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Communication

Two Blind Mice: It Is Time for Greater Collaboration between Engineers and Social Scientists around the RDD & D of Industrial Technologies

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Abstract: Within this short communication article, we consider the value that closer and earlier collaboration between engineers and social scientists could offer the research, development, demonstration and deployment (RDD & D) of industrial technologies. We consider perspectives taken from both the social sciences and engineering in order to highlight the prejudices and misunderstandings that currently limit the extent and quality of such collaboration. It is reasoned that the complex engineering challenges of the future demand a move towards greater interdisciplinarity. Current successful approaches towards fostering interdisciplinarity within the Carbon Dioxide Utilisation (CDU) research community are then used to illustrate the benefits of employing a more holistic approach to the design and introduction of new industrial technologies. It is our hope that this article will catalyse similar collaborative research efforts within other sectors.

Keywords: carbon dioxide utilisation; carbon capture and utilisation; energy; technology; public perception; interdisciplinary research; social science; engineering

1. The Town Mouse and the Country Mouse

In the classic Aesop fable (#352, Perry Index), a town mouse visits the rural backwaters of his cousin, the country mouse. Having tucked into a basic—and to the town mouse fairly uninspiring—meal, the town mouse invites his cousin to sample the culinary delights of the big city. However, while eating they are interrupted by a dog and are forced to abandon their lavish feast. Following this unwelcome intrusion, the country mouse decides that the fast-paced city life is not for him and promptly returns to the quiet, secure existence in his rustic idyll. While there are different interpretations of the moral of this idiom, a common one is that people (or mice in this case) are different; that lifestyles vary and that what is considered 'right' by one person may be viewed differently by others, but that we should respect these differences.

Why, though, start a communication article in a science and engineering journal with a tale of two mice? For us, this story of two visibly similar, although differently-minded, creatures briefly sampling one-another's lifestyles only to promptly retreat back to the familiarity of their own territory, strikes marked parallels with the relationships shared by social scientists (country mice) and engineers (town mice) around the development and introduction of new industrial technologies.

Within this short article, we—a country mouse and town mouse, respectively—seek to explore some of the potential barriers to collaboration between engineers and social scientists, from our

differing disciplinary perspectives (*i.e.*, "a view from the country" and "a view from the town"). While the focus of some of our arguments might differ, we jointly argue that there is inherent value in fostering more meaningful and timely collaboration between engineers and social scientists in the research, development, demonstration and deployment (RDD & D) of emerging industrial technologies, and will use recent advances in Carbon Dioxide Utilisation (CDU) technology research at the University of Sheffield as a case study for how things are changing. Together we conclude that the engineering challenges of the present and future should prompt a paradigmatic shift in the way that we work together (*i.e.*, "a move to the suburbs").

2. A View from the Country

I, a country mouse with around 10 year's research experience in assessing public perceptions of energy technologies, was recently invited to attend an engineering-focussed energy research workshop. The fact that I had been invited to the engineering feast perhaps could be viewed as indicative of the emerging recognition of the value that the social sciences could bring to such discussions; an invitation to the big city that I could not ignore! The instruction to the room was simple: discuss potential innovative RDD & D projects with a practicable, applied focus. This instruction was, however, accompanied by a further troubling steer towards avoiding the temptation to engage in social-scientific-esque over-analysis of the complexities surrounding any opportunities identified. The implication was that such 'softer' discussions would stand to over-complicate the identification of optimal engineering solutions to the quandaries facing the energy sector. This instruction—much like the dog in the Aesop fable that provides a framework for this article—interrupted the intended feast (even before it got started), leading me to question the sincerity of my invitation and prompting thoughts of an escape back to the country.

While being the first to admit that social scientists do enjoy deconstructing debates to identify hidden complexity or nuance, the suggestion that by 'over-complicating' matters in this way *we* are somehow responsible for stifling engineering progress for me was a false truism. This is not because there is inaccuracy in the assertion that the social sciences can complicate the path of technical research and development—we do—but rather because there is inaccuracy in the belief that appreciation of the social context into which innovations are introduced is somehow *the* limiting factor to innovation. Indeed, the opposite tenet is arguably the more accurate: it is an ignorance of the social context that is the limiting factor.

This assertion is evidenced by an increasing list of examples of where good engineering has failed to generate the intended impact due to failures to appropriately understand and engage with those within society set to receive the technology. For example, the often reported 'rebound effect' (or take-back effect) illustrates how the realised energy-efficiency savings of new technologies can be partially (or in some cases fully) undermined by the behaviour of the recipients [1]. A commonly used illustration of this is the consumer who purchases a more fuel-efficient car. If the consumer were to continue to use the car as they did previously then the net benefit of this switch could be fairly substantial. However, because of the lower per kilometre operating costs of the new vehicle, the consumer uses the car more, which lessens the net benefit of the switch (or in some cases ends up with a net detriment). Research being conducted by myself and others is seeking to clarify the mechanisms that might feed into this effect, in order to hopefully reduce its impact [2,3].

In the context of industrial-scale technologies, the influence that society can exert on the success of a given technology is exemplified by the perennial difficulty that developers face when attempting to construct well-engineered and apparently favoured technology options (e.g., renewable energy facilities) in specific local contexts. After all, why would people object to the prospect of having cutting-edge engineering solutions to global problems like climate change in their backyards? The automatic assumption tends to be that people are being hypocritical and selfish; however, social scientific research has shown that there are hidden depths to local opposition that go well beyond this so-called NIMBYism (Not in My Backyard) [4]. The reasons for objection of local facilities, much like

the people who hold them, are diverse and can be driven and shaped by, among other things, concerns about the perceived risks of a technology that those designing or promoting it would not always anticipate (e.g., [5–9]). In short, I would argue that the eventual success of innovation often has less to do with the objective qualities of the technology—although evidently certain thresholds of use, quality, reliability and cost need to be reached—than a typical engineer might think. Rather, success is in a large part determined by how well the social context for the introduction of a technology is understood and primed (e.g., the extent, timeliness and quality of public engagement and communication around the introduction of an innovation). With this in mind, it stands to reason that a willingness to embrace the 'fluffiness' (as my co-author would call it) of the social sciences—while ostensibly adding additional complexity—should paradoxically serve to speed up rather than delay the RDD & D of new technologies; as while the social sciences *do* complicate the path of technological innovation, they do so necessarily because society is complex!

Although the above example is framed by research into public perception, one should avoid drawing the simplistic conclusion that assessment of public perception is all that social sciences have to offer. The social acceptance of technological innovation hinges upon more than just an assessment of what 'the public' thinks [10]. As such, developing a broader understanding of the social context—and the different actors (e.g., politicians, businesses) and institutions (e.g., governments and markets) operating within it—informed by research from a variety of social scientific disciplines (e.g., political science, economics, sociology, management science, *etc.*) is key.

Crucially, I am not suggesting here that engineers should be asked to 'permanently move to the country' (*i.e.*, become social scientists) but rather to seek the involvement and contribution of the social sciences at an earlier stage and in a more meaningful, participatory way. Perhaps we can draw parallels with the findings of research into the involvement of publics in decision-making around proposed industrial facilities (e.g., wind farms). This research shows that early, sustained and participatory involvement in decision-making—where publics have a realistic sense of agency—can have a number of substantive benefits (e.g., the local knowledge that publics bring to the table can mean that more appropriate sites are selected) (e.g., [11–13]). While the relationships between engineers and social scientists are invariably different from those shared by publics and developers; the principle of working together to reach substantively better decisions remains sound. Arguably, then, now is the time to apply this paradigm to our own working relationships within the academic community, to more earnestly practice what we preach.

I use the term 'academic community' purposefully as this is not a criticism targeted solely at the engineering community. While more effective collaboration will hinge upon: (a) a greater willingness of 'hard' engineers to openly court the expertise of the 'softer' social sciences; and (b) to move beyond an erroneous belief that all that social scientists do is poll public opinion—or worse act as the public facing disseminators of innovation (salespeople if you will)—it is also incumbent on social scientists to (c) be more forthcoming and aware of their use within such research contexts; and (d) adapt to a different purpose and pace of work within interdisciplinary teams, particularly those driven by engineers.

To some extent I am doing my fellow country mice a disservice by eschewing the benefits of such a paradigmatic shift. I, like many of my counterparts, have made a career from assessing the fall-out from flawed attempts to impose an array of technologies on a diversity of publics. Importantly, the conclusion from such observation is usually the same: that the troubles observed might have been avoided (or at least lessened) with more considered, upstream, and/or participatory involvement of those who are ultimately affected by the decisions (e.g., [10–13]). Is it appropriate, then, for social scientists to sit back and repeatedly criticise the failings of technology and/or its promotion after the event—to delight in the morbid curiosity of technological failure and societal dis-ease—or should they be acting earlier to work with others to reduce the likelihood that technologies become as controversial as they sometimes do?

Perhaps our unwillingness to get involved relates in part to the thorny issue of maintaining one's scientific credibility. That is, working with engineers to the anticipated betterment of *Technology X* could be viewed as advocacy, thus conflicting with our hard-fought desire to be considered as scientists. However, if the message that we report from our research in this field is that better decisions can often be reached by giving those who are likely to be affected (*i.e.*, publics) a voice (although, see [14]), would it be not be hypocritical of us to reduce the potential for this to occur—particularly at a time when it can make a difference—basically on the grounds that we wish to remain objectively distant observers, safe in our country cottages (or ivory towers)?

A fear of advocacy is of course just one explanation of our reluctance to engage in technical RDD & D projects; other explanations include the inherent differences in the 'pace of innovation' within the social sciences relative to engineering and 'language differences' (*i.e.*, concern over our abilities to communicate due to the subject-specific nature of our terms of reference). Personally, I have never found language to be a serious obstacle to working with engineers. While social scientists and engineers both have their own jargon and favoured TLAs (Three Letter Acronyms), overcoming this barrier can be solved by a willingness to listen and learn. In fact, in my experience it is arguably the different dialects *within* the social sciences that are a source of more confusion.

The 'pace of innovation' argument is interesting. Compared with engineering—which tends to be underpinned by established constants (e.g., the laws of thermodynamics)—the pace of progress in the social sciences *is* often much slower, because it is underpinned by more fluid, contested and evolving principles (e.g., those shaped by social dynamics). With this in mind, it is understandable that social scientists might perceive the fast-pace of technological RDD & D as unwelcoming. However, it is important that social scientists do not lose sight of the specific target of innovation within such collaborative contexts. While broader theoretical innovation is clearly desirable and can occur in such environments, the target of innovation—and therefore the focus of the research—is typically the technology and the context for its introduction. As such, the situation requires social scientists to operate in a more applied capacity; using their understanding of contemporary theory and methods to inform the development and deployment of the technology. In these more applied surroundings, I would argue, there are much narrower gaps in the speed at which engineers and social scientists operate and innovate.

In short, and returning to the point I made above; successful interdisciplinary collaboration around technological RDD & D does not only require engineers to update their perceptions of the value of the social sciences, but it will require social sciences to adapt to their role within such teams.

While the fast-pace of the town can be off-putting, it is often the case that 'a dog's bark is worse than its bite' and so I feel that it is incumbent on social scientists to be more courageous in promoting their research and to seek out more opportunities to engage with engineers (and others) around the RDD & D of technological innovation.

3. A View from the Town

The experience of the 'country mouse' at the energy research workshop is unsurprising to me given the reluctance of the 'traditional engineer' to accept yet more externalities impacting on the development of solutions to real world problems, such as climate change. Engineers (town mice) apparently face ever-increasing, ever-diverse and ever-changing barriers to the development and deployment of new technologies. This is a situation that is exemplified by changes to the UK energy sector, within which I have worked for over 40 years as a research and development engineer, director, advocate and advisor, and which will serve as a lens for much of my view from the town.

Within a liberalised marketplace which is supposedly free of government interference and influence—such as that which exists in the UK energy sector—leaving the market to decide on the future energy mix seems like a viable and workable option. In reality, however, UK government policy decisions on how environmental, fuel poverty and security of supply challenges should be met do strongly shape the look of the energy sector. Thus, the lack of a clear government direction introduces

the risk that potentially attractive new technologies could become stranded assets at the whim of one transient government minister or another. There is therefore an understandable reluctance on the part of the largely multi-national conglomerates active in the UK to fund the commercial demonstration of many of the technologies that could form part of the solution package for a sustainable, low-carbon future. This indecision and growing complexity over the future of our energy provision—and the gradual erosion of the UK's position as a global leader in technology innovation—has introduced a level of frustration amongst the engineering community that has often led me to reminisce about times gone by when engineers were set technical challenges and were allowed free rein to invent and install new and improved concepts, largely against performance and cost considerations only.

For example, throughout the rapid increase in UK energy consumption and supply in the 1960's and 70's there was a clear and understandable emphasis on how quickly the necessary technology could be installed to meet demand, tempered only to some extent by cost. Efficiency was also a consideration, but the cheap cost of primary energy, mostly coal and oil, and the relative immaturity of materials research and development which would allow higher thermodynamic cycle efficiencies, meant that there was little scope or incentive for massive improvement. There was an obvious, simple engineering challenge (*i.e.*, meet growing energy demand as quickly and cheaply as possible) that was solved through the development and deployment of 'appropriate' technological solutions (*i.e.*, fossil fuel power stations). A combination of the fact that relevant industries were in government ownership and that the energy system largely relied on the UK's indigenous resources—and hence guaranteed full employment—meant that the pace of innovation was relatively high and any public resistance to change was relatively low—at least within the fossil fuel sector, the nuclear power sector is perhaps a different story.

The world has, however, not stopped spinning and things have changed noticeably since the mid-part of last century—not least to correct some of the unintended consequences of prior decisions (e.g., reducing particulate emissions, CO_2, NOx and SOx from fossil fuel plant). Large-scale privatisation of major industry (including within the energy sector); regional devolution and empowerment of communities to drive and affect local decision-making; the changing cost, distribution and availability of primary resources; the increasing complexity and competition within global markets (affecting jobs provision and security); and ever tightening pollution and emission legislation designed to address the spectre of climate change—among many other factors—have created a tangled web of new problems to solve. For instance, in the energy sector the understood concept of an energy trilemma illustrates the complexities and conflicts of trying to meet environmental targets (with CO_2 now at the forefront of thinking), without adversely impacting on affordability and security of energy supply.

In short, the days of engineers making a largely unconstrained contribution to addressing challenges, such as the supply and use of energy, are now over. It is no longer feasible to develop technologies with a consideration for a single (or even double) bottom-line, even if that is what we'd wish to do. The engineering challenges of the present and the future are different than before; more nebulous in nature, requiring a broader and more appreciative view of the politico-socio-economic implications of technological advancement. Engineering solutions to the real world problems that we face are increasingly subject to in-depth analyses (e.g., Life-cycle analysis and Political, Economic, Social, Technological, Legislative and Environmental [PESTLE] analysis), which assess their sustainability credentials, market potential and broader social acceptability before they can be considered serious contenders for societal deployment (e.g., [15,16]). As such, while we can seek comfort in the engineering practices of old, there is only so long we can or indeed should hide in our burrows and ignore the outside world. Now is the time to start having more meaningful conversations with those who know more about it; our cousins in the country.

Engineering arguably already has most of the necessary technical solutions for a less polluted world; it is the economic considerations, political landscape and vociferous opposition from the public that is complicating and delaying their successful introduction. With specific regard to the impact that the public exert on the introduction of new industrial technologies at a local level I, like my

co-author, increasingly see fit to question the extent to which we should put the objection down to simple NIMBYism. While I remain convinced that self-interested objection is a thing, it is clear that assuming NIMBY to be a 'self-evident truth' [17] is both erroneous and unhelpful; not least because it asserts that the fault of faltering deployment rests solely with those set to receive the technology. This simplistic way of thinking—while convenient for proponents of a given technology or facility—is clearly self-limiting as it slows necessary innovation in the manner in which technologies are designed and promoted: If it is not our fault why should we change? The problem is that the fault often does lay, at least partially, with the simplistic reasoning of those wishing to promote technological innovation. For me then, it makes pragmatic sense that we should seek to engage those who have a good grasp of such issues if we are intent on seeing these technical solutions succeed. The question we should be asking ourselves is not *if* we should engage more with the social sciences around technological RDD & D but rather *when* should we and to *what extent*?

Naturally, there are barriers to engagement between such disparate disciplines; as outlined by my co-author, our dialects and pace of life differ from those of our country cousins. But to the extent that the engineering challenges of the future necessitate a broader, interdisciplinary focus, it pays to think practically and pragmatically about these things. Working together with social scientists to the betterment of our understanding of the social context for the introduction of new technologies would appear to be a small price to pay for improving the potential for our innovations to see the light of day.

Importantly, I feel that the involvement of the social sciences could occur earlier than it does currently. My co-author speaks rightly of the fact that many engineers still perceive the involvement of the social sciences as something that occurs at the end of the development cycle, when we already have designed and developed the technologies that we wish to introduce into society. Granted, there is a role for the social sciences at this stage but this 'bolt-on' mentality has limitations. Could we have designed a better, more socially acceptable technology or facility if we had thought to involve those who understand more about the nature and complexity of the social context at an earlier stage?

4. A Move to the Suburbs

Together, we feel that there is common message arising from our two viewpoints; if we are intent on advancing the pace of industrial technological RDD & D there is a need for closer, more upstream collaboration between engineers and social scientists. However much we would like to retain our isolated existences, the pace and complexity of global change requires evermore joined-up thinking, which in turn necessitates increased collaboration. Importantly, this will require that our current country and town mice will have to live an increasingly 'suburban' existence.

This paradigmatic shift will not come easily for some; old, ingrained prejudices about one another's practices and purpose—those highlighted in the workshop that began the 'view from the country'—will take time to soften or dissolve. Importantly, such prejudices—in our experience—do not come from a place of disrespect but rather one of misunderstanding. In attempting to solve the wicked, 'post-normal' [18] scientific problems of the future it is incumbent to those on both sides of the divide to seek to adapt their approaches to accommodate the dialects and working practices of the others; to develop their understanding of the value that each-other can bring to an inter-, multi- or trans-disciplinary team.

Crucially, moving to the suburbs does not necessarily require a physical relocation and rehousing of people; while physical relocation could assist collaboration it is not a requirement of the 'move'. Rather, we prefer to use the term more figuratively in order to point to a virtual relocation, fostered principally by a change from the 'just visiting' mindset to one that that seeks more sustained, deeper interdisciplinary collaboration. Equally, while moving to the suburbs does mean that compromises must be made, these should be compromises in isolation rather than integrity. Moving to the suburbs does not mean that we should forget our cultural best-practices or forgo academic rigour. Indeed, if anything, the need to defend our approaches to those less well-versed in such matters could be seen as an opportunity to tighten-up on such things. Equally, a move to the suburbs does not mean that

engineers should become social scientists or *vice versa*; although a little 'bilingualism' would be nice, we are experts in our own fields for a reason and should not be forced to compromise our interests. All that a move to the suburb demands is that we become more willing, open and practiced in working alongside those from other disciplines.

Thankfully, there are now a number of encouraging examples of where interdisciplinary teams of engineers, social scientists and scientists are beginning to collaborate in a meaningful, upstream sense, around the RDD & D of new technologies. This is particularly evident around the advancement of Carbon Dioxide Utilisation (CDU) technologies; exemplified perhaps by the prominence of integrated considerations of 'public perception' in initiatives like the CO2Chem network—an EPSRC grand challenge network that unites academics, industrialists and policy makers from a wide range of disciplines to consider the utilisation of carbon dioxide as a feedstock for the production of value added products—alongside more 'obvious' clusters (e.g., advanced mineralisation, fuels, chemical transformations) [19].

While sceptics might contend that the inclusion of a dedicated 'public perception' cluster within the CO2Chem network simply represents a means to an end prompted by shifting research funding structures, we remain optimistic that there are genuine substantive motivations behind this invitation. Indeed, while the funding for the CO2Chem network was secured *before* the inclusion of the 'public perception' cluster—and thus, while it was the case that the country mice were invited to the feast fairly late in the day—we were not recruited in a tokenistic manner and we now have a regular place at the table and our dialect is increasingly recognised and influential in shaping the future of CDU technical research and development. In fact, the collaborations formed around this table have, for our more rural author alone, already yielded several innovative publications [20–22]—including this one—involvement at a recent Faraday Discussion on CDU (September, 2015) [22,23] and a keynote speech at an International Conference on CDU (September, 2016); as well as invitations to present to audiences at related initiatives (e.g., 4CU project [24], SCOT project [25]) and a place on the board of directors of the new UK Centre for CDU (CDUUK) [26].

Indeed, in CDUUK we feel that we have a concrete example of what 'suburbia' could look like for the advancement of CDU technologies. Launched in 2013 and hosted by the University of Sheffield, CDUUK provides a cohesive, virtual centre for interdisciplinary research into Carbon Dioxide Utilisation; actioned in part through funded initiatives like 4CU and CO2Chem. The centre currently unites researchers in seven academic departments across engineering (e.g., chemical and biological engineering), the sciences (e.g., physics, chemistry, psychology) and the social sciences (e.g., management) with the focus of pursuing research into all areas of CDU; from the development of carbon capture agents, life-cycle analysis of product options and public perception among others (e.g., [21,22,27,28]). Beyond the internal opportunities afforded to the University of Sheffield, CDUUK also provides an international knowledge-exchange and networking forum for external academics, industry, research funders and policy makers; with the ultimate aim of creating a critical mass of world class CDU research.

CDUUK is already yielding pioneering results. Through the *What a Waste!* project [21]—a collaboration between chemical engineering (Styring and Armstrong) and psychology (Jones)—for instance, we now know more about the emerging nature of public opinions of a number of CDU technology options. The project not only trialled a new method for assessing public perceptions of CDU in order to counter the prospect of registering pseudo-attitudes (e.g., [29]) but highlighted potentially important areas of agreement and disagreement in the perceived risks and benefits of CDU among experts and lay-people. The collaboration did, for example, reveal a healthy degree of scepticism among those interviewed over the stated long-term environmental benefits of the technology (e.g., in mitigating climate change); a finding which clashes with the favoured 'frame' being used by engineers to advocate the technology.

The social knowledge created by the project can now be used by those wishing to promote CDU in order to develop more appropriate communication materials regarding the technology and its

applications (*i.e.*, materials which map more closely to the actual rather than the perceived concerns of lay-publics); thereby replicating a model that is being used successfully around the promotion of Carbon Capture and Storage (CCS) [30]. Importantly, while it would be overly optimistic to presume that the generation of social knowledge will be sufficient to guarantee the acceptance of or negate all opposition to future facilities, we would argue that it does at least hold the potential to lessen the chance of prohibitive opposition forming.

A central remit of the centre is one of dissemination and advocacy; seeking to produce and publish strategy documents and briefings to help set the agenda for the advancement and integration of CDU technologies in the UK and across Europe [31,32], akin to the Global CCS Institute in Australia [33]. The emphasis on advocacy has aligned CDUUK with other similarly-minded initiatives at the University of Sheffield, notably the Grantham Centre for Sustainable Futures [34], which in turn has yielded further interdisciplinary collaboration in the form of a 4-year research studentship, called *Ureaka*! This project seeks to advance understanding of emerging socio-political perceptions of CDU technologies, which could stand to promote the sustainable manufacture of widely-used, urea-based products (e.g., agricultural fertilizers and pesticides).

In summary, while still in its formative years, CDUUK is already delivering results and is an example of what can be achieved if we are able to shake the 'just visiting' mindset and create the right conditions for meaningful interdisciplinary collaboration.

5. Conclusions

Within this short communication article, we have attempted to use the well-known 'town mouse and country mouse' fable as a framework for stimulating debate and discussion about a matter of increasing importance: the necessity of earlier more meaningful collaboration between engineers and social scientists around the RDD & D of industrial technologies. While it is increasingly common that interdisciplinary teams of engineers and social-scientists (and others) will coalesce around technical projects, it is questionable as to whether or not this reflects a growing recognition and respect of the value that such unions can bring to projects or is simply utilitarian and designed to satisfy the requirements of research funders is a question. We hope it is the former; however, we fear that the experiences of our lead author at the energy workshop, while perhaps on the wane, are still shared by other social scientists attending 'town meetings' and other fora relating to the RDD & D of new technologies.

So what is the moral of *our* story? Like our favoured interpretation of the town mouse and country mouse idiom, we share the belief that it is important to develop a more-informed and healthy respect for the value of each-other's disciplines (*i.e.*, lifestyles) in an attempt to avoid or dissolve the prejudices of the past. We should be encouraged that the two mice in the fable—despite their obviously different backgrounds—took the time to sample each-other's lifestyles. It was only by making the time to experience one another's worlds that the potential to unearth common ground and to correct for misunderstanding could have occurred. Unlike the conclusion to the fable, however, we take issue with brevity of the interaction and the swiftness of the desire to retreat back behind entrenched lines at the first sign of trouble. Meaningful interdisciplinary collaboration is difficult and does take time to develop. It cannot be realistically achieved by short trips to the town or occasional walks in the country. If we are serious about developing and deploying the next generation of technologies to tackle global, complex issues like climate change, we need to 'move' to the suburbs.

We feel that the inclusive, interdisciplinary approach being championed and employed by the CDUUK, the CO2Chem network (and related initiatives) around the advancement of the RDD & D of CDU technologies is a model of suburbia that is succeeding. Moreover, it is a mode of technology development and assessment that recognises the growth in the popularity of industrial ecology (e.g., [35]), life-cycle analysis (e.g., [36]) and broader systems-thinking (e.g., [37]), and is sympathetic to the evolving demands of the research-funding landscape; a landscape that increasingly demands

more 'responsible research and innovation' (e.g., EU Horizon 2020) [38]. We would now like to see this template applied to future collaborative research efforts in other sectors.

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Abbreviations

The following abbreviations are used in this manuscript:

RDD & D	Research, Development, Demonstration and Deployment
CDU	Carbon Dioxide Utilisation
NIMBY	Not In My Backyard
CO_2	Carbon Dioxide
NOx	Nitrogen Oxides
SOx	Sulphur Oxides
PESTLE analysis	Political, Economic, Social, Technological, Legislative and Environmental analyses
CO2Chem	Carbon Dioxide Utilisation network
4CU	A comprehensive and coordinated approach to Carbon Capture and Utilisation (4CU)
SCOT	Smart CO2 Transformation project (SCOT)
CDUUK	UK Centre for Carbon Dioxide Utilisation (CDUUK)

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