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Using futures analysis to develop resilient climate change mitigation strategies

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Headlines

- Current strategies for climate change mitigation – reducing greenhouse gas emissions to stem climate change – need to be as resilient as possible to future developments. Otherwise they might have to be fundamentally re-thought or abandoned for more drastic, ill thought-out or damaging courses of action.
- Communities producing mitigation analysis should consider a far greater range of political, economic, technological, social and environmental possibilities than they currently do, to secure this resilience.
- Futures analysis methods such as qualitative scenarios, expert judgements, simulation and agent-based models, and even science fiction narratives should be used more frequently to complement the modelling approaches most commonly used.
- Robust decision making and other scenario discovery approaches can be used to identify those mitigation strategies most resilient to the many plausible outcomes produced by our expanded methods and imaginations.
- Policy makers should be aware of, and prepare for, the full range of potential challenges that will face their mitigation strategies in the coming years as a result of future developments.

Contents

Grantham Briefings analyse climate change and environmental research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other publications are available from **www.imperial.ac.uk/grantham/publications**

Introduction

Climate change is one of the greatest challenges we face this century, which is why so much effort has been invested in analysis of low-carbon pathways. Yet several other threats and potential disruptors are now emerging that could profoundly affect the long-term mitigation plans of policy makers, businesses and other stakeholders. It is critical that analysts producing mitigation pathways consider a wide range of factors so that they can effectively support the development of mitigation plans that are as resilient as possible to these factors.

A variety of key technological developments are not yet routinely considered in mitigation pathways. These include rapidly emerging digital technologies such as artificial intelligence, cryptocurrencies and blockchain and the recent re-emergence of space exploration, all of which could create significant new demands for energy. On the other hand, nuclear fusion could help meet this demand in a low-carbon way, should it become technically and then economically viable in the coming decades. And some emerging technologies may help reduce energy demand, including new materials to enhance building energy efficiency; 3D printing to reduce the material and energy intensity of manufacturing and construction; and smart, autonomous technologies to help integrate variable-output low-carbon renewables like solar and wind power into our energy systems.

Beyond technological innovations, social, behavioural, economic and political changes could have just as great an impact. Positive examples include changes to lifestyles such as the rise of vegetarianism and veganism, home-working, a sharing economy in which potentially fewer assets are more intensively utilised, as well as community and distributed energy models that do not have to rely on centralised energy supply and large energy infrastructures. Negative examples could include rampant increases in consumerism, driven by ever-cheaper manufacturing of material-intensive products, and an ever-increasing range of products and services. Finally, a changing environment could itself lead to disruptions affecting our economy, energy and land systems, and society as a whole. Table 1 summarises some recent developments and their implications, including for mitigation planning.

Table 1: Recent developments with wide-ranging repercussions, including on mitigation efforts

Disruption type	Examples	Implications
Economic	Global financial crisis and Great Recession of 2008-9	Change in the global financial system towards lower rates of leverage, leading to a ‘credit crunch’. Significant reduction in global economic growth. Rise of austerity and fiscal consolidation, with lower state spending (as a portion of total GDP) on welfare and other public goods.
Political	Rise of neo-nationalism	Election of right-of-centre (in some countries far right) parties, with a shrinking back of the welfare state, as well as threats to free trade agreements.
	Russia annexation of Crimea	Challenge to NATO’s authority
Social	Reaction to globalisation and increasing discontent with immigration	Decision of the UK to leave the European Union (Brexit)
	Arab Spring	Unseating of a number of Arab dictators; war in Syria
	Climate protests	Increased pressure on governments to enact ambitious climate targets and policies
Technological	Rapid improvement in cost of renewable energy technologies like wind and solar photovoltaics	Cost-effective substitution of renewables for fossil-fuelled power generation (especially coal) plants
	Advent of cost-competitive battery storage and electric vehicles	Strategic shift towards electric vehicle production by world’s major car manufacturers
	Increasing use of artificial intelligence	Advent of autonomous vehicles, targeted advertising, influencing on social media
Environmental	Increasing attention to frequency of extreme events, including wildfires, heat waves, flooding and droughts	Pressure to tackle climate change more rapidly, a major driver for the passing of the Paris Agreement.

Sources: authors, informed by Gowing and Langdon (2018)[1], Gambhir (2019)[2], Falkner (2016)[3], Carbon Tracker and Grantham Institute (2017)[4] and Zoega (2016)[5].

The international communities involved in developing mitigation pathways analysis have made great efforts to incorporate a wide range of possible future socio-economic, political and technological developments into mitigation scenarios, notably through the process of developing the Shared Socio-economic Pathways (SSPs) framework. But such scenarios still do not fully explore the broadest possible range of plausible developments, such as large-scale international conflict, regional or global pandemics, or environmental breakdown, at least to the extent that these could have a radical and lasting long-term impact on socio-economic development patterns.

Some of these disruptions could plausibly occur in the next few decades (or even next few years, given the rate of disruption we are now experiencing in several social, political and technological spheres) and they could affect society's ability to reach stretching mitigation goals, which already sit on a knife-edge thanks to decades of inadequate action to tackle climate change.

It is now important that those who are developing mitigation pathways analysis actively consider the consequences of employing a wide range of techniques to scan the horizon for possible changes and disruptions that might have long-term impacts on achieving low-carbon pathways. Only by doing so can mitigation strategies and decisions made today be resilient to these disruptions, both at a regional and global scale, and climate change mitigation pursued confidently and achieved effectively.

This paper explores how these communities can go about envisaging a wide range of future possibilities and their implications, in order to accomplish the challenging task of helping decision makers plan mitigation strategies in the context of uncertainties. It is structured according to the following sections:

- **The first section** describes how the integrated assessment modelling community analyses the future of mitigation, and the strengths and weaknesses of this analytical approach.
- **The second section** discusses how futures analysis has historically been undertaken in a range of disciplines, as well as different attempts to categorise techniques and toolkits.
- **We then consider** why we tend not to envisage the broadest range of possibilities about the future, before considering the different methods that should help to expand our vision.
- **Next we outline** what types of outputs could arise from using a broad range of different techniques to plan mitigation strategies, before discussing different methods that can help manage a large number of future mitigation pathways to identify favourable or robust mitigation strategies.
- **The paper finishes with** recommendations to help mitigation analysts draw on a wide range of methods to develop future scenarios that capture a broader range of possibilities, in order to inform the development of robust mitigation pathways.

How is mitigation analysis currently undertaken?

Integrated Assessment Models and Shared Socio-economic Pathways

The dominant community that leads global mitigation analysis is the integrated assessment modelling consortium (IAMC). This group of researchers self-organised into a community in 2007 to undertake coordinated analysis of mitigation-related questions[6].

The use of integrated assessment models (IAMs) has been a critical element of mitigation analysis for around a quarter of a century, stemming from the second report of the Intergovernmental Panel on Climate Change (IPCC)[7], where IAMs formed the underpinning analysis of mitigation trajectories of the IPCC's report on mitigation solutions[8]. IAMs represent the world's energy, agricultural and land systems over time periods spanning from the present to (most commonly) the end of the 21st century and in some cases beyond. They link emissions from these systems to atmospheric and/or surface temperature change levels, including information on the costs of operating these systems using different technologies and fuels. This representation allows the models to determine the least costly pathways (in terms of technologies and fuels used) of limiting global temperature changes to pre-determined levels.

IAMs do not produce socio-economic scenarios of the future themselves. Rather, they calculate the mix of energy technologies and fuels, as well as agricultural and land-based measures, which together deliver specified climate outcomes for a given set of socio-economic inputs. These include population and economic growth, and how the demand for energy, agricultural and land services increase with these underlying socio-economic drivers.

There have been many different exercises to develop scenarios for the IPCC assessment reports[6], including the 'SA90' and 'IS92' generations for the first and second reports respectively and the storylines used in the third and fourth reports, as detailed in the Special Report on Emissions Scenarios (SRES)[9]. For the IPCC's fifth assessment report, the IAMC group of modellers began a new scenario development exercise, based on three major elements[10,11,12,13]:

1. The **Representative Concentration Pathways (RCPs),** each reaching a different climate radiative forcing level by the 21st century. For example, RCP 2.6 is a scenario with a forcing of 2.6 Watts per m^2 in 2100, deemed consistent with a below 2°C limit to global warming.

2. The **Shared Socio-economic Pathways (SSPs),** a set of five narratives on how the world and different regions within it could develop over the 21st century, describing population growth, economic growth, technological and political developments, and how these could translate into demand for energy and other greenhouse gas-emitting resources and goods.

3. The **Shared Policy Assumptions (SPAs),** a set of assumptions on which policies can be implemented in different regions, and at what time, in order to achieve a specified climate forcing with a specified set of socio-economic assumptions.

The RCP-SSP-SPA framework (hereafter the SSP framework) represents a degree of formalisation and standardisation of many of the key input elements required for mitigation modelling. This framework allows greater comparability between different modelling groups' analysis of different mitigation scenarios. This has also enabled a better understanding of how climate change mitigation futures can differ according to assumptions about socio-economic drivers, how different IAM teams interpret the same socio-economic climate change mitigation future in different ways and, importantly, under which socio-economic assumptions the IAMs can and cannot find solutions to meeting different mitigation targets. This is illustrated in figure 1, which shows how successful six IAMs have been in modelling feasible mitigation pathways to achieve six different radiative forcing targets, under the five different SSPs.

Responses to the IAMC and SSP approach

IAMs have attracted a range of criticisms in recent years, including around: a perceived lack of transparency in model assumptions and workings; the difficulty in forecasting key input assumptions, such as technology costs beyond just a few years; and over-reliance on certain technologies to meet stringent mitigation targets, notably negative emissions technologies such as bio-energy with carbon capture and storage (BECCS)[8,15]. In addition, the models cannot themselves predict disruptions in political, economic, societal, technological and environmental factors[2]. Nevertheless, it has been asserted that, as a result of policy makers' requirement for quantification of mitigation variables, such as low-carbon technology shares and mitigation costs, there will continue to be a requirement for such IAMs. So rather than scrap them, as some have suggested, they should be supplemented with a range of other futures analysis methods[2,8].

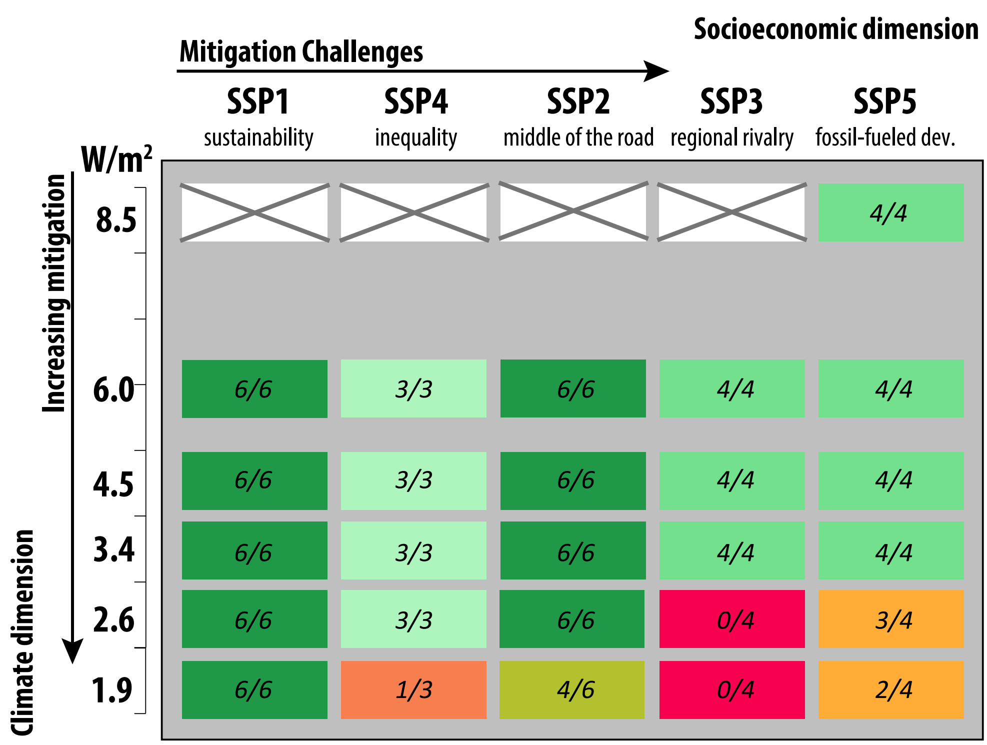

Figure 1: Overview of scenarios created with the SSP framework. Five standardised socioeconomic futures of the SSPs are shown in columns, with different standardised levels of climate change mitigation stringency (indicated by the 2100 radiative forcing level in W/m^2) are shown in rows from top to bottom. Values in each box represent the number of available scenarios over the number of IAMs that attempted to create a run under the combined SSP and climate change stringency specification. Note that under some combinations no scenarios were created despite being attempted – also communicating important information. Figure reproduced (with permission) from Rogelj et al. (2018)[14].

Regarding the SSP framework, whilst the standardisation of scenarios helps avoid duplication of effort and provides a consistent framework for undertaking foresight exercises, it has been noted that standardisation can prevent rapid updating of assumptions, to prevent them becoming out of date:

> *"Scenario planning is generally a continuous process, whereas scenarios are usually generated in one-time exercises. At present in the environmental sciences, for example, there are a plethora of scenarios developed in individual studies or by individual projects in the period 2005–2015, with time frames to 2030 or 2050, whose premise has subsequently become outdated because of events such as Brexit." (Wiebe et al., 2018, Section 3.3.5[16])*

It has also been noted that scenarios such as the SRES storylines that preceded the SSPs are not "maximally diverse", meaning that they minimise their overlap with regard to future possibilities[17]. The SSPs were not intended to be maximally diverse, with each SSP representing a storyline within a domain of mitigation-adaptation challenges, rather than an extreme case for either goal[12]. Whilst this is understandable, it does mean that such standardised scenarios may miss important developments that a wider span of the future possibility space would include.

In fact the IPCC's Special Report on 1.5°C[18], which used four illustrative pathways to set out different ways of meeting the temperature goal, did not rely solely on mitigation pathways using the SSPs. It also included a pathway based on a very low energy demand case[19], specifically designed to minimise the reliance on (as yet untested at scale) negative emissions technologies.

Finally, it has been cautioned that scenarios based on detailed storylines are more likely to lead to systematic overconfidence rather than expanding our judgement around the range of uncertainty[20]. Particular instances of such overconfidence include attaching a low likelihood to categories or events not explicitly stated in the storylines[21] as well as the risk of "conjunction fallacy" – that detailed storylines may make combinations of unrelated events occurring together (as part of the same story) seem more probable than the individual events occurring alone, which violates probability laws[22]. One modelling exercise has avoided over-reliance on single SSP storylines, instead combining different elements from different SSPs to explore a wider possibility space[23], but even this is limited to considering only those developments encompassed within the span of the different SSPs.

In summary, there continues to be a requirement to look beyond the existing set of socio-economic scenarios and integrated assessment modelled mitigation pathways based on those scenarios, in order to understand the broadest possible share of the future possibility space. Supplementing IAMs and the SSP framework is possible given the wide range of futures analysis methods that have long been in existence and used by various futures practitioners for several decades, as explained in the next section.

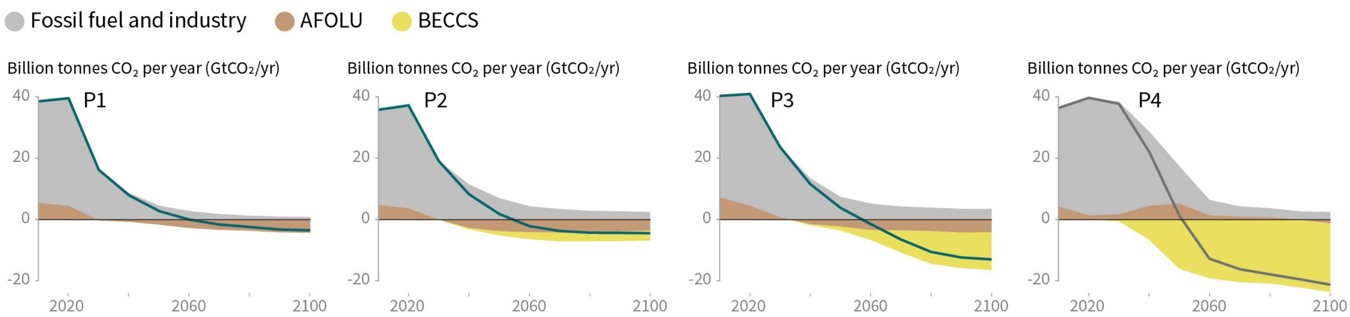

Figure 2: Four Paris-compliant illustrative CO2 emissions reduction scenarios detailing different contributions from fossil fuel and industry, agriculture, forestry and land use (AFOLU) and bioenergy with carbon capture and storage (BECCS). Whilst P2-4 are based on underlying scenarios within the SSP framework, P1 uses a different underlying scenario, where energy efficient technologies and energy-saving societal behaviours occur to such a degree that there is no requirement for BECCS. Reproduced from the IPCC (2018)[18].

What other futures analysis methods can we use for low-carbon pathways analysis?

Futures Analysis

A large number of terms have been used to describe the broad field that deals with the study of the future, including 'futures studies', 'futurology', 'futuristics', 'futurism' and 'foresight'[24]. In this paper we simply keep to the literal term futures analysis. A variety of futures analysis methods have been developed and applied over past decades, including scenarios and modelling tools such as those used by the IAMC, as already discussed. Three major periods of modern futures studies in the West have been identified as follows:[25]

1. **The period following World War II, from 1945 to the 1960s** when those engaged in futures thinking began to use approaches such as scenario planning, statistical trend extrapolation, game theoretic analysis and expert views. In this period, futures thinking was targeted towards developing new technologies and political systems to support rapid post-War economic growth and modernisation, as well as strategic thinking around Cold War, nuclear and other security threats. This period saw the establishment of a number of futures-focused institutions, including the Futuribles Internationales in 1960, the Mankind 2000 Project in 1965, the World Future Society in 1966 and the Club of Rome in 1968.

2. **The period spanning the 1970s and 1980s**, which saw futures studies become more global in its outlook, driven in large part by the publication of the Club of Rome's *Limits to Growth* in 1972. This warned of the possibility of unchecked population and economic growth leading to natural resource scarcity, environmental degradation, malnutrition and economic collapse. However, this neo-Malthusian vision was countered by the belief that human ingenuity and technological capability would deliver a more prosperous future. The computer modelling used in the *Limits to Growth* helped establish this method as a central tool in futures analysis. This period also saw the involvement of businesses in futures studies, notably Royal Dutch Shell, whose scenarios method in 1972 foresaw the possibility of an oil crisis. When it came to pass the following year this allowed the well-prepared company to become a major global oil player.

3. **The period starting in the 1990s to the present time**, which has seen the dominance of neo-liberalism in future visions, stimulated by the end of the Cold War. These visions grant a central role to individual entrepreneurs in a framework of free markets. This period has also seen the dominance of futures analysis methods emphasising science, technology and innovation. At the same time, there has been a fragmentation in futures analysis methods, resulting in large part from the increasing uncertainty in the world, as well as the growing specialisation in all disciplines.

It is arguable that the third of these periods has now come to an end, giving way to a period in which the dominance of neo-liberalism is on the wane. These more modern periods developed from a much longer history of futures analysis, encompassing five broad waves, stemming from an oral tradition in ancient times, through to the modern age of complexity and emergence[26]. Figure 3 shows a history of futures thought spanning the 14th to 21st centuries.

The history of futures analysis as set out above provides some insights into the different methods that have been used to date. There are many ways of categorising these different methods, with one taxonomy[27] placing 33 different methods of futures analysis into three groups:

- **Qualitative methods**, which apply subjectivity and creativity to understand future possibilities, using techniques such as brainstorming, workshops, surveys, expert panels and even science fiction analogies;
- **Quantitative methods**, which use analytical techniques such as trend extrapolations, time series analyses and modelling;
- **Semi-quantitative methods**, which apply mathematical methods to quantify the views of experts and commentators.

Several other taxonomies have been identified[28], including many which re-state the distinction between quantitative and qualitative methods. Many such methods appear in futures methodological toolkits such as those of long-time futures practitioner Wendy Shultz. In describing her substantial work with the UK government on horizon scanning[29], Shultz lists arrays of methods to help identify change, assess its potential impact, imagine alternative futures and envision preferred outcomes, before planning and implementing changes aimed at achieving those outcomes. The UK Government Office for Science (GO-Science) *Futures Toolkit*,[30] in much the same vein, lists different methods to achieve these aims:

1. **Gathering intelligence** about the future, through for example horizon scanning, interviews with stakeholders and exercises to gather opinions from experts;

2. **Exploring the dynamics of change**, through identifying drivers of change and critical uncertainties;

3. **Describing what the future might look like**, through for example developing scenarios, stories and narratives, including SWOT analyses for different strategies;

4. **Testing policies and strategies** against ranges of future scenarios, as well as using back-casting to understand how a future state might be reached from the current one.

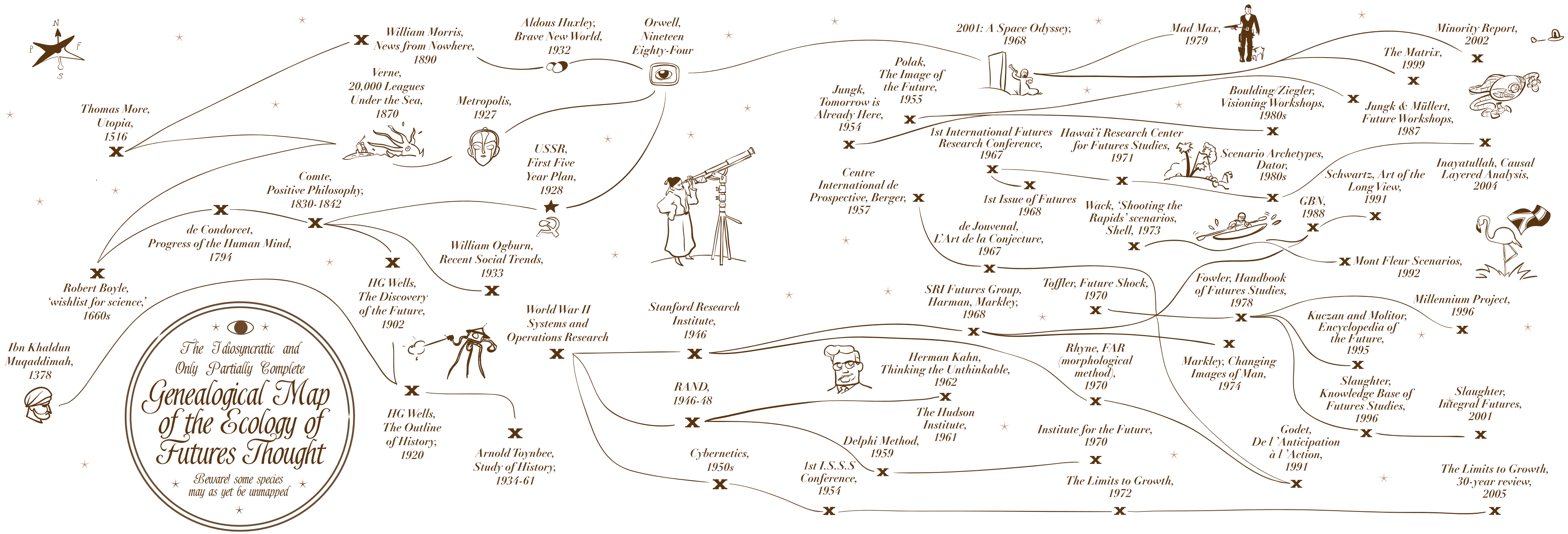

Figure 3: A detailed and playful exploration of the history of 'Futures Thought' as appears in Schultz (2015)[26], reproduced with permission from the Association of Professional Futurists (APF), also with credit to the map's designer, Jason Forrest.

Central to all futures toolkits are scenarios, which have been described as the "archetypal" product of futures studies[31], with several different techniques available to formulate them, using judgement and quantification. Scenarios themselves have been categorised using a variety of taxonomies[16,32], depending on whether they are predictive, explorative, normative, speculative or projections.

There is no settled classification of futures analysis methods, a fact deemed to be the greatest weakness in the field[28]. But, given this multitude of tools and processes to imagine and chart a course towards different futures, it is arguably something of a curiosity that systems modelling, based primarily on optimisation-based IAMs to find "least-cost" pathways, has such dominance in the discourse around mitigation analysis, certainly at a global level as framed in IPCC reports. On reflection it is perhaps not so surprising, given policy makers' need to have quantifications of pathways, in terms of technology mixes, fuel demands, emissions and mitigation costs. But to rely solely on such models, without drawing on the richer toolkit of futures analysis methods introduced in this section, would be to forego the opportunity to explore a wider set of future possibilities.

Welcome to the world of (un)known (un)knowns

Many of the methods outlined above are designed to help us think outside the box. This means making ourselves better at engaging with different categories of unknowns. One of the most highly-quoted taxonomies of our lack of knowledge about the future comes from Donald Rumsfeld, who in 2002 (when Secretary of Defence in George W Bush's Government) described the US Government's level of intelligence about possible links between the Iraq regime and the supply of weapons of mass destruction to terrorists, as follows:

> *"Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones."*[33]

Several others have discussed the presence and attributes of unknowns. Notably, Nassim Nicholas Taleb's 2007 book *The black swan: the impact of the highly improbable*[34] describes the eponymous swan as an outlier event compared to regular expectations, which has an extreme impact. It has become synonymous with the concept of an unknown unknown. Gowing and Langdon's 2018 *Thinking the unthinkable*[1] contrasts black swans with black elephants – *known* unknowns which for various reasons are ignored. One key reason is their unpalatable nature and our inability or unwillingness to deal with them – they are the elephant in the room. Figure 4 sets out this epistemic taxonomy pictorially.

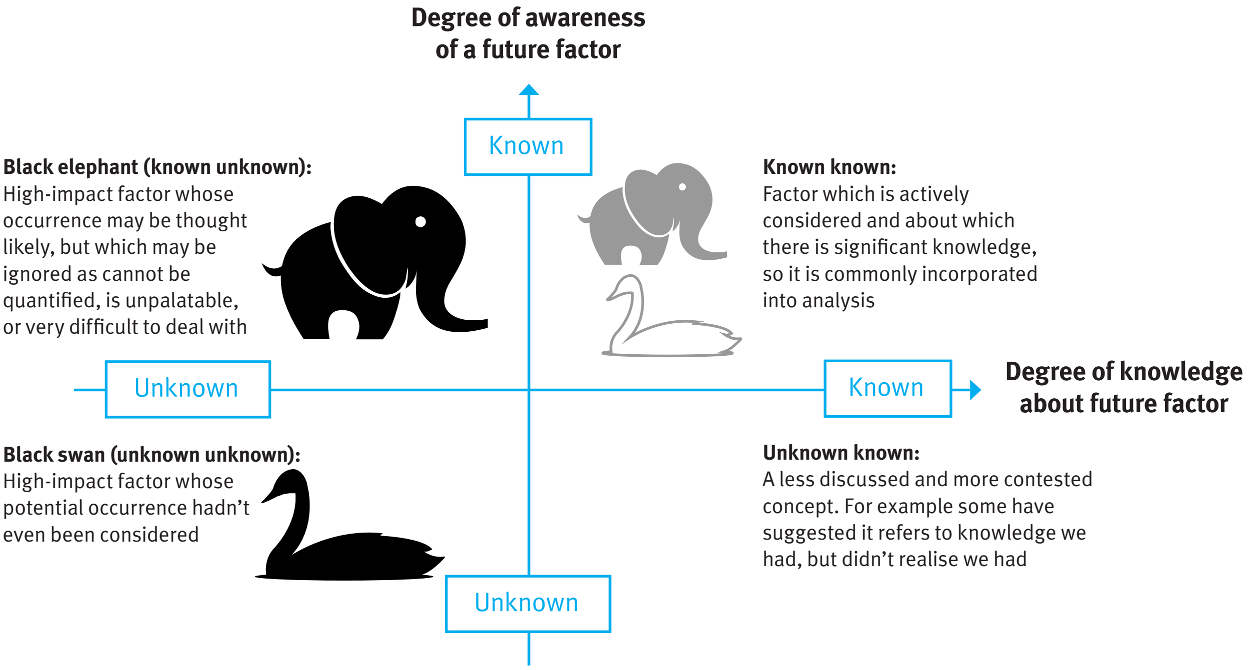

Figure 4: Known knowns, known unknowns and unknown unknowns, as envisaged by the authors, building on Gowing and Langdon (2018)[1], Rumsfeld (2002)[32] and Taleb (2007)[33].

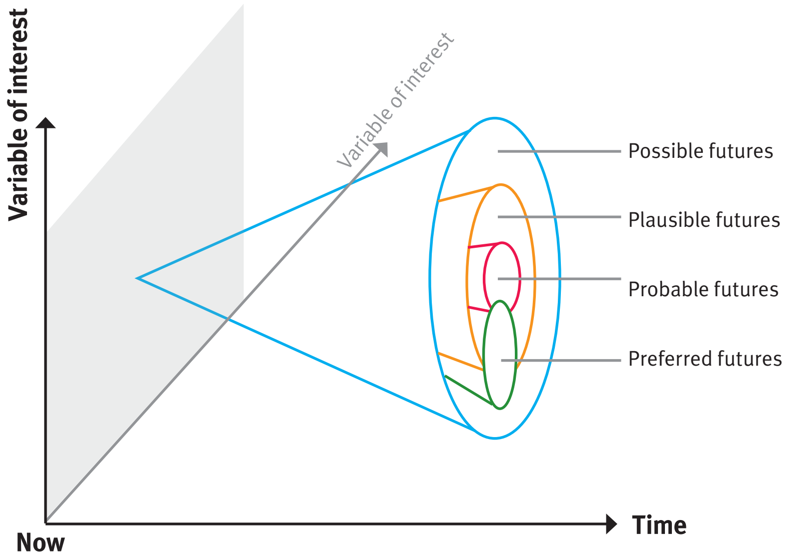

Figure 5: The Futures Cone of increasing uncertainty around variables of interest over time, by the authors, based on van Dorsser *et al.* (2018)[35], Hancock and Bezold (1994)[36] and Voros (2003)[37].

There is a range of both **levels** as well as **types** of uncertainty around different unknowns:

- **Levels of uncertainty** reflect the lack of knowledge stemming from uncertainty, often relating to how far away different developments might be, or how rapid or unprecedented are the changes occurring in systems of interest;
- **Types of uncertainty** are those uncertainties which can be inherent in analytical processes, such as scenario development and modelling of mitigation pathways under different scenarios, including uncertainties around key parameters (e.g. population or economic growth) that influence such analysis.

Different uncertainties can relate to different timescales of analysis, and different types of futures analysis may be appropriate in light of uncertainties across these timescales. For example, it may only be sensible to make projections based on deterministic forecasting over relatively short periods (perhaps one to two years into the future), with probabilistic or stochastic forecasting being suitable for slightly longer timespans. When it comes to thinking about periods greater than a few years into the future, it may be inappropriate to use models, and better to use more speculative, judgement-based methods. Indeed, it has been asserted that use of models should be "parsimonious", reflecting that as we move further into the future, our level of uncertainty increases[20]. The notion of increasing uncertainty as we move further into the future is most strikingly illustrated in the *Futures Cone* as shown in figure 5, where possibilities expand over time, well beyond what may be considered probable or preferred futures.

In imagining a broader set of possibilities about the future, we are in effect attempting to address uncertainty by reducing the number of unknown unknowns, first making them known unknowns, and where possible known knowns. However, there are a number of factors which limit our ability to consider such a broad range of future possibilities.

One such factor is groupthink, stemming from members of even highly intelligent groups of people failing to challenge each other (or indeed themselves) in order to avoid conflict and adhere to group norms[38]. This leads to a lack of critical discussion of group decisions, conformity of group members and/or silence from those who disagree. This offers the illusion that a decision is unanimous, and a sense that any dissent would weaken prior decisions, rather than strengthen them through challenging and changing them[38]. Further limiting factors include the inability or choice not to contemplate unpalatable scenarios which may require drastic courses of action, as well as risk aversion and cognitive overload[1].

Evidence from neuroscientific studies suggests we are poor at imagining future developments which are deeply different to past trends. This is because there is a significant overlap between those brain regions used for memory and those used for imagining the future and we draw from past experiences when imagining hypothetical events and situations[39]. As such, memory, imagination and prediction do not appear to be distinct cognitive functions, but rather intimately linked[40].

Many of the aforementioned limitations have been placed in the ever-expanding group of recognised cognitive biases. This concept was first popularised in 1974 by Tversky and Kahneman[41], who identified three such biases: basing our estimates and predictions on available data, anchoring our further adjustments to initial estimates and being overconfident in our estimated ranges. Nearly two hundred biases are now recognised[42], including many related to factors alluded to above (in-group bias, status quo bias, hindsight bias) as well as many others which clearly have the potential to prevent individuals or groups as a whole from thinking far outside the box (optimism bias, pessimism bias, zero-risk bias).

As Tversky and Kahneman note[41]: *"A better understanding of these heuristics and of the biases to which they lead could improve judgements and decisions in situations of uncertainty."* There are specific ways in which many of these biases may be addressed, through for example actively challenging initial perceptions, making available a wide array of information, and constantly questioning the degree to which opinions may have inherent biases[43,44].

Nevertheless, the sheer level of complexity and interconnectedness amongst the different economic, social, political, technological and environmental factors driving disruptive change means that there is a widening gap between this complexity and our cognitive capabilities to cope with it. This increases the potential for blind spots, in spite of our best efforts[45]. For example, a set of interviews of UK energy experts on major uncertainties surrounding the UK's ability to meet its 2050 mitigation target found that most only discussed uncertainties that had already been well explored[46]. By contrast, only a few described more radical (yet still widely documented) futures developments resulting from automation, artificial intelligence and the internet of things[46].

As already noted, our ability to consider a broader array of factors beyond commonly discussed or run-of-the mill possibilities is likely to be enhanced if we draw from a wide variety of sources.

How can we expand our imagination to identify a broader range of futures?

What is imagination?

According to the authors of the 2016 book *Pragmatic Imagination*[47], imagination is not simply about producing novel images to fuel creativity, nor is it separate from other cognitive processes such as reasoning. Rather, it is involved in perception, through reasoning, and on to speculation. Beyond speculation is experimental imagination, which uses existing knowledge to push boundaries towards new ideas, and free play imagination, which is far less steeped in experience or knowledge and far more exploratory. As we move from perception and reasoning through to increasingly speculative possibilities, our imagination must address widening gaps between our current knowledge and experiences, and those future possibilities that are as yet unknown to us[47].

Imagination around the factors affecting mitigation efforts is likely to be enhanced by engaging with futures thinking outside the field of climate change. Over recent years there have been several books on the coming threats and opportunities that will face civilisation in the 21st century. One example is theoretical physicist and futurist Michio Kaku's *The future of humanity*[48]. The book discusses long-term human endeavours to ensure the continuation of the species, even if the Earth is no longer habitable. Thus Kaku takes us through the practicalities of establishing bases on the Moon and Mars and then beyond our solar system, including the critical role of artificial intelligence, biotechnology and robotics.

In *Homo Deus*[49], historian and futurist Yuval Noah Harari contends that advances in biotechnology, including brain-computer interfaces and genetic engineering, will serve to usher in a post-human species, at least for those that can afford to implement these technological advances, thereby superseding Homo Sapiens. Harari's later book, *21 lessons for the 21st Century*[50], broadens the scope further to discuss the degree to which we are being hacked by computer technology. This is driven by advances in artificial intelligence that can, with increasing accuracy, predict our consumer, voting, socialising and other preferences and is increasingly able to influence them. Max Tegmark's *Life 3.0*[51] highlights just how fast artificial intelligence is advancing, arguing that the emergence of AI is already changing our economy and will have several applications that could have direct consequences on our energy systems.

Energy demand drivers will also come from a host of other near-term technological advances, as outlined in Kevin Kelly's *The Inevitable*[52], which discusses a range of trends in the way we interact with technology and how this will develop by the 2030s. For example, Kelly contends that we will increasingly use virtual reality environments in our media and communications, be surrounded by screens to a far greater extent than we already are, and use increasing computer power to share, tailor and develop new products.

Although they may seem a fanciful distraction from near-term decarbonisation actions, many of the developments outlined above – space travel, AI, biotechnology, and new media – are already rapidly advancing, and could affect the context within which we have to achieve deep mitigation within the coming years and decades. Consider, for example, Harari's and Tegmark's contentions around the degree to which our economy, political institutions and even brains are being influenced by AI. What might be the implications for the long-term viability of international governance mechanisms to tackle climate change, whether through treaties such as the Paris Agreement, or through global carbon pricing?

As well as immersing ourselves in the future to expand our imaginations and see beyond our extrapolations of historical trends, it should not be forgotten that the past has valuable lessons to offer us. For example, financial analysts have been worrying over the early 2019 inversion of yield curves for government bonds. This indicates that long-term interest rates may be lower than short-term rates and might be a sign of an oncoming recession, as these two events have frequently been linked in the past[53]. Mitigation analysts themselves sometimes look to the past to understand the scale of the challenge associated with deploying the low-carbon energy capacity required to meet stringent mitigation targets, to get a sense of the feasibility of these goals[54,55,56]. The past may not be an accurate guide to the future but neither is it bereft of potentially critical insights.

The role of science and climate fiction in building visions of a future world

Another way of expanding our imagination is through greater use of science fiction narratives. A 2019 Economist lead article[57] highlighted the central role of science fiction, along with scenario planning and trendspotting, in its own categorisation of what it termed futurology, and why this can make it easier to respond to unexpected events.

There are a number of well-known examples of technologies envisaged in science fiction novels inspiring, or at least preceding, actual technological inventions. These include: the 'seashells' featured in Ray Bradbury's 1953 novel *Fahrenheit 451*[58]. These earphones that transmit sound into the ear have been realised as Apple's AirPods and other wireless earphones in the last decade. The tablet computer featured in Stanley Kubrik's adaptation of Arthur C Clarke's 2001: *A Space Odyssey*[59], released in 1968, inspired many attempts at tablet devices culminating in the Apple iPad in 2010. And William Gibson's 1984 novel *Neuromancer*[60] introduced the concept of the public internet (and the term Cyberspace) five years before its actual introduction by Tim Berners-Lee.

There have been several predictions beyond the digital world, notably Jules Verne's highly prescient 1865 novel *From the Earth to the Moon*[61], accurately foreseeing many aspects of the first moon landing over a hundred years later. Clearly there are many inspirations for technological R&D and invention, and sci-fi can reasonably be considered a strong driver of the direction of research towards advanced technological goals, given that these technologies' potential uses have already been envisaged and demonstrated. A recent high-profile example is the space-faring endeavours of Elon Musk, whose February 2018 Falcon Heavy rocket launch had a payload including Isaac Asimov's iconic *Foundation* series of novels[62]. In these books set several thousand years into the future, civilisation has become interplanetary, with quadrillions of people occupying millions of planets throughout the galaxy. Musk has made no secret of the inspiration he draws from Asimov in driving civilisation towards this inter-planetary goal.

In addition, sci-fi has much to say about the potential development of social systems as well as technologies, whether it be the development of intra-state wars as depicted in the *Star Wars* films, the breakdown of democracy and rise of totalitarian regimes resulting from a pandemic as in the DC / Vertigo Comics *V for Vendetta* series, or the development of racial segregation into districts as in the *Hunger Games* trilogy of novels[63]. It is no wonder, given the disruptive changes we are seeing in so many spheres of life, that the use of science fiction in forecasting is now big business[64]. Indeed, it is one of the 33 listed futures analysis techniques in Popper's categorisation[27] (as already discussed), and former Intel in-house futurist Brian David Johnson has written an entire book on using science fiction short stories (or prototypes, as he calls them) to demonstrate and test the consequences of as-yet uninvented technologies[65].

Johnson's prototyping examples demonstrate vividly that sci-fi is not simply about showcasing future technologies, but rather understanding how we will interact with such technologies and the other profoundly different environments and systems in which we may find ourselves. In December 2017, the journal *Nature* published an article containing six science fiction writers' views on the importance and relevance of their craft in a world of rapid innovation and uncertainty[66]. A theme that repeats throughout their writings is that sci-fi is not as useful for precise prediction as it is for better understanding ourselves and constructing a picture of what and who we are in an ever-changing world, solar system or universe. To the extent that fiction can increase our empathy[67] and understanding of different worlds, sci-fi provides a compelling method for imagining different futures in which technological and related social developments dominate, thereby helping to "augment everyday cognition"[68].

Stories set in a future with climate change or other environmental impacts are becoming increasingly prevalent in the science fiction literature, with 'climate fiction', or 'cli-fi' now being identified as an explicit genre, or at least sub-genre, of sci fi[69]. Some of the best-known cli-fi tales, such as Margaret Atwood's *Oryx and Crake*[70] and Kim Stanley Robinson's *New York 2140*[71], detail futures in which the impacts of climate change take centre stage. Indeed the majority of cli-fi stories concern themselves with futures in which at least some degree of dangerous climate change has not been avoided. However, not all cli-fi tales depict failure. As an example, the *Nature Futures* short stories (published in each issue of *Nature*) concern themselves with climate change and between them depict a broad range of outcomes, with some examples shown in table 2.

These more narrative-based depictions of future scenarios combine visions of how society functions in a low-carbon, climate-friendly manner in the context of all the other changes that might be experienced in society. This lends richness and arguably makes them a critical addition to the more focused visions of low-carbon systems in the dominant modelled scenarios. Such narratives are examples of 'world building', allowing audiences to become deeply immersed in future visions, enhancing the speculative, exploratory and free-play layers of the imagination[77].

In summary, there is no shortage of ways to expand our imagination through world-building. Given the increasing risk of blind spots occurring in our futures analysis and the vast and increasing complexity of the world outpacing our cognitive capacities, it is of critical importance that we utilise this broader toolkit to try to understand the future more fully.

What outputs might we expect from using these methods and how can we respond?

Different exercises, different outputs

An example exercise for exploring alternative futures and their climate change mitigation implications is the *Broadening the Dialogue* process[78] undertaken by ClimateWorks and Futures CoLab. This was aimed at developing a range of alternative future visions to address blind spots that would not necessarily be made visible with traditional climate change mitigation models and scenarios. In addition, it was aimed at augmenting the somewhat technical nature of quantitative modelling and scenarios by capturing narratives and drivers of the deep societal changes that could result from climate change and the different policy responses to it, as well as other important mega-trends.

Table 2: From climate change dystopia to utopia – and beyond! Stories from *Nature Futures*

Title	Backdrop to story
Cold Memories (Jan 2019)[72]	Humans have long abandoned Earth as a result of crop failures and other devastations presumably caused by climate change, leading to it becoming "a ruined, blighted planet". However, the temperature has dropped a half-degree in the past 40 years, which indicates that Earth may be recovering. Prospectors seeking precious metals on asteroids across the solar system dream of earning enough money to one day return home.
When Last I saw the stars (May 2015)[73]	A granddaughter and grandmother discuss the stars, which are no longer visible because a geoengineering project has spread a haze of aerosols across the Earth's sky to control the climate and counter emissions from coal burning. Discussions of mitigation measures such as responsible energy use are things of the past.
The Brown Revolution (September 2008)[74]	Fossil fuels have been replaced as the world's dominant energy resource by human and animal excrement. Solar collectors and panels are used to brew methane from it, from which energy is derived in sealed, closed-loop generators, recycling the resulting carbon dioxide into carbohydrates via artificial photosynthesis.
How science saved the world (January 2000)[75]	At the start of the third millennium (i.e. the year 2000) is a period referred to by future historians as the "overshoot", when global warming and a major loss of human life occurred. Many technical advances of the era did nothing to mitigate ecological disaster. But scientists ultimately transformed capitalism into a more scientific system, with far greater sustainability – termed the "permaculture".
Climate Change (May 2005)[76]	In an imaginary past, nuclear fusion power "swept all before it" after an unexpected breakthrough in 1969. But the huge amounts of seawater used in the fusion reactors' processing plants led to the production of millions of tonnes of microscopic salt particles which were "thrown up" into the atmosphere – causing global cooling. The third meeting of the Intergovernmental Panel on Climate Change desperately tries to find a solution.

The exercise used an online community discussion and voting platform to lead an international group of participants through a customised scenario exercise. This adapted a conventional scenario planning process for digital use and was more practical than meeting in person for a large, diverse, international group of participants across many different time zones. This builds on evidence of the efficacy of such online platforms to engage a broad and diverse group of stakeholders[79].

The wide range of economic, social, political, technological and environmental drivers suggested by the participants were grouped into five different scenarios:

- **Hollowed Out**, a world characterised by extreme inequality and the concentration of power amongst a minority of powerful groups controlling global systems;
- **National Rivals**, dominated by protectionist policies and hostility between nation states;
- **Connected Communities and Cities**, where decentralised, local leadership is increasingly important, though tensions between urban and rural areas and inequalities within cities persist;
- **Consumers in Charge**, where corporations serve consumers and the tensions between material consumption and sustainability rise;
- **Trust returns**, where institutions and governance structures are sufficiently flexible to cope with the increasing challenges posed by climate change.

These scenarios, unlike the SSPs discussed earlier, were not designed to form the basis of integrated assessment modelling runs with varying degrees of difficulty and challenge toward adaptation and mitigation goals. Instead they were designed to identify risks and opportunities for currently planned or new strategies to achieve mitigation.

Such exercises are likely to add richness to the narratives that emerge from purely modelled scenarios, for example by more vividly identifying risks to the underlying drivers of mitigation action and opportunities to accelerate it. In the *Broadening the Dialogue* exercise, risks identified include: ever-growing material consumption and energy use, stemming from the demand for new technologies and services; the erosion of international and national governance systems; and other global mega-trends that relegate climate change to a secondary issue. Opportunities include technologies which haven't yet been simulated in models, such as those resulting from new nanomaterial and synthetic biological advances.

The painting of such "possible worlds" is an insightful and important part of scenario planning. For example, figure 6 uses a number of speculative events to imagine a scenario in which deep emissions reductions, potentially consistent with a well-below 2°C future climate-change goal, are achieved.

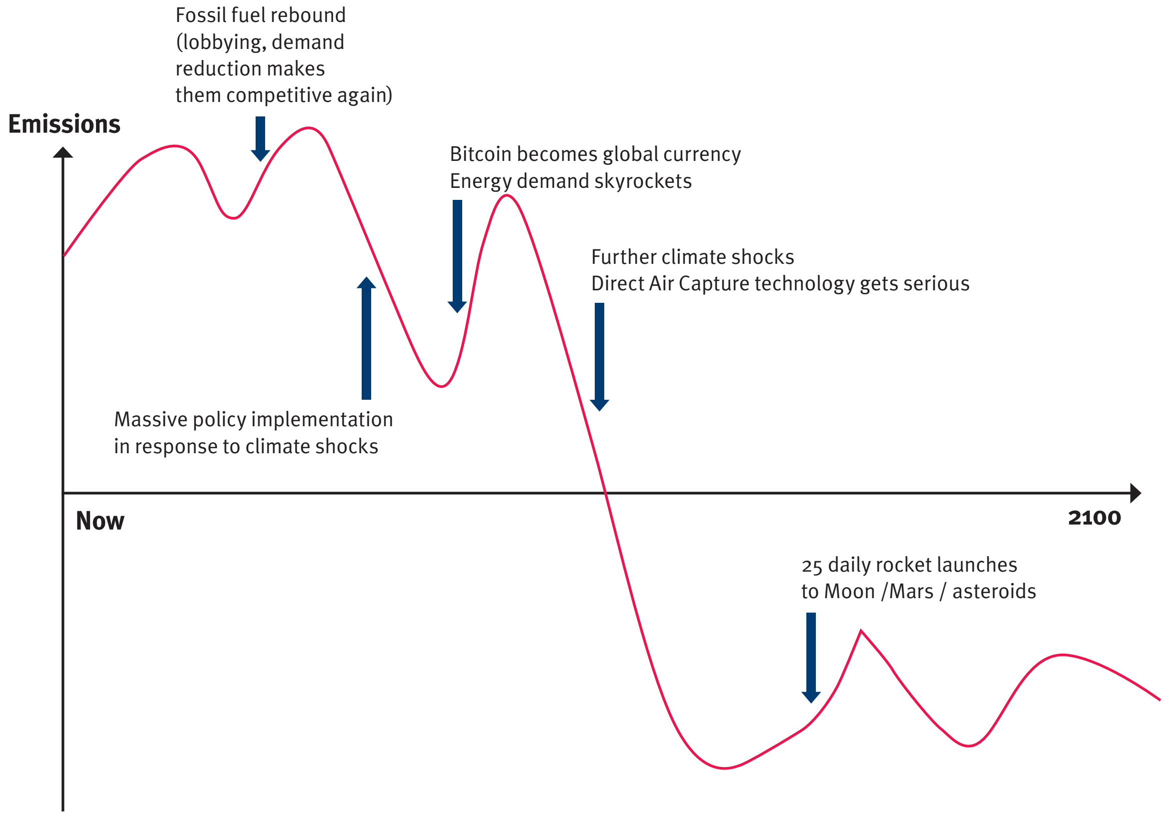

Figure 6: One possible pathway to 1.5°C? A speculative / provocative scenario, by the authors using their own imagination

This scenario has nothing like the smooth adjustment trajectory that often follows from integrated assessment and energy system modelling. Nor does it confine itself technologically, politically or environmentally, instead exploring the potential role of events which are clearly visible on the horizon, if not already present.

Other recent examples of futures speculation which are likely to provide important complements to the dominant modelled low-carbon pathways include one focusing on the geopolitical risks of energy transitions from fossil fuels to renewables. This highlights the tensions and rivalries resulting from the creation of new winners and losers[80]. Another discusses the potential for using 'strategic intervention points' to design and target policy interventions to accelerate the transition along an existing pathway or shift towards an entirely different pathway. These could unleash processes including increasing returns and entrenched support that will accelerate the low-carbon transition, driven by processes which are not yet represented in integrated assessment models[81].

A recent review of disruptions in energy systems modelling found that in cases where disruptions did feature, they were most commonly derived from qualitative scenarios using horizon scanning techniques to identify wild cards and black swans, as well as long-term interconnecting trends resulting in gradual but profound disruptions[82]. The review also found that agent based and simulation models were more frequently used to explore disruptions than equilibrium and long-term foresight optimisation models (such as the IAMs which dominate mitigation analysis). Others have contended that combining quantitative modelling with human 'red teams' is a useful way of filling in gaps or surprises that models may have missed[83].

Whilst many scenarios and futures analysis exercises will overlap heavily with the socio-economic drivers and contexts already identified and explored in the SSP framework, they cannot help but add to the richness of the narratives developed to describe the paths and pitfalls along the low-carbon transition. This is critical in helping to identify more of what are currently – at least in mainstream mitigation analysis – either consciously or by default relegated to the unknown unknowns or known unknowns categories described earlier.

Navigating through the possibilities

The tools so far discussed in this paper, if applied broadly, are likely to result in a multitude of scenarios and visions of the development of future factors that will help or hinder mitigation efforts. This breadth is arguably in and of itself a useful result of applying a variety of futures analysis methods, since it will help open decision makers' eyes to future possibilities. But it raises the obvious, and critical, question of how decision makers should act in the face of such variety. The dominant paradigm in which scenarios are currently produced, i.e. using cost-minimising or welfare-maximising energy and integrated assessment models, allows one form of decision-making – to pursue a strategy which through at least one lens (i.e. that of expected utility) might be deemed optimal. But there are other ways of choosing preferred scenarios from the wider possibility space, for example the precautionary and 'robust decision making' (RDM) approaches[84].

- **The precautionary approach** holds that decision makers should undertake actions to prevent or minimise future damages in the context of uncertainty around how different actions might lead to different outcomes. An example is a doctor deciding not to prescribe a treatment which has a small but uncertain risk of a side-effect that would more-than-offset its benefit. Though effective at managing risk, this approach doesn't allow the weighing of costs and benefits.
- **Robust decision making (RDM)** characterises uncertainty by running multiple scenarios of the future with a view to identifying those courses of action which are most robust to achieving desired goals in the face of the different events contained within these scenarios. Whereas expected utility approaches seek to identify an optimum course of actions in the context of a particular view of the future, RDM seeks to identify solutions that work "well enough" over a wide range of futures.

RDM requires a detailed understanding of the different factors that might influence the future, as well as some attempt to characterise their uncertainty, and the confidence about their uncertainty. As such, it is a computationally and analytically more resource-intensive method than either expected utility or precautionary approaches. But it is nevertheless a potentially useful method for identifying robust courses of action in light of multiple future scenarios and uncertainties.

The use of RDM strategies would be facilitated by an iterative exchange between analysts, and policy and decision makers to ensure the development of appropriate scenario choices that are most relevant to the decisions at hand[85]. Such exchanges could be enabled through various visualisation techniques and scenario discovery methods, so as to allow the identification and discovery of different scenarios and pathways that deliver the most useful and detailed information to inform decisions[86].

Recommendations and conclusions

What next?

This paper has highlighted the importance of considering a very broad range of factors that could influence our ability to mitigate climate change in the future. In doing so, it has reflected on the methods that currently dominate in the development of global mitigation pathways analysis and on the multitude of other futures analysis methods that could help further flesh out the future possibility space. The paper has also explored the different limitations to our imagination when considering futures and how these can be overcome, and how we can engage with large numbers of scenarios describing plausible futures. Our recommendations are targeted primarily at the analytical communities developing mitigation pathways within different scenario frameworks, for use in policy formation and other decision-making processes.

1. Actively seek the black elephants

There are several factors that we know stand a good chance of profoundly affecting our politics, economy, environment and society in the coming years. Yet these are still not routinely considered in mitigation pathways. We know energy demand technologies and behaviours could lead to very low levels of future energy demand[19,87], but we have not yet considered all the new ways in which energy demand could explode. We hope we can repeat the solar photovoltaic, offshore wind and lithium ion battery cost reduction miracles we have seen in recent years, but we do not know for which technologies. We suspect technologies like nuclear fusion, hyperloops, autonomous vehicles, AI, human-computer interfaces, missions to Mars, bitcoin and blockchain could be game-changers, but few if any mainstream mitigation scenarios consider them in detail. We fear another global economic recession is imminent, yet we assume that long-term economic growth is assured in all major mitigation pathways scenarios. And we see before our very eyes how our environmental, political, media and social systems are changing. Yet we could do much more to explore the consequences of these changes on our mitigation pathways. Scenarios contain many factors that we know will potentially be relevant to our ability to mitigate, but their impacts are uncertain – they are in effect known unknowns, or black elephants. By engaging with a fuller set of such unknowns the analytical community can highlight a wide range of relevant and potentially critical possibilities worth considering in the development of mitigation pathways.

2. Increasingly engage with black swans

Factors which are unknown cannot be identified. Yet one feature of black swans – or unknown unknowns – is that there is commonly an attempt to justify their occurrence post-hoc[33]. It is therefore worth attempting to learn from past such events, and why we were blind to them, to better understand whether we can make future events more predictable. To help do this, mitigation pathways analysts should create venues to engage with a broad range of methods and communities outside of their own, to minimise groupthink and other heuristics and biases, and learn from other perspectives. Such methods include those in the broader futures analysis field, including horizon scanning, expert interviews, judgement and visualisations, SWOT and cross-impact analyses. These can complement and enrich the currently dominant method of scenario development combined with systems modelling. Key communities include writers of science fiction and climate fiction, and other such 'world builders' engaged in developing more speculative, but still-plausible, visions of the future. Other significant communities worth engaging with include historians, defence and military strategists, catastrophe insurance modellers, and others whose professions are focused on engaging specifically with lower probability, higher impact events.

3. Address uncertainty head-on in undertaking and communicating this analysis

A deeper engagement with uncertainty, as elaborated above, should be accompanied by a more explicit communication of it in reported mitigation pathways analysis. As Smith and Stern (2011) put it:

> *"There is value in scientists engaging in a deep conversation with policy-makers and others, not merely 'delivering' results or analyses and then playing no further role. Communicating the policy relevance of different varieties of uncertainty, including imprecision, ambiguity, intractability and indeterminism, is an important part of this conversation. Uncertainty is handled better when scientists engage with policy-makers."* [88]

The new paradigm of complexity and deep uncertainty means analytical communities should use more appropriate tools and timescales for the tasks at hand. For example, systems models may be highly appropriate for exploring specific questions for which parameterisation is feasible. But when looking further into the future, more qualitative scenario-based analyses, or perhaps simulation or agent-based models, may be more appropriate to the levels of uncertainty at play. Recognition of uncertainty should also be acted upon by seeking to identify policies and actions which are most resilient to the multiple outcomes identified. This would be a significant departure from the current dominant mode of identifying cost-optimal mitigation strategies for different scenarios. Techniques such as robust decision making can identify how different policy strategies and actions could fare under different future developments.

Here, a range of tools can be used to aid engagement with policy makers, including visualisation strategies that help better engage with a wide range of scenarios, discover those which are most resilient and communicate their implications.

And finally (for now)

Together, the recommendations outlined above are likely to help analysts engage more actively with our increasingly turbulent world, recognising their own biases and blind spots, and their tools' limitations. This should expand the number of outcomes that we actively consider in our mitigation pathways analysis, allowing us to be more prepared for the inevitable surprises along the way.

In reflecting on the ways in which the analytical community can develop scenarios and mitigation pathways that are more resilient to future uncertainties, we deliberately stop short of a complete consideration of the explicit role of policy and decision makers in acting on this analysis. While partially addressed through our discussion on the need for the analytical and policy communities to more closely engage, there is nevertheless a far greater range of considerations for policy makers around whether and how to enact those policies identified as most resilient in the face of uncertainty. This will depend on the political context, other priorities and a range of complex considerations which deserve their own detailed reflection and analysis. Nevertheless, if enacted, the above recommendations should prove critical in furnishing these considerations with the most useful mitigation analysis possible.

"Neither a wise man nor a brave man lies down on the tracks of history to wait for the train of the future to run over him."
Dwight D Eisenhower

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