Towards innovation democracy?

participation, responsibility and precaution in the politics of science and technology

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Abstract

Innovation is about more than technological invention. It involves change of many kinds: cultural, organisational and behavioural as well as technological. And there are no guarantees that any particular realised innovation will necessarily be positive. Accordingly, innovation is not a one-track race to the future. Indeed, it is not so much about optimizing a single trajectory, as it is a collaborative process for exploring diverse pathways. So, in order to realise the enormous progressive potential of particular kinds of innovation, what is needed is a more realistic, rational and vibrant 'innovation democracy'.

Yet conventional innovation policy and regulation tend simply to assume that whatever products or technologies are most energetically advanced, are in some way self-evidently beneficial. Scrutiny tends only to be through narrow forms of quantitative 'risk assessment' – often addressing innovation pathways at a time too late for significant change. Attention is directed only in circumscribed ways at the *pace* of innovation and whether risks are 'tolerable'. The result is a serious neglect for the crucial issue of the *direction* of innovation in any given area – and increased vulnerability to various kinds of 'lock in'.

These patterns show up across all sectors. Beyond GM crops, for example, there exist many other innovations for improving global food sustainability. But the relatively low potential for commercial benefits often leave many promising options seriously neglected. And this 'closing down' of innovation is intensified by deliberate exercise of powerful interests at the earliest stages. For instance, official statistics often conceal the extent to which patterns of support are concentrated in favour of particular innovation pathways. And where uncertainties are side-lined, even scientific evidence itself can carry the imprint of vested interests. Yet these effects of power remain unacknowledged in policy making. Policy is stated simply as 'pro-innovation' – a self-evident technical (rather than political) matter.

To address these challenges, innovation policy should more explicitly and transparently acknowledge the inherently political nature of the interests and motivations driving contending pathways. Here, this paper explores the potential for three emerging bodies of practice, relevant across all areas: participation, responsibility and precaution. Each involves a range of practical methods and new institutions. Precaution in particular is a subject of much misunderstanding and mischief. Among other qualities, this offers a crucial guard against the error of treating the absence of evidence of harm as evidence of absence of harm – and highlights the importance of wider human and environmental values.

Together, qualities of participation, responsibility and precaution extend scrutiny beyond anticipated consequences alone, to also interrogate the driving purposes of innovation. They allow societies to exercise agency not only over the rate and riskiness of innovation, but also over its direction. And they offer means to enable hitherto more distributed and marginal forms of innovation – which presently manage only rarely (like renewable energy or ecological farming) to struggle to major global scale. Together, these qualities celebrate that innovation is not a matter of fear-driven technical imperatives, but of a democratic politics of contending hopes.

1: The Breadth and Diversity of Innovation

Innovation is not just about technological inventions. It encompasses all the many ways of furthering human wellbeing. This includes improved production and use of goods or services in firms and other organisations [1]. But it also includes new practices and relations in communities, households and the workplace [2]. Advanced science and technological research can help drive and enable innovation [3]. Yet many other new forms of knowledge and action are also important [4]. Innovation can be created and guided by social venturing [5] and mobilisation [5] as much as commercial entrepreneurialism [6]. So grassroots movements [7], civil society [8], creative arts [9], and wider culture [10] feature alongside small business, service industries [11] and the public sector [12] in being as important for innovation as universities, research labs and high-tech companies.

Of course, there are no guarantees that any particular innovation in any of these areas will necessarily be positive. To take extreme examples that most may agree on, new forms of torture [13], financial fraud [14] or weapons of mass destruction [15,16,17,18,19,20] are all active areas for innovation that might be judged to be generally negative. For other kinds of innovation, the picture is varyingly ambiguous. But it is rare that any given innovation is entirely, unconditionally or self-evidently positive [21]. And judgements are always relative. So, the unqualified claim in the current British Government slogan – "*innovation is Great… Britain*" [22] – is not automatically true. Like other prevailing high-level talk of 'pro-innovation' policy — for instance, around the European Union's 'Innovation Union' strategy [23,24,25] — this misses the crucial point that the most important queries are about 'which innovation?'. Whether or not any given innovation is preferable on balance to alternatives – let alone unreservedly 'good', still less "*great*" – is not just a technical issue. It is also a fundamentally political question. This means that even quite detailed aspects of innovation policy are legitimate matters for democracy [26–32].

In these widest of senses, however, well-conceived innovations can undoubtedly offer important aids not only to economic productivity [33], but also to enhancing many kinds of human flourishing or the public good [34]. And this need not be a bone of contention, even under the most critical views [35]. The more ambitious the aspirations to progressive social change, the greater the need for broad, diverse (and carefully scrutinised) kinds of innovation [36] [37]. An example lies in the imperatives for transformations towards a more Sustainable [38], equitable, healthy and peaceful world. Whatever forms these possible futures are held to take, they require radical kinds of innovation in the widest of senses [39].

Some innovation opportunities can be effectively addressed by well-governed fair and efficient markets [40]. So, one important role for innovation policy lies in helping to foster commercial innovation in the public interest [41]. But not all benefits, risks or impacts are restricted to those private actors typically most directly involved in steering business innovation [42]. Established understandings, motivations and incentives driving the most powerful market actors, often fail fully to prioritise wider relevant social values and interests [43]. In areas like health, agriculture, energy, environment, water, mobility, security, waste and housing, many of the least privileged (most vulnerable) people around the world are disproportionately excluded from conventional global patterns of innovation [44]. Nor (as we shall see below) are many important forms of uncertainty and ambiguity always fully or appropriately addressed by relatively narrow market-based signals or official statistics [45].

Depending on the context, then, market processes alone do not necessarily drive the best orientations for the kinds of innovation that are most needed from broader social viewpoints. This is true both across different domains of policy as well as within any given sector. For instance, the single largest area for public expenditure on research and innovation – in the UK as worldwide – is military [46] [47]. Innovation towards less violent means for conflict resolution are relatively neglected [48] [49] [50]. Likewise, the most strongly-pursued energy options are those that offer greatest returns on established infrastructures and supply chains, rather than new distributed forms of renewable power or energy services [51] [52] [53] [54]. For it's part, biomedical research tends to focus more on health disorders of the rich than the poor, and on therapeutics rather than prevention [55]. This is especially so in speculative (but potentially lucrative) new areas like 'human enhancement' and 'life extension' [56] [57] [58], with the Royal Society raising particular questions about patterns of prioritisation in neuroscience [59]. Consequently, there are important roles for public policy in helping to prioritise across sectors, as well as encourage and support appropriate scales and directions for innovation within particular areas. And (as we shall see later), public policy is also crucial in helping to address the many uncertainties and ambiguities – by promoting greater analysis, deliberation and political accountability [60].

In nurturing these qualities, public policy can also fulfil other significant roles. Alongside higher education, business and civil society, government policy can do much to promote the knowledges, capabilities and environments that best facilitate socially effective innovation [61]. So, the more demanding the challenges for innovation (like poverty, ill health or environmental damage), the greater becomes the importance of effective policy [62] [63]. These challenges of innovation policy go well beyond simplistic notions of governments trying to "pick winners" [64] [65]. In any case, imperfect or self-serving foresight does not exclusively afflict the public sector, but also applies to powerful market actors [66]. Though manifest differently, essentially similar degrees of uncertainty, intractability and deficiency are equally experienced in government, business and civil society [67]. Instead then, the central challenge in innovation policy is about helping to harness the differences [68]. This is about culturing the most fruitfully cross-fertilising conditions across society as a whole, for collectively seeding and selecting across many alternative possibilities and together nurturing the most potentially fruitful [39]. This involves collaboratively deliberating, negotiating and constructing what 'winning' even means, not just how best to achieve it. These are the questions on which this paper will focus.

2: Policy and the Politics of Choice

The most important (but neglected [69]) issue here, is that innovation of all kinds in any given area is not a one-track race to the future [70]. Instead, it is about social choices across a variety of continually branching alternative pathways for change [71]. In this sense, innovation is more like an evolutionary process than a race [72] [73]. It is as much about exploring a space of different possibilities, as optimising any one [74–76]. As already mentioned, it is rarely self-evident – and often hotly contested – what should count as the most 'desirable' directions for discovery. This is true, for instance, of particular domains like Sustainable agriculture, zero carbon energy services or clinical and preventive responses to improving public health. In all these areas, there unfold many radically contrasting alternative pathways for innovation. Two of the most pervasively important qualities in choosing which pathways to prioritise, are therefore: *(i)* attending fairly to a ***diversity*** of possible directions and strategies [77]; and *(ii)* including a ***plurality*** of perspectives in appraising any one [78–80].

Consequently, it is not only important that innovation be efficient and competitive in any particular direction. It is also crucial equally for economic and wider social wellbeing, that the directions that are prioritised for innovation, are as robustly deliberated, accountable and legitimate as possible [81]. An economy that fails to do this, exposes itself to the risk that it will become committed to inferior innovation pathways, that other more responsibly and responsively steered economies may avoid. In other words, innovation may "go forward" quickly, but in the wrong directions.

History presents plenty of examples of innovation trajectories that later proved to be misguided – for instance involving asbestos, benzene, thalidomide, dioxins, lead in petrol, tobacco, many pesticides, mercury, chlorine and endocrine-disrupting compounds, as well as chlorofluorocarbons, high sulphur fuels and fossil fuels in general [82,83]. In all these and many other cases, delayed recognition of adverse effects incurred not only serious environmental or health impacts, but massive expense and reductions in competitiveness for firms and economies persisting in the wrong path [84] [85]. Innovations reinforcing fossil fuel energy strategies [65] – like hydraulic fracturing [86] – arguably offer a contemporary prospective example. And similar dilemmas are presented by the otherwise exciting new possibilities of nanotechnology [87] – both internally within this field and externally with respect to alternative ways to address the same priority social needs [88].

The key conundrum here, is that each alternative innovation pathway in any given area (like food, energy, health or security), will typically display contrasting pros and cons under contending perspectives. Animated differences emerge, for instance, around infrastructures for urban automobiles or cycling [89], nuclear power or renewable energy [66] and violent or peaceful approaches to national security [50] [49]. Each involves different innovation trajectories. Competing pathways will also routinely differ in their social distributions of benefits and harms, winners and losers. And – in any view – the whole picture is further obscured by many deep unknowns. Crucially, a decision *not* to innovate will also present its own mix of pros, cons and uncertainties. Innovating in any particular direction will – for instance, through foregone resources and opportunity costs – typically diminish innovation in others. Whether deliberate or inadvertent, each direction for innovation is a social choice – involving issues of uncertainty, legitimacy and accountability as well as competitiveness.

It is important to acknowledge these complexities of choice, because innovation debates in particular areas often become quite simplistic and polarised. For instance, innovation in fields like food, health, energy or warfare is frequently discussed as if it were a one-track race [70], rather than an exploratory process – simply about whether to '*go forward*' or not. But the crucial questions in such areas are typically not just about '*yes or no?*', '*how fast?*' or '*who's winning?*'. What often matters more instead, are queries over '*which way?*', '*what alternatives?*', '*who says?*' and '*why?*' [90]. And the scope for uncertainties under these wider questions, compound the scope for controversy. So, conflicts can become especially intensive and disabling (and potentially economically disastrous), if these broader questions are ignored.

Across all fields, the key challenge is that there exists no single definitive 'sound scientific' or 'evidence based' way to calculate the most rational balance of resources to expend on alternative innovation pathways within or across different domains [91]. A robust knowledge base and rigorous analysis are both necessary. But these are typically insufficient. The merit rankings constructed for different innovation choices by expert analysis invariably overlap – and may often be inverted – under contrasting equally reasonable assumptions and value judgements [92] [93] [94] [95] [96]. Decisions concerning which kinds (or areas or aims) of innovation to prioritise are therefore inherently partly subjective, rather than purely technical or economic. This is why research and innovation remain intrinsically political matters, irrespective of whether or not they are acknowledged to be so.

This makes it all the more important that high quality information concerning public policy in and around innovation, is available for wider scrutiny and debate. But the recent House of Lords Select Committee on Science and Technology report on the setting of priorities for publicly funded research, identified several important areas for improvement [97]. The Committee confirmed that there remains important scope for enhancing the quality of official UK statistics concerning public support for contrasting innovation pathways. It made recommendations that this information be clarified in several particular ways. Yet these recommendations remain to be implemented. Consequently, further deliberate efforts are required in order to enable more transparent and accountable democratic politics concerning the directions and rationales underlying UK innovation policy.

3: Steering Innovation Pathways

One reason why it is important to address the politics of choice in innovation, is that chosen pathways can quickly become effectively irreversible. A diversity of well understood social, political and economic processes exert various kinds of positive feedback as innovation pathways unfold. These can act to reinforce the trajectories favoured by the most powerful interests, and exclude others that may be more widely beneficial.

Typically, it takes a lot of effort for people, organisations and markets to learn about any new way of doing things, capitalise on the opportunities and adapt to the changed requirements. As these efforts become 'sunk investments' in a particular innovation, they can help reinforce commitments to the associated pathway. This can occur, even if the innovation in question is widely seen to be unsatisfactory [98]. Although complicated [99], a classic example of this remains the QWERTY keyboard [100,101]. This was originally designed for nineteenth century mechanical typewriters, specifically to adjust typing in order to reduce jamming of the type bars for letters frequently used together. But this very property of modulating typing speed, helps aggravate office injuries [102]. There exist better keyboard configurations [103]. Yet the deeply socially embedded familiarity of QWERTY makes it difficult for alternatives to become established. So, the problem persists through successive innovations in electronic typewriters, computers and touchscreen tablets, continuing several technological generations after the initial rationale lapsed. Even where the incumbent innovation is essentially a product of historical chance, then – with no powerful backing – it can prove very difficult to reverse the associated path dependency.

This dynamic of path dependency makes it especially important to do whatever is achievable at the earliest stages of innovation, to give confidence that unfolding directions are as appropriate as possible [104]. The dilemma is, of course, that this is precisely the time when the positive and negative implications are most uncertain [105,106]. So, there can be enormous pressures on all sides, to exaggerate the confidence with which evidence can be interpreted and to understate the scope for competing interpretations [107]. One reasonable response to this, is to be much more open and questioning about uncertainties [91]. Another rational measure, is to extend scrutiny beyond anticipated consequences and also look at the driving purposes of innovation [108]. Whilst the variously claimed positive, negative and indirect effects may remain uncertain, the motivating values, interests and incentives that lie behind particular innovation pathways are typically much clearer [109]. In this way, critical appraisal of the driving forces behind alternative innovation pathways (not just the claimed aims) can be undertaken with confidence at an early stage, despite the uncertainties [110].

This kind of careful broad-based societal consideration is, however, rarely evident in mainstream innovation. More often, it is a narrower range of expectations about the future that most strongly drive directions for change. The values upheld by particular communities of researchers themselves may be influential, as well the interests of leading firms, powerful financiers or particular users [111]. If a specific pathway is strongly held to be more likely than others by these kinds of influential actors, then this can become self-fulfilling [112]. Examples include competing media formats or software operating systems, where early market penetration can be driven more strongly by expectations about future adoption, than by assessments of performance [73]. Some degree of performance shortfall is often the price for collective compatibility [113]. Consequently, expectations can add to path dependencies mentioned above, compounding the 'locking in' of a particular innovation, and the 'crowding out' of alternatives [114]. This is an issue that arises, for instance, from the conditions described in Box Y in the case of nanotechnology [58].

Processes of learning, volume production and economies of scale can add to these positive feedbacks. For instance, 'lock in' can be significantly further reinforced by measures to standardise infrastructures [115], establish organisational momentum [116], appropriate intellectual property [117] [118], build monopolies [119], realise rent on value chains [120], condition user preferences through marketing [121], 'capture' regulators [122] and 'entrap' competing political interests [123]. The overall result of such so-called 'network externalities', are a range of powerful 'increasing returns' that can entrench a particular favoured trajectory and exclude other paths [124]. Despite being ignored in the apparently simple policy language of '*going forward*', these more complex dynamics in science and innovation do not go unnoticed by interests wishing variously to reinforce (or disrupt) particular pathways [125] [126]. So, if innovation policy is to be fair and effective, it is therefore important that it attends to these processes in explicit, direct and accountable ways.

These challenges are formidable enough. But, as indicated above, problems of 'lock in' are intensified where important roles are also played by the deliberate exercise of powerful interests at the earliest stages of an innovation process, in order intentionally to promote particular favoured pathways or disadvantage others [127] [128]. For instance, automobile manufacturers and allied industries sought historically to promote the car by suppressing competing urban public transport systems [129]. Likewise, lead compounds were promoted as anti-knocking agents in transport fuels, at the expense of less profitable alcohol-based products, even though these were very early known to be less harmful [82]. A further example of this more deliberate type of lock-in includes the strategies of the tobacco industry over the past century to maintain high levels of consumption [130]. Before it was finally abandoned in most countries, the nuclear fuel reprocessing industry also worked for many decades actively to engineer continuing government support [123]. And now, ostensibly disinterested debates over alternative radioactive waste management strategies also inherently depend on – and help condition – future prospects for new nuclear power [131,132]. Most recently, pharmaceutical industry strategies have been challenged for neglecting innovation of medically vital antimicrobials due to their low profitability [133]. Where innovation systems are driven by these kinds of dynamics, there are especially important roles for democratically responsive government policy and collaborative international pressure.

It is crucial not to misunderstand the implications of 'lock in'. In order to be successfully achieved, even the most positive innovation pathway will require some closing down in associated standards, regulations and practices [134]. So 'lock in' in some sense, is not in itself necessarily a bad thing. But it remains a significant policy dilemma, since it means that not all potentially good innovations that are technically practicable, economically feasible or socially viable will actually prove to be historically realisable. The most important point then, is that these issues need to be discussed and addressed openly – and democratically – rather than brushed under the carpet or drowned in simplistic and polarising 'pro' claims (or 'anti' accusations) over innovation in general.

4: Opening Up Innovation Portfolios

Many of the above examples are retrospective – judged with the benefit of hindsight. Looking forward in any given area, it becomes even more difficult to conclude definitively which of a variety of innovation pathways offers the most favourable balance of pros and cons. One especially important prospective example lies in the field of innovation for more Sustainable global food systems [135]. How will a growing world population be fed at a time when natural environments are increasingly stressed [136]? Here there exists a particularly rich diversity of possible innovation pathways, each with contrasting implications [137]. Many kinds of diversity are possible [138]. But public debates display a shared tendency on all sides to close down discussions as if about just being 'for' or 'against' the single family of innovations around 'genetic modification' (GM), favoured by the most powerful interests in this sector.

With resulting policy debates polarised by this especially deep form of power play [139] [140], it is often portrayed as if GM were – self-evidently and in-principle – either individually indispensable or uniquely unacceptable. Whatever reasonable political perspectives are taken on the pros and cons of the many disparate innovation pathways in this field, neither of these positions is actually tenable. In fact, the much-discussed (apparently specific) innovation of 'GM plant breeding' is much more complex and ambiguous than often suggested by either critics or advocates alike. Apparently technical variations like 'transgenics', 'cisgenics', 'apomixis', 'gene editing', 'genomic assist' and 'marker selection' [141] each offer partly overlapping and partly contrasting benefits and risks – and present important differences in their potential social, political, economic and ecological implications [142].

For example, among the more striking recent claims made for UK Government supported research towards enhanced Sustainability in global staple crops, are the remarkable flood tolerance qualities reported for 'scuba rice' [143]. But these have been achieved through 'marker assisted backcrossing', rather than any form of transgenics [144]. So, the most important factor typically differentiating "GM" technologies is not that they offer a unique means to secure crop improvement. The crucial distinction lies more often in the potential for innovating firms to recoup investments by obtaining rents on intellectual property or global supply and value chains [145]. For instance, transgenic crops are often deliberately engineered for tolerance to particular proprietary broad spectrum herbicides, thus expanding their sales [146]. Or the inclusion of particular transgenes can make the resulting organisms patentable, and thus more reliable sources of royalties [147]. It is the resulting forces and counterforces that help make the ensuing discussions so regrettably polarised.

This point becomes even more important as attention extends beyond science-intensive innovations. Outside the techniques of molecular genetics, there are many other promising innovations for improving global food sustainability [137]. These include participatory breeding [148], agricultural extension services [149] and open source seed sharing methods [150], which harness the innovative capacities of farmers themselves and help tailor crop development to important local conditions [151]. Likewise, there exist many innovations in wider agricultural practices that also offer significant benefits to the productivity of small farmers [152], including intercropping [153], integrated pest management [154] and other methods of ecological farming [155] and Sustainable agriculture [156].

Likewise organisational innovations in the food chain also offer potentially major benefits, including reforms to distribution systems, storage provision and better food waste management [157]. Arguably the greatest implications for equitable global food availability, however, are presented by innovations that are still wider in scope [158], including reforms to land tenure and agricultural property rights [148], income support for marginal famers [159], social equality between different rural groups [160], or moving diets towards lower meat consumption [137]. These kinds of innovation may often offer significantly greater benefits to poor farmers, consumers or communities than science-intensive technological solutions. But their less attractive commercial benefits mean they remain, like Cinderella, too often uninvited to the innovation party.

What is shown by this food sector example, is that – even in a specific area – innovation is not about simply '*forging ahead*', '*lagging behind*' or '*catching up*' [161]. It is not a single-track race driven by a particular privileged field of science. Instead, it is about diversity, exploration and choice. This is why it is misleading to uphold particular pathways as offering exclusively '*sound scientific*', definitively '*evidence based*' or uniquely '*pro innovation*' options (…or for all contingently-emerging innovation to be asserted necessarily to be "great"). And this is why exaggerated '*no alternatives*' language (on any side) can polarise controversy and so also impede effective innovation policy. By seeking to invoke the general authority of science and technology in partisan ways, this kind of language does not only threaten effective innovation. It also risks compromising science and undermining democracy itself [162]. More mature and rational debate recognises that choosing between the pros and cons of alternative innovation pathways like those exemplified here, are less technical than they are political.

A more reasonable and productive way to handle these crucial issues in innovation policy is to be more transparent, deliberate and accountable about when it is right to 'open up' and when to 'close down' in any particular field [163]. This means that no particular innovation should be unduly favoured by policy making, simply because of its appeal to particular powerful vested interests within a given innovation system. Nor should it be treated on these grounds as self-evidently existentially unacceptable. Either position requires context and perspective -specific argument. In other words, what is needed is mature political debate, as much as ostensibly definitive analysis [164]. What can be recognised as well, though, are the benefits of some requisite degree of diversity [165]. And (as we shall see), this is a general quality that can be achieved in many different ways – also potentially excluding any particular innovation.

This can be illustrated by the further example of the challenge of mitigating climate change by building zero carbon energy infrastructures. Here decades of intensive research by government and industry bodies has shown that there exist (despite the formidable constraints) a range of alternative innovation pathways that are viable under contrasting equally-informed understandings [166]. For some, the solutions centre around nuclear power [167]. Others highlight large scale use of carbon capture and storage [168]. In the wings, momentum is growing behind expedient and idealised aspirations somehow deliberately to control the global climate through 'geoengineering' [169–173] – a technology threatening particularly acute and irreversible forms of 'lock in' [174 175]. Yet all the time (albeit not backed by such powerful interests), a rich array of renewable energy technologies is available for addressing climate change in a diversity of radically different distributed or centralised ways [176–179].

The crucial point is, that there is no definitive technical or economic reason why any of the above energy strategies cannot (for better or worse) provide a basis for a variety of zero carbon UK or global energy futures. Crucially, this includes the clear feasibility (equally for the UK and Europe [180 181 182 179 183 184] and the world as a whole [166 185 118 119]) of energy strategies built entirely around efficiency and renewables. Yet one of the main obstacles to this, lies in high profile self-fulfilling assertions to the contrary – including by authoritative policy figures [188 189]. In energy as in the food sector discussed above, then, the obstacles to less favoured strategies are typically more commercial, institutional and cultural than they are technical. Amongst the most potent of these political obstructions are claims from partisan interests – like incumbent nuclear or fossil fuel industries – that there exists 'no alternative' to their favoured innovations and policies [188]. Even given the formidable constraints bearing on sustainable energy and agriculture then [190], there remains much hidden scope for radical choice. This is a matter for critical democratic deliberation as much as technical analysis [39].

There are many ways to resist such unhelpful syndromes and to develop more reasonable debates about innovation. These will be returned to below. Some are about the style of discourse – developing a greater tolerance on all sides, for embracing adverse public reactions to particular innovations. When they transcend privileged 'not in my backyard' parochialisms, general public preferences offer an important guide to the general orienting of innovation [191]. Just as scepticism is one of the crucial constituting qualities in science itself [192 193], so space for healthy critical debate and public dissent can help improve the quality of innovation more generally [194 195]. With mainstream institutions often especially strongly disciplined by incumbent powerful interests, the role of delivering on this important quality of scepticism often falls disproportionately to civil society [196].

And this crucial role of social movements and wider civil society extends beyond debate and controversy. It is remarkable how many presently major global industries are building around once-marginal technologies like wind turbines, ecological farming, super energy-efficient buildings, or green chemistry [7]. All of these owe key elements in their pioneering origins to early development by grassroots social movements [197]. For instance, without the small country of Denmark remaining partly 'below the radar' of international nuclear interests, able to nurture alternative energy strategies in the 1970s driven strongly by anti-nuclear social movements, it is arguable that the present multinational wind industry might never have become competitive [198]. This is just one of the examples of innovations that were systematically marginalised – sometimes actively suppressed – by incumbent interests in science, government and industry [199].

It is of course important not to become too romantic about the dynamics of social movements and their favoured innovations [196]. These too warrant exactly the same kinds of healthy scepticism appropriate to other actors in innovation debates. But history does make clear where it is that many of the ostensibly driving environmental and social justice concerns come from, that currently play such prominent roles in the justification of innovation policy. Without decades of struggle by social movements dedicated to humanitarianism, environmentalism and social justice, it is doubtful that high level global agenda-setting developments like the Stockholm Environment Conference or the Brundtland Commission or the Millenium Development Goals would ever have become as formative as they are now in shaping the general climate of global governance – or innovation debates in particular [200–203] [204,205] [206]. Here, the same basic pattern is arguably reproduced, as in the crucial roles played by social movements in other emancipatory transformations around colonialism, slavery, women's and gay rights [207] [208] [209,210].

Just as the famous astronomical missing mass stabilises the visible structures of galaxies, so these apparently intangible distributed social forces help condition the gradients that ultimately help forge and steer new directions for innovation [211]. The greater the critical interest in the most progressive orientations for innovation – rather than those that preserve the status quo – the more this is generally true.

5: Risk, Uncertainty, Ambiguity and Ignorance

As has been mentioned, these policy making challenges are compounded, because the pros and cons of different innovation pathways are – under all views – subject to seriously incomplete knowledge. The normal way to address these dilemmas, is by means of regulatory risk assessment [212 213 214]. Although often not implemented in full, this prevailing approach invokes the apparent authority of probabilistic analysis [215 216 217] to assert a notionally single 'sound scientific' or 'evidence-based' picture [218 219 220 221]. This task can be approached in many variously complex ways [222 223 224]. But at root, it involves alternative possible positive and negative outcomes being weighted by their respective perceived likelihoods to derive a single overall 'expected value' for the balance of future benefits and harms [225 216].

In conventional innovation policy and regulation then, it is simply assumed that whatever products or technologies are most energetically advanced for assessment of risk, are in some way self-evidently beneficial [226 227]. Questions then typically focus on whether any associated risks will be 'tolerable' [228 229 230]. It is rare for the claimed benefits themselves to be rigorously scrutinised [231], let alone compared in a balanced way with other potential benefits of alternative innovation pathways [232 83]. So, existing forms of risk regulation do little to address the wider issues in innovation politics discussed above.

Further challenges arise in the reliance of risk-based regulation on the methods provided by probability theory [233 234]. Probabilistic tools can be useful in tackling familiar, high-frequency, relatively unchanging challenges, as found (for instance) in risk regulation of many urban transport or public health systems [235 236]. Where empirical evidence arising in past experience is held to be a reliable guide to the future, these tools can be very powerful – as in established responses to familiar safety risks [237]. But where an innovation pathway (or its context) is novel, complex or rapidly changing, uncertainties cannot confidently be reduced to single definite probabilities [238]. Such inabilities to justify a single picture of probabilities can arise, for instance, in the regulation of nanotechnologies [239] (see Box Y), endocrine disrupting chemicals [240], or novel living organisms [241]. Under these conditions, it can be irrational to assert a single definitive 'evidence based' picture [242]. In these fields (as more widely), policy making must often contend with contrasting – but equally reasonable – interpretations of uncertainty [107 91]. These cannot reliably or rationally be reduced to simple single numbers for probabilities.

These are not the only limits to risk assessment. Beyond uncertainty in the above sense [243 244 245], there exists a further array of challenges [246 247]. These involve not the relative likelihoods of different outcomes, but the meanings of the possibilities themselves. For instance, divergent views may exist over how to categorise or partition different kinds of benefit or harm. Or there may be major questions over how to frame the various dimensions under which these are defined [248]. What are the appropriate imaginations, understandings, values, or interests according to which they should be interpreted or prioritised [249]? There may also be differences over which innovation pathways to include or exclude from scrutiny, or how to allocate attention [105].

These are challenges of ambiguity, rather than strict uncertainty [250]. Here, the problem is not so much about uncertainty, as contradictory certainties [251]. And risk assessment is no more able fully to resolve these disagreements over meanings as over likelihoods [252]. Indeed, Nobel Prizes have been awarded in rational choice theory, for axiomatic proofs demonstrating there can be no definitive way to guarantee the calculation of a particular optimum balance between contending ways to interpret, measure or prioritise possible outcomes [253] [254] [255]. Yet such challenges remain not only the norm in many innovation debates, but constitute the key issues in contention in controversies like those over alternative agricultural, energy or health strategies [256]. Under ambiguity, claims to single definitive 'sound scientific' or 'evidence-based' prescriptions are not only seriously misleading, they are an oxymoron [257].

The above difficulties may seem tricky enough. But even more intractable than uncertainty and ambiguity, is the further challenge of ignorance [258] [106] [246] [259]. Here possibilities are not just disagreed about, but at least some are entirely unexpected [247] [260]. This was the case, for instance, in the early regulatory history of bovine spongiform encephalopathy (BSE) [261], endocrine disrupting chemicals [262] and damage by CFCs to stratospheric ozone [263]. Like many other cases [82,83], these involved mechanisms that were not just thought unlikely at the inception of the issue, but were at the time 'unknown unknowns' [264]. Where we don't know what we don't know [265] the prospect is raised of possible 'black swans' [266]. These challenges are not about calculable risk, but inherently unquantifiable surprises [267,268]. Here again, to seek to assign single definite values for 'risk' are not just irrational but dangerous [269].

Of course, surprise is not necessarily always a bad thing. It is intrinsic to the rationale for 'blue skies' science – as well as research and innovation more generally – that positive benefits can also be entirely unexpected [267]. An example might be the laser – a novel laboratory phenomenon that was for a long time a 'tool' without a use [270]. Likewise (albeit involving many variously questionable applications), the internet has also undoubtedly given rise to a host of positive benefits that were initially entirely unexpected [271]. But it is also clear – for instance in areas like nanotechnology (Box Y) [272] – that there is no guarantee that further research will necessarily reduce uncertainty, ambiguity or ignorance [273]. As Einstein famously observed, it is often the case that the more we learn, the more we find we don't know [274]. And, of course, this is not necessarily bad. Indeed, it is a key motivation in science [275]. It is political pressures that resist the humility of acknowledging ignorance [276].

Either way, it is clear that some of the greatest dilemmas in innovation governance extend well beyond risk – they are about surprises. With conventional regulatory risk assessment entirely unable to deal with this deepest form of incertitude, the importance of robust critical deliberation and wider political argument about innovation, is seriously reinforced.

6: Precaution and Diversity

One widely established and intensely debated response to these challenges in innovation policy, is the precautionary principle [277] [278] [279] . Although it comes in many forms [280], a classic general expression of precaution, is that scientific uncertainty is not a reason for inaction in preventing serious damage to human health or the environment [281]. By explicitly hinging on uncertainty rather than risk, precaution helps promote recognition that social choices in innovation are not reducible to ostensibly precise, value-free, technical risk assessments [282]. These dilemmas are instead explicitly recognised to involve wider issues and alternatives requiring overtly value-based – and so 'political' in this sense – deliberations over policy.

This message is inconvenient to many partisan perspectives wishing to dragoon the authority of science as a whole in favour of specific interests [283]. Often driven by such motives, opposition to precaution rests largely on assertions (or assumptions) that established 'science based' regulatory risk assessment offers a sufficient general response to the challenges of social choices across alternative innovation pathways – and a particular way to justify favoured technologies [284] [285]. So, precaution remains a subject of much misunderstanding and mischief [286] [287] [288] [289]. This often involves ironically emotive rhetoric in supposed defence of reason [219]. It is on these grounds, for instance, that arguments are sometimes made that it is somehow irrational not to always use probabilities to qualify potential hazards [290]. In this way, many critics of precaution mistakenly ignore uncertainty, ambiguity and ignorance, insisting instead that these be treated as if they were risk [225]. The precautionary principle has played a crucial role in fostering more rational reflection about these highly political pressures on the use and abuse of science in technology regulation.

Treating general dilemmas of uncertainty, ambiguity and ignorance as a simple state of risk, perpetrates the misunderstandings discussed above – that probabilistic analysis is universally applicable and that innovation is a single-track race. When these misapprehensions are corrected, precaution can be recognised simply as a guide to the more reasonable and realistic steering of social choice among possible innovation pathways [291]. So precaution is not (as often alleged) about being somehow generally 'anti-innovation' or 'anti-science' [292] [293] [219]. Instead, it simply urges greater rational consideration of different aspects of incertitude than can reasonably be reduced merely to risk [83,264,269,294,295].

Consequently, precaution does not automatically mean abandoning any particular innovation, still less innovation in general [296]. Contrary to many claims [297], there is nothing inherent in the precautionary principle that automatically requires bans [298], or makes it partisan in its applicability to innovations of contrasting provenance [299] [300]. Precautionary action inhibiting any one innovation pathway, inevitably favours another [294]. And precaution does not even mean abandoning risk assessment [237,301]. It simply reminds that risk-based approaches do not offer a complete response to deeper challenges of choice.

Precaution is also a guard against the error of treating absence of evidence of harm as evidence of absence of harm [302]. This is often a particular danger for innovations whose novelty means there has been little time for evidence to accumulate, or where incumbent interests discourage research or assessment of the requisite kinds [303]. Before invoking a lack of evidence of harm, it is necessary to think about how visible this evidence might actually be expected to be if it existed – or how vigorously it is sought [304]. Identifying false negatives is often more important than avoiding false positives [82]. In this respect, precaution is a guard against wilful and misleading blinkers favouring incumbent interests and the inertia of the status quo [305].

In essence, precaution simply highlights that innovation policy and associated politics should pay more careful attention to the intrinsically problematic nature of knowledge – and its vulnerability to economic and political pressures. But it does not just highlight problems. The precautionary principle also opens the door to solutions – pointing to a range of rigorous and practical strategies and practices for dealing with the realities of uncertainty, ambiguity and ignorance in innovation [83 269 282 306 307 308 309 310 311]. These 'Cinderella methods' can be neglected, where there persist preoccupations solely with deterministic notions of 'risk', 'exposure' and 'vulnerability' (rather than 'uncertainty','ambiguity' and 'ignorance') – and a consequent sense that risk assessment alone is sufficient [269]. Practical examples include a range of different tools for 'opening up' regulatory appraisal [312], research strategies [313] and innovation policy [314], as well as more general prioritising of qualities like reversibility [315], resilience [316] and flexibility [317].

Rather than resting hubristically on an ostensibly definitive picture in the balancing of benefits and harms, these precautionary strategies acknowledge stronger grounds for greater humility [276]. Instead of wishful thinking about the quality of risk information, they prioritise more humble measures to consider alternatives, explore uncertainties, maximise learning [246] and promote adaptability [318] in careful, reversible, step-by-step implementation [319]. Where there is uncertainty over probabilities, potential hazards do remain relevant in their own right – with particular care necessary where they might be irreversible [298]. And the dilemmas are accentuated where associated infrastructures might also prove to be especially inflexible [299]. All else being equal, where a range of innovation pathways look as if they present similar balances of pros and cons, precaution simply highlights that it is reasonable to prioritise that which is more reversible over the less flexible alternatives [320].

At root, a key value of precaution lies in helping to free policy debates from the Panglossian fallacy that the most powerfully favoured innovation pathways are somehow necessarily the best or only option [321]. It reminds that particular values (other than profit), also need to be prioritised – especially around human health and environmental integrity [322]. This enables societies to discuss rationally and directly when it is right for governance deliberately to discourage or discontinue a particular entrenched trajectory [323]. The crucial point is, that precaution makes this possible without incurring existential anxieties over innovation in general. As a general principle, it offers a practical and flexible means to avoid simply relying on optimistic hopes that powerful vested interests will automatically be spontaneously relinquished or themselves become entirely benign.

And in this, precaution points to a further quality in research and innovation systems, namely diversity. Even though it is not a panacea, nor a 'free lunch' [324], nor self-evident in its composition, diversity is a vital consideration in research and innovation policy [77]. Like other strategies, it brings its own challenges and remains intrinsically a matter for political judgement. But in any given area, recognition of the importance of diversity encourages caution about concentrating resources in support of the particular innovations that happen to be favoured by the most powerful interests [325]. Diversity urges instead greater attention to alternatives, leading to more deliberately and systematically-constituted portfolios comprised of some balanced variety of disparate innovation pathways [77].

In these terms, diversity offers a remarkably practical way to help address several otherwise intractable innovation problems. It offers a 'resource pool' [326] helping to nurture creativity [68], mitigate lock-in [124], hedge against surprise [327], accommodate ambiguity [328], resolve irreconcilable interests [329], promote learning [246] and cultivate resilience [330]. And by fostering more intensive encounters between varying kinds of knowledge and practice, deliberate diversification can also help enhance innovation processes themselves [331] – and make them more effective and socially robust [332]. It is remarkable to find so many otherwise intractable challenges addressed (albeit always provisionally and incompletely) by a single operational strategy. And there exist plenty of useful tools to help focus more concretely at the level of diverse innovation portfolios, rather than individual programmes [333 334 335].

Consequently, deliberate diversification is one key pragmatic way to enable greater precaution, while also helping to diffuse unhelpful polarisation in debates over innovation [336]. This is aided by more explicit and measured pursuit of repertoires of innovations in particular areas, rather than single privileged supposedly 'sound scientific', 'evidence based', 'solutions'. Moreover, a focus on diversity may also help develop greater political tolerance, for the otherwise difficult – but inevitable – kinds of failure that are so essential to effective learning [337]. If commitments lie at the level of diverse portfolios rather than single supposedly 'no alternative' solutions, then it becomes easier to accept and justify the kinds of failures that contribute so much to learning.

To help realise these concrete benefits, however, diversity must move away from being a fig leaf or argument-of-last-resort for some otherwise ill-favoured but powerfully-backed choice [338]. It is all too easy to support otherwise indefensible proposals, simply on the grounds that "we must do everything" [339]. This invites powerful interests to insist on adoption of their own preferred policy, simply on grounds that every option must be pursued [340]. There are typically many kinds of diversity, each exclusive in some ways and inclusive in others [325] [341]. So, as with individual innovation pathways, the detailed constituting of diversity also involves inherently political judgements. By urging this greater attention to diversity (as in other ways), precaution can be as much a spur to innovation in general, as a brake on any specific kind.

7: Three Key Conclusions

Formulating a adequate response to the challenges discussed in this paper requires being clear about the resulting practical implications for policy. Here, there have been many recent interventions developing concrete recommendations for research and innovation practices and the wider policy procedures and political debates in which these are set. The European Science Foundation reviewed key background in research and innovation systems across Europe [342]. The Expert Group on Science and Governance put this in the context of the European 'Knowledge Society' [295]. The Nuffield Council on Bioethics recommended new institutional ways more effectively to govern emerging technologies [58]. The EPSRC identified a number of responsibilities to be encouraged across all actors in innovation systems [343]. An ESRC-funded 'new manifesto' explores some of the global implications [344]. And many other international initiatives contribute much further detail [345] [346,347]. But the general practical upshot is quite readily summarised in terms of three overarching principles: ***participation***, ***responsibility*** and ***precaution*** [305].

First, there is ***public participation in innovation***. Here, innovation strategies should more explicitly and transparently acknowledge the inherently partly political (rather than restrictively technical) nature of the interests and motivations driving contending pathways. This requires many forms of sincere, well-resourced, participatory deliberation – especially including the most marginalised interests [348]. This is not about fostering credibility, trust or acceptance, but about informing policy and helping substantively to determine the priority directions for research and innovation themselves [349]. Nor is participation about 'political correctness' or relativism about science (implying a position that 'anything goes' [350]). Indeed, it offers the most effective way to draw on wider knowledges in order to illuminate how dominant narrow understandings are often untenable. In essence, public participation in innovation is simply about more rigorous exploration of specific ways in which legitimate judgements about 'benefits', 'excellence', 'relevance', 'risk', 'evidence' and 'impact' all depend in part (but irreducibly), on contexts, values and assumptions.

In other words, public participation addresses the fact that what counts as a positive direction for research and innovation in any given area is inherently 'plural and conditional' [134]. 'Plural', because a number of contrasting pathways are typically equally valid [351]. 'Conditional', because this validity depends partly on perspectives and circumstances. A rich variety of carefully-developed inclusive, participatory and deliberative practices are available to address this challenge, with varying kinds of value in different circumstances [352] [353] [354] [355] [356] [357] [358] [359]. And crucially, participation does not just mean talking about innovation, but also inclusion in the means for supporting the actual doing of innovation itself [7] [84] [199] [345] [360] [361]. Here, there are key roles for the creative arts, humanities and local communities as well as workers and civil society more generally. Some approaches are more formally structured than others – involving 'uninvited' as well as 'invited' participation [362]. Together, these help 'open up' deeper and wider explorations of practical alternatives [314]. In this way, diverse styles of public participation supplement, enrich and inform (rather than substitute), the conventional procedures of representative democracy [363]. And freed from pressures to pretend at (potentially enormously expensive and protracted) ostensibly singular definitive 'evidence based' status, unfolding processes of innovation can become not only more democratically accountable and legitimate, but also more efficient and timely.

Alongside (and mutually reinforcing) greater participation, there is a second major policy imperative. This is for ***all actors involved in research and innovation processes*** – especially the most powerful – to assume more direct and explicit ***responsibility*** for the consequences and uncertainties of their activities. This in turn requires serious efforts on the part of innovators to be reflective in anticipating, analysing and addressing the impacts that might arise, as well as their attendant ambiguities and unknowns. It helps avoid the "organised irresponsibility" of otherwise 'passing the buck' to insurers, regulators, victims, the state, or 'society' at large to deal with inevitable unintended and indirect outcomes [364]. And (assisted by participation) responsibility involves being more openly accountable for motivating aims and interests. So, responsibility is not about aspiring – let alone claiming – to predict or control consequences [365]. Nor is it abut simple exhortations to trust [366]. Instead, responsibility is about trustworthiness [367]. It means going beyond conventional narrow institutional and economic interests, to care – and be accountable – for wider social and environmental concerns and implications.

A crucial aim of responsibility is that scientists, engineers, businesses, regulators – and government itself – move away from fixations merely with 'risk' around whatever are the particular privileged pathways for innovation in given fields. Instead, responsibility on the part of these influential actors, helps inform and open the necessary space for participation by others: by illuminating contending motives and a range of alternative directions for progress. Nor is there anything about this, that necessarily impedes decision making on innovation – or makes it more protracted or burdensome. Indeed, by helping to avert ill-advised trajectories at an early stage, participation and responsibility can assist innovation to become more effective in addressing diverse social values of a kind that might otherwise invite a costly backlash [62]. But there do arise here, particular responsibilities for the media. The discussion in this paper has shown that it is quite simply irresponsible to pretend (as is too often the case [368]) that science and technology are free of interests, values or alternatives [369] [370]. What is required instead, is less simplistic and romantic portrayals of technical expertise [371]. The media hold especially important responsibilities for enabling more realistic, mature and open debates about the inherently contestible and power-laden nature of both scientific knowledge and technological innovation [372].

This leads to the third and final general policy implication. This is, that greater and more deliberate efforts are needed to moderate the powerful forces of closure and lock-in in science and technology. It is here that this paper has shown the particular value of ***precaution in regulation***. Rather than treating existing patterns of research and innovation as value-free, the precautionary principle strikes an explicitly stronger balance in favour of human health, environmental integrity and social well-being in the steering of priority directions. Thus guided (but not determined) by precaution, participation and responsibility can explore and elucidate more clearly what might be meant by these values in any given context. So together, these complementary principles and practices help provide a selection and balancing process, to harness incumbent and energetic private interests. In particular, precaution directly addresses the tendencies for uncertainties, ambiguities and ignorance to be closed down in the most convenient directions, as if they were just 'risk'.

When innovation is recognised as a branching rather than single-track process, it becomes clear that precaution is also not about impeding innovation, but steering it in ways that better favour human health and the environment. Acknowledging the scope for systematic deliberation over values, priorities and alternatives under uncertainty, precaution broadens out risk regulation to allow greater space for responsibility and participation – and greater consideration for a wider plurality of issues, options, perspectives and scenarios. This can help enable entrepreneurs, small business, new entrants, civil society groups and marginalised communities (as well as government) to better challenge established trajectories. As we have seen, precaution also implies a greater focus on qualities of diversity, flexibility and responsiveness in technology strategies. And a final key lesson of precaution is that regulation and innovation policy should seek to respect and embrace (rather than manage or curtail) public mobilisation and critical dissent. In essence, precaution expresses the fundamental principle that – in innovation just as in science itself – reasoned scepticism fosters greater quality.

In concluding this paper, then, we can return to a point made at the beginning. In any given area, innovation is not so much about a race to optimise a single pathway, as a collaborative process for exploring diverse alternatives. Current noisy anxieties over 'falling behind' in single-track 'zero sum' competitive innovation 'races' are misleading and counterproductive. They can conceal underlying motives, interests and alternatives – and supress the associated politics. Instead, inter-related practices of ***responsibility*** among researchers and innovators, ***precaution*** in regulatory processes and ***participation*** in policy making and innovation itself, can help innovation escape from these restrictive fear-driven technical imperatives. They illuminate instead how innovation is fundamentally about the politics of contending hopes [39]. Most importantly of all, it is in these ways that narrow technocratic ideas of a knowledge economy [295], can give way to the nurturing of a more inclusive, rational and vibrant ***innovation democracy***.

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