social, environmental, economic, regulatory, political and ethical framework.[29]

This is illustrated in Figure 1, which shows how systems approach used in chemical engineering can be combined with life cycle thinking when addressing sustainability issues. Although this is very similar to the traditional systems approach, there are some distinct differences:

i. First, the system is much larger: it goes beyond unit operations and a production plant to span a whole supply chain, tracking inputs into and outputs from the system across the globe, implying different spatial scales.

ii. Another difference is that inputs into the system are not only materials, energy and micro-costs (e.g. capital and operating) typically considered in engineering projects but also macro-economic aspects and various social resources; the 'outputs' are then defined by the related environmental, economic and social impacts, both positive and negative.

iii. The third difference is that all the inputs and outputs (i.e. resources and impacts, respectively) are considered on a life cycle basis, or from 'cradle to grave'. This applies not only to environmental impacts – something that chemical engineers are getting more familiar with – but also economic and social. Therefore, all materials, energy, micro- and macro-economic costs as well as various social impacts must be traced and evaluated along the whole supply chain, from the beginning ('cradle') to the end ('grave') of the supply chain.

iv. Further, there is a much larger number of often disparate criteria that must be integrated and considered simultaneously. In addition to the traditional criteria such as material and energy flows and capital and operating costs, a range of other environmental, economic and social impacts are also quantified to obtain a full picture of the sustainability of a system and ensure that decision made do not solve one "wicked" sustainability problem at the expense of another.

v. Disparate criteria imply different groups of stakeholders with differing temporal scales. By definition, sustainable development is predicated on very long timescales, considering many future generations. On the other hand, governments and policy makers operate on a four-year election cycle while companies have even shorter time horizons, driven by yearly planning cycles. Consumer timescales can vary from immediate to long-term.

Various tool can be used to quantify and integrate different dimensions of sustainability, including life cycle assessment (LCA) for environmental impacts, life cycle costing (LCC) for economic costs and life cycle social sustainability indicators for social aspects. Chemical engineers are familiar with and have been using LCA for many years, so that it is gradually becoming one of the core tools in chemical engineering. In fact, the idea of integrating life cycle thinking, LCA and systems approach is not new in chemical engineering – it goes back to the 1990s (see refs. 30–32). Today, LCA can be used routinely in chemical engineering analyses owing to a wide availability of databases such as Ecoinvent[33] and software, including GaBi[34] and SimaPro.[35] However, LCC is still to become mainstream – while micro-economic costing is used routinely as a basis for any engineering project, estimations of costs on a life cycle basis, including costs to consumers and society, are rare. This is even more so for social sustainability assessment which is still to gain momentum in chemical engineering applications. This is not surprising as methodologies for social sustainability assessment are still developing and there is no universal agreement as to which one to use. An early attempt to develop life cycle social sustainability indicators for use in the chemical and other industries includes that by Azapagic and Perdan.[29] The IChemE Sustainability Metrics[36] and the AIChE Sustainability Index[37] developed specifically for the chemical industry, also comprise some social aspects, but they do not follow a life cycle approach. More recently, a methodology for Social Life Cycle Assessment (SLCA) has been developed,[38] following the ISO methodology for LCA.[39] One of the advantages of SLCA is that it complements LCA and LCC; however, the methodology is complex, even more so than for LCA, and social life cycle data are scant and uncertain. The latter also applies to both LCA and LCC owing to many factors, including incomplete, imprecise or missing data as well as a highly dynamic nature of large systems considered.[40]

The number of sustainability aspects and related indicators to be considered depends on the system studied and stakeholder priorities. A comprehensive study will typically consider more than 15 and in some cases over 50 indicators. Considering them simultaneously and trying to make decisions based on so many different criteria is not an easy task (even for chemical engineers!). To aid this process, a range of tools are available, including multiobjective optimisation (MO) and multi-criteria decision analysis (MCDA). The former is well known and widely used in chemical engineering, but has so far largely focused on economic and environmental (LCA) criteria,[41–44] with social criteria starting to be considered only very recently.[45] MCDA methods have also been used widely, either with or without MO to help aggregate various criteria into a single sustainability index, based on stakeholder preferences for different sustainability aspects.

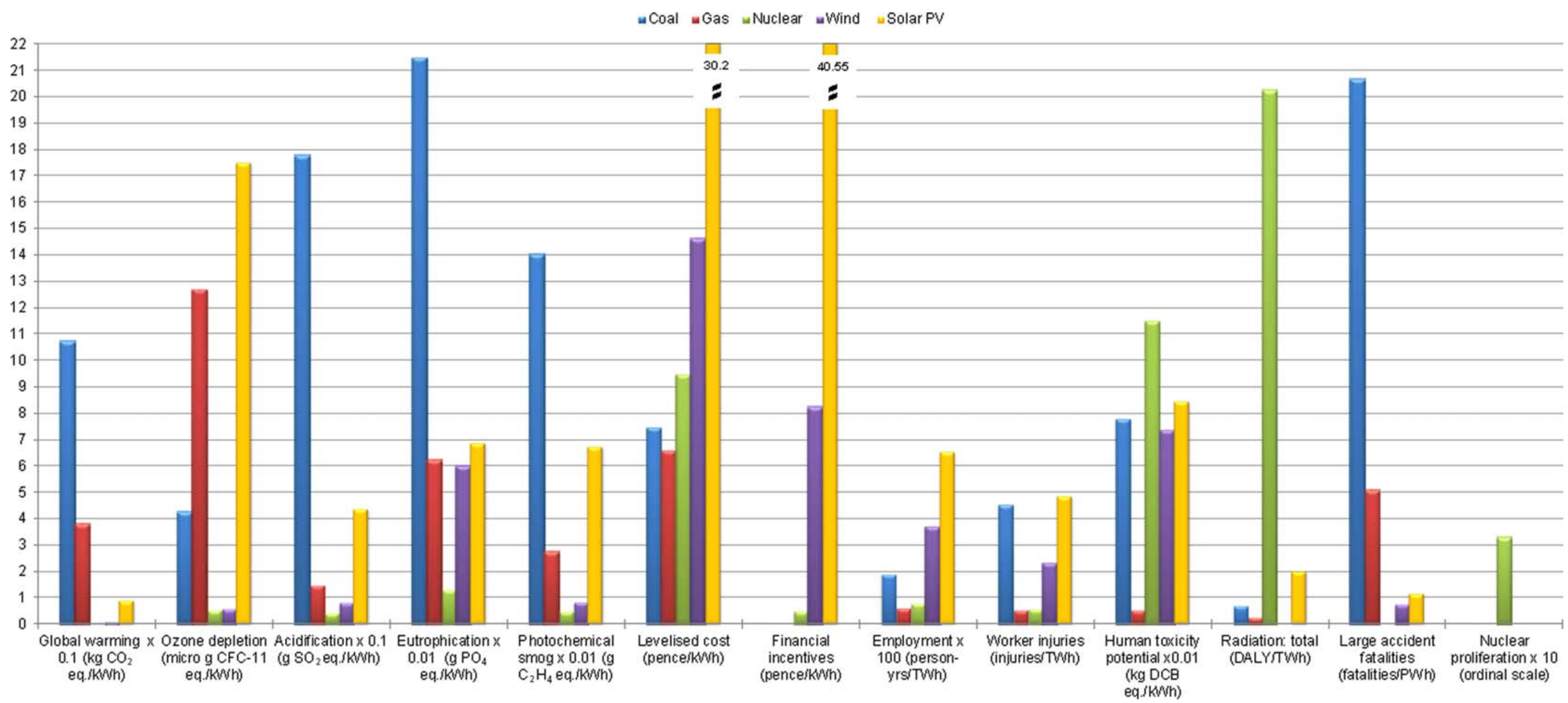

Figure 2. Life cycle sustainability of electricity options (based on ref. 46).

Coal: pulverised; Gas: CCGT; Nuclear: PWR; Wind: offshore; Solar PV: an average world mix of PV technologies. For further details on the technologies and definitions of sustainability indicators, see the above source. Some impacts have been scaled to fit – to obtain the original values, multiply with the factor shown against relevant impacts. DCB: dichlorobenzene; DALY: disability-adjusted life years.

The following sections consider a couple of "wicked" sustainability problems to illustrate how the above-described life cycle systems approach can be applied in addressing them. The first example is related to energy and the second to biofuels used for transport. The latter also considers issues in the energy-water-food nexus.

Energy

Key sustainability challenges associated with the provision of energy in most countries are over-dependence on fossil fuels and the related security of supply and climate change issues. To address them, a range of options are being considered by governments around the world, including renewables, nuclear, carbon capture, storage and utilisation, energy storage and unconventional gas and oil. All of these provide opportunities for chemical engineers to contribute to a sustainable development of the energy sector. But, the question is: what are the most sustainable solutions – which ones should we be developing and implementing and which ones should be avoided?

In an attempt to answer this question, let us consider electricity generation as an example and evaluate the sustainability of fossil-fuel sources compared to nuclear and some widely-used renewables. Their environmental, economic and social aspects are compared in Figure 2, all considered on a life cycle basis, from 'cradle to grave'. The analysis refers to UK conditions but is broadly applicable to other countries. Note that we consider only selective impacts here for the purposes of illustration; for further impacts, see Stamford and Azapagic.[46]

As shown in Figure 2, if the priority is to combat climate change, then it is clear that nuclear power and renewables such as wind and solar PV should be prioritised over fossil fuels as their life cycle carbon emissions are several orders of magnitude lower. However, when we consider other environmental impacts, a different picture emerges, with solar PV having higher impacts than natural gas for all the categories considered and wind power being comparable to gas for eutrophication. Nuclear power is the best option across all the impacts.

The picture changes again when we look at the economic impacts. For the life cycle levelised costs, natural gas is the best option, followed by coal, while wind and solar PV are 3–5 times more expensive per MWh of electricity generated; they also receive the highest government subsidies. Considering life cycle social aspects, we find out that wind and solar PV provide the highest employment opportunities in the supply chain but also have a higher number of worker injuries than electricity generation from gas on a life cycle basis; solar PV has even higher worker injuries than coal power, regardless of the high injury rate during coal mining, primarily because of its high employment per MWh and low efficiency compared to coal. For life cycle human toxicity potential, nuclear is the worst option, followed by solar PV. The latter is worse than coal power for this impact because of the use of toxic materials in the manufacture of solar cells. Unsurprisingly, nuclear is the worst option for radiation (although other options are not radiation-free either, as indicated in Figure 2) and proliferation of nuclear weapons. Finally, and contrary to popular belief, nuclear is the best option for large accident fatalities, with coal being the worst. This is due to a low number of accidents from nuclear power plant with large fatalities (estimated at 1 in every 315 years). By contrast, coal power is associated with high-frequency, moderate-impact accidents, the vast majority of which occur during extraction, processing and transportation of coal.

This example, albeit simplified for the purposes of our illustration here, demonstrates how complex and "wicked" sustainability issues are in the energy sector. In policy and the public arena, this complexity is often missed, as there is a focus on a limited number of sustainability issues: usually costs, security of supply and/or climate change. As a result, policy and other decisions are being made on the basis of these drivers – they may well address these issues, but at the expense of many other sustainability aspects that may come back to haunt us in the future. We may also bring back some of the problems that we have successfully solved through appropriate regulation, including ozone layer depletion and acidification. As demonstrated by the above example, this can be avoided by taking a systems, life cycle approach and considering simultaneously a broader range of relevant sustainability issues. Which technological option(s) get chosen in the end will depend on the specific decision-making contexts and stakeholder preferences: while there is no 'silver bullet' for "wicked" problems, at least discussions can be based on facts, helping to make more informed – and more sustainable – decisions. As chemical engineers, we have both the knowledge and the responsibility to inform these debates by providing policy makers and the public with facts and helping to demystify the sustainability of different technological options.

As promised earlier in the paper, we now turn our attention to another "wicked" problem – biofuels – to consider how life cycle systems thinking can help to address sustainability issues in the energy-water-food nexus.

Biofuels

One of the main reasons that biofuels are being promoted is that they provide a low-carbon alternative to conventional fuels, also helping nations to improve self-sufficiency of fuel supply.[47] As a result, global production of bioethanol is predicted to double, from 75 bn litres in 2007/09 to 160 bn litres in 2019, with the majority (~90%) expected to be produced from coarse grains and sugar cane.[48]

Let us then examine how sustainable bioethanol is with respect to its low-carbon potential in comparison to petrol (due to space constraints, we consider only bioethanol and exclude biodiesel). As indicated in Figure 3a, on a life cycle basis, the global warming potential of ethanol from corn produced in the US is higher by 22% than for petrol.[49] This may come as a surprise but it is what is found when taking into account the whole life cycle, including crop cultivation and use of the fuel in vehicles – although bioethanol is considered to be neutral with respect to 'biogenic' carbon (the amount of CO_2 sequestered during cultivation equals the amount released during combustion), the emissions of 'fossil' carbon equivalent are still very high because of the release of N_2O during the application of fertilisers. Therefore, ethanol from corn does not even solve the climate change problem, the main reason for its existence, while

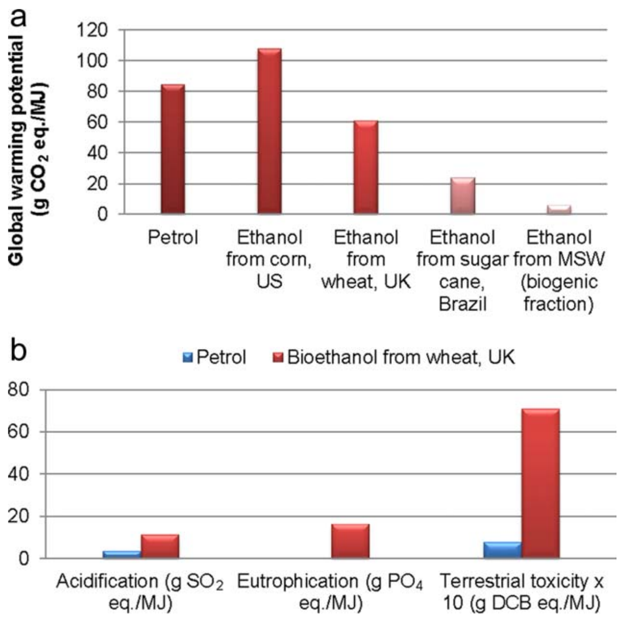

Figure 3. Life cycle environmental impacts of bioethanol from 1st generation feedstocks.

a) All 1st generation ethanol data are from DFT,[49] assuming conservative values. Ethanol from MSW is from Stichnothe and Azapagic.[50] Land-use change is not included. b) Data from Ecoinvent.[33] DCB: dichlorobenzene.

causing various other sustainability problems, including land-use change and market perturbations – to which we will return a bit later. For now, let us look at the other ethanol feedstocks in Figure 3a. We can see, for example, that ethanol from wheat produced in the UK does offer some savings of GHG emissions compared to petrol – around 28%. However, this assumes a 100% replacement of petrol by bioethanol, while the maximum substitution allowed in the UK is 5% (as stipulated by law). Therefore, the overall saving is very small (~1%) and yet it causes all other social and environmental problems associated with diverting food crops to biofuel production. Ethanol from sugar cane in Brazil, on the other hand, offers a much greater carbon saving on petrol (72%); this is a real saving as in Brazil bioethanol is largely used instead of petrol. Even higher savings (93%) can be achieved if ethanol is produced from the biogenic fraction present in municipal solid waste.[50]

If we extend the analysis to other environmental impacts, we find that biofuels are often worse than petrol. This is illustrated in Figure 3b which considers the example of ethanol from UK wheat: it is apparent that its impacts are much higher than for petrol. Specifically, the acidification potential is three times higher, terrestrial ecotoxicity nine times and eutrophication 71 times.

Regarding the water part of the nexus, 1st generation biofuels are rather 'thirsty' as they require water for the cultivation of crops from which they are produced. However, the amount of water itself is not an issue, but rather the impact that may have on water-stressed regions. So, for example, bioethanol from corn produced in Egypt has a much higher water-stressweighted impact (~90 m^3/GJ) than that in USA (<1 m^3/GJ).[51] Therefore, like GHG emissions, the impact on water is highly dependent on where cultivation of the crop takes place.

So, based on the above environmental considerations, 1st generation fuels are arguably unsustainable. Similar is true for social issues, particularly those related to the food part of the nexus. Biofuels are thought to be a major factor behind the 2007–2008 spike in world commodity prices which, according to some estimates, contributed to one-third of the maize price increase.[52] Additional factors also contribute to the "wickedness" of the problem, such as rising food demand in emerging economies, fluctuating oil and gas prices, commodity speculation, extreme weather conditions and related low harvests. Other social issues include those that arise primarily at the feedstock cultivation stage, such as human health, human and labour rights, land ownership, community development and impact on indigenous peoples.[49]

But, are 2nd generation biofuels any better? And what about the emerging concept of biorefineries – can they help to improve the sustainability of biofuels? Comparison of the life cycle environmental impacts of 2nd generation bioethanol produced from Miscanthus and forest residues in a biochemical integrated refinery suggests that these options are environmentally more sustainable than 1st generation fuels (Figure 4). This is notably true for GHG emissions which are now negative because of the system credits for chemicals and electricity co-produced with ethanol. This means that a significant amount of carbon is saved compared to 1st generation fuels produced, for example, from UK wheat and sugar beet. Some other impacts are also negative, including human and marine toxicity. Thus, we can conclude from this analysis that overall, these 2nd generation fuels are environmentally more sustainable than 1st generation, except for freshwater ecotoxicity which is higher for both 2nd generation fuels considered than that for ethanol from sugar beet (but still lower than for ethanol from wheat).

However, neither of these results includes the climate change impact from land-use change. Given that both wheat and sugar beet are well established crops in the UK, land-use change is less likely and it is irrelevant for waste feedstocks; however, it is relevant for energy crops such as Miscanthus. When direct land-use change is considered for the latter, assuming conversion of grassland, the global warming potential increases from −139 to 2185 g CO_2 eq. per litre of fuel. This is now 11% higher than for ethanol from wheat and 83% higher than that from sugar beet, and by implication higher than petrol.[55] The situation is much worse if we assume conversion of forest to grow Miscanthus: the global warming potential goes up to 6800 g CO_2 eq./l, several orders of magnitude higher than for petrol. Therefore, the results are very sensitive to land-use change and should be considered carefully, together with indirect land-use change and other sustainability issues before irreversible decisions are made.

If we ignore the issue of land-use change for the moment, in comparison to petrol, significant GHG emissions savings can be achieved from 2nd generation ethanol produced in integrated biorefineries, ranging from 72% for wheat straw to 87% for forest residue.[55] However, this is again on the basis of a 100% replacement of petrol by ethanol. As mentioned earlier, at currently prevalent 5% ethanol blends in

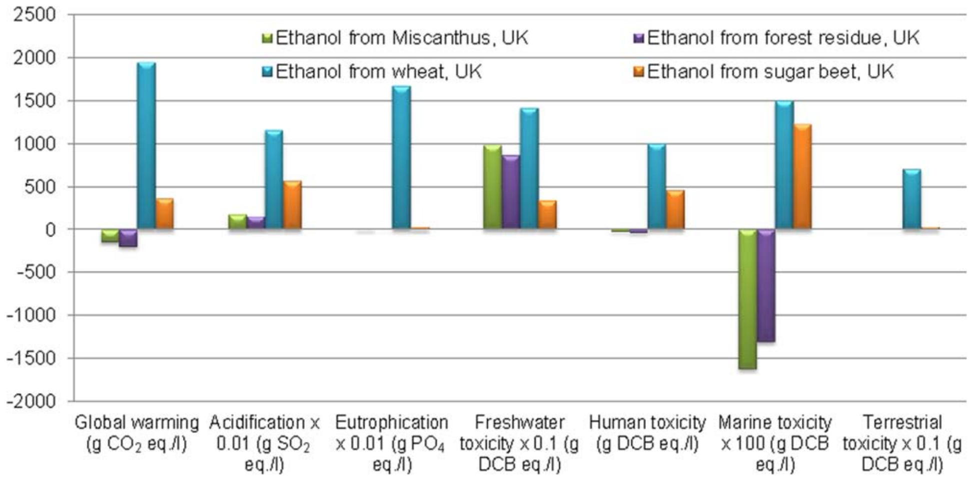

Figure 4. Life cycle environmental impacts of bioethanol from 2nd generation feedstocks produced in integrated biorefineries (based on ref. 55).

All impacts are on a life cycle basis calculated using LCA and are expressed per litre of fuel. The results refer to the biochemical route. Allocation has been carried out using system expansion with the system credited for the production of acetic and lactic acids and electricity exported to the grid. Land-use change is not considered. Some impacts have been scaled to fit – to obtain the original values, multiply with the factors shown against relevant impacts. DCB: dichlorobenzene.

the UK (and elsewhere), the savings are much smaller, up to 2.8% per MJ of fuel. Our research shows that even if all petrol used today in the UK were to be replaced by 5% of ethanol, the GHG emissions saving at the national level would be only 0.3% per year or around 10% by 2050. Similar is true for most of the other environmental impacts. Therefore, unless higher ethanol blends were used, the contribution of 2nd generation ethanol to the reduction of GHG emissions – the very driver for their production – would be insignificant.

So, is that all worth it? Taking a systems approach, one could argue that more could be achieved by consuming less fuel of whatever kind – but that would, of course, require radical changes in the way we live and work. Nevertheless, it remains one of the most sustainable options, at the risk of stating the obvious.

Perhaps less obvious is that we may also achieve more by switching from diesel to petrol on both environmental and social grounds, instead of using biofuels. For example, in the UK, more than half of cars use diesel (29 million), which has been promoted over the years by the government through reduced tax on the grounds of its being more efficient and having lower GHG emissions per MJ of fuel. However, evidence is now emerging that pollution levels in UK cities have risen dramatically over the past few years because of diesel cars and buses, to the point that the air concentration of NOx is now higher in London than in Shanghai: in the summer of 2013, a peak NOx concentration of 810 μg NO_2/m^3 was recorded in London, compared to a peak 600 μg NO_2/m^3 in Shanghai.[53] It is estimated that this additional pollution, attributed to the switch from petrol to diesel vehicles, costs around 7000 lives every year.[54] Had a systems, life cycle perspective been taken at the time the decision was being taken to promote diesel, and a broader range of sustainability aspects considered, we would not need to worry now about fixing the problem that had already been solved through previous legislation – air pollution and associated loss of human life through ill health – while we were trying to solve the problem of climate change.

Conclusions

We started the paper by mentioning George E. Davis, regarded by many as the father of chemical engineering. Davis also worked as an inspector for the Alkali Act of 1863, a very early piece of environmental legislation in the UK that required soda manufacturers to reduce atmospheric emissions of hydrochloric acid from their factories. Together with amendments, the Alkali Act became the main legislative control of industrial pollution in the UK.

We mention this to illustrate that from the very beginning chemical engineers like Davis have been concerned with and have taken measures to protect the environment and society from the adverse effects of chemical processes and activities.

However, today challenges posed to the profession – climate change, resource scarcity, food security, water access, ever-increasing energy demand, etc. – go well beyond the issues addressed by the Alkali Act. They are unprecedented challenges which require innovative approaches. With their interdependencies, multiple causes, internally conflicting goals and unforeseen consequences, these sustainability issues present "wicked" problems for which there are no simple solutions. To quote H. L. Mencken, an American journalist: "For every complex question there is a simple answer, and it is wrong."[56]

We argued that addressing such problems calls for a systems approach, considering the whole life cycle of products and technologies and taking into account all relevant environmental, economic and social aspects. Without knowing the trade-offs between different sustainability issues – and there will usually be trade-offs because of the complexity of "wicked" problems – we will not know how solving one problem affects another until it is too late. Arguably, much of engineering today is needed to overcome the problems engineering created in the past – we should see this as a great opportunity not to repeat the mistakes from the past.

Because "wicked" issues are not exclusively engineering problems, it is essential that we work with non-engineering disciplines, including social sciences and humanities, to help us understand others' perspectives and address problems adequately. Furthermore, if we are to help society move towards a more-sustainable lifestyle, we must engage with the public and understand consumer behaviour – unsustainable consumption drives unsustainable production and vice versa, so that they cannot be tackled in isolation of each other. At the same time, we should engage more actively with policy makers by providing robust evidence and helping to shape more-sustainable policies. Above all, we must work on educating the next generation of chemical engineer with sustainability in mind – this is the only way to ensure a sustainable chemical engineering discipline that will thrive long into the future.

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