



ECONOMICS OF ENERGY INNOVATION
AND SYSTEM TRANSITION

Risk-opportunity analysis for transformative policy design and appraisal.

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C-EENRG Working Papers, 2020-4

November 2020

C-EENRG Working Papers, 2020-4

Please cite this paper as:

J.-F. Mercure, S. Sharpe, J. Vinales, M. Ives, M. Grubb, H. Pollitt, F. Knobloch, F. J. M. M. Nijse. "Risk-opportunity analysis for transformative policy design and appraisal." C-EENRG Working Papers, 2020-4. pp. 1-40. Cambridge Centre for Environment, Energy and Natural Resource Governance, University of Cambridge.

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Risk-opportunity analysis for transformative policy design and appraisal

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ABSTRACT

The climate crisis demands a strong response from policy-makers worldwide. Technological change, innovation, labour markets and the financial system must be led towards an orderly and rapid low-carbon transition. Yet progress has been slow and incremental. Inadequacies of policy appraisal frameworks used worldwide may be significant contributors to the problem, because they frequently fail to adequately account for the dynamics of societal and technological change. Risks are underestimated, and the economic opportunities from innovation are generally not assessed in practice, even if they ought to be in theory. Here we set out some of the root causes of those inadequacies. We propose a generalisation of existing frameworks for policy appraisal to help evaluate situations of transformational change. We use the term “risk-opportunity analysis” to capture the generalised approach, in which conventional economic cost-benefit analysis is a special case. New guiding principles for policy-making during dynamic and transformational change are offered.

1. INTRODUCTION: THE LOW-CARBON INNOVATION POLICY PROBLEM

The urgency of climate change and the inadequacy of the global response has led some to ask, ‘why are we waiting?’ (Stern, 2015). Part of the answer may lie in the inadequacy of the tools most commonly used to guide decision-making processes (Mercure *et al.*, 2016; Farmer *et al.* 2015). The problem of reducing global emissions of greenhouse gases pose three challenges that standard and prevailing welfare economics policy assessment methods¹ are generally not in an ideal position to address: the pervasive and transformative nature of the necessary changes (Fouquet, 2016; IPCC, 2018) including non-marginal elements (Dietz and Hepburn, 2013); the highly heterogeneous interests of different actors, stakeholders and decision-makers (Geels, Berkhout and van Vuuren, 2016); and the high uncertainty regarding costs, benefits and outcomes of policy strategies (Hughes, Strachan and Gross, 2013). Conventional textbook welfare economic methods, as applied in current policy appraisal, are well-suited to analyse marginal changes with relatively uniform stakeholders. Transformative change may not, however, be successfully triggered by informing policy with a paradigm designed for managing marginal change (Dietz and Hepburn, 2013). Furthermore, as could be observed during both the 2008 financial crisis and the COVID-19 crisis, marginal analysis, by ignoring systemic risk, may also be leading policy-makers to design fragile systems with insufficient resilience to handle increasingly frequent extreme events (Schwarcz, 2019).

Climate change policy epitomises a need for change in approach felt in several domains of policy-making where substantial change is desired but not materialising. Other areas include innovation policy, industrial strategy, finance, infrastructure, regional development and productivity growth. Marginal analysis is useful over a vast domain. But in these areas of transformative policy-making, such as policy towards climate change, marginal analysis is not appropriate. These problems of transformational change require a more general approach with corresponding definitions and methods.²

The radical and rapid correction of economic course required by climate policy involves complex and significant intervention in the economy involving a more explicit industrial strategy. How should such measures be evaluated? A more general set of social scientific methods (Kattel *et al.*, 2018), both quantitative and qualitative, is necessary for these situations, and could serve as a part of the general paradigm for policy appraisal. An appropriate approach would admit the limits to available knowledge to adaptively guide the

¹ Prevailing assessment methods tend to employ either cost-benefit analysis (CBA, as defined by HM Treasury, 2018), or more generally, equilibrium economic approaches (EEA). Most conventional approaches are based on equilibrium models including general and partial equilibrium, optimal growth, utility/cost-optimisation, dynamic stochastic general equilibrium modelling (see Mercure *et al.*, 2019).

² I.e. providing a definition for non-marginal change and guidelines to use for policy appraisal in cases where that definition applies, notably in the UK’s Green Book (HM Treasury, 2018).

approximate direction of change of a complex transition, rather than attempt to identify a highly uncertain distant end point with false precision. A practical scientific handling of deep uncertainty emerges more naturally from complexity science than it does from traditional welfare economics (Arthur, 1999).

In this paper, we propose the scientific basis for a new policy appraisal framework, which we call 'Risk-Opportunity Analysis' (ROA). A number of methodologies exists for analysing decision-making options under deep uncertainty (Marchau *et al.*, 2019 for a detailed review), to which ROA is to some degree related.³ What these lacks, however, is the broad philosophical pedigree of welfare economics going back to 18th century, through which much of our present day understanding of legitimacy-building in the eyes of the public and public institutions during policy appraisal has been developed, as well as the mechanisms of the science-policy interface itself.⁴ ROA is a generalisation of widely used 'Cost-Benefit Analysis' (CBA), which thus benefits from the same intuitive philosophical background, while avoiding the most important pitfalls of CBA.

In section 2, we consider the inadequacy of marginal analysis in the appraisal of policy design for transformative change, using climate change policy as the main testing ground. Section 3 sets out the scientific basis for our proposed, more general policy analysis framework, which we refer to as Risk-Opportunity Analysis (ROA). Section 4 sets out the framework itself. Section 5 provides an example application and section 6 concludes.

³ E.g. Robust Decision-Making (RDM) involves the search of complex scenario spaces to identify strategies that are robust to most exogenous or even endogenous uncertainties. This is a useful approach for the analysis of alternatives, for example, for company executive board decision-making, or military decision-making.

⁴ Here we refer to philosophical texts and debates of the consequentialist and deontological views of moral philosophy going back to Bentham, Locke, Smith, Kant and later Coase, all of which have together led to the development of the mechanisms of the science-policy interfaces and its legitimacy in the Anglo-American world and beyond. RDM is designed to optimise the use of information but does not address issues of legitimacy in public policy-making, where it could be perceived as having a black box lack of transparency.

2. CHALLENGES TO BE ADDRESSED BY POLICY APPRAISAL FRAMEWORKS

i. Preamble

Basic welfare economics principles, as applied in finance ministries, are most useful when

- (1) An intervention does not substantially change the background economic situation (e.g. prices of goods and services and GDP growth) nor the relationships between variables (Dietz and Hepburn, 2013);
- (2) The heterogeneity of affected stakeholders, and of the dimensions of policy outcomes, is not highly relevant for the objectives to be considered achieved;
- (3) All parameters and outcomes involved in policy analysis are sufficiently confidently known, with quantified uncertainty, such that expected values are considered robust.

For many situations, including notably policy that concerns innovation, these requirements do not hold, invalidating any conclusions based on the application of basic welfare economics. Three useful definitions relate to the reliability of the knowledge that decision-makers use: heavy-tailed and fundamental uncertainty, and systemic risk.⁵

Heavy-tailed uncertainty is characterised by a probability distribution where very large events are sufficiently likely that the variance fails to exist. This means that if one tries to compute it, the estimated value of the variance gets larger and larger and diverges to infinity as the sample size gets large. In extreme cases the mean also fails to exist, but even if it does exist, averages converge very slowly with the addition of data, which makes it unreliable.

Fundamental uncertainty about the future involves unknown unknowns, arising when one cannot enumerate and rank all possible futures. We propose that fundamental uncertainty is generally related to heavy-tailed uncertainty.

Systemic risk is associated with complex interdependencies within a system and can precipitate systemic collapse based on the cumulative contribution of certain actions by the individual entities that collectively compose that system. It can arise when the actions of any individuals do not necessarily pose a risk to themselves directly, but contribute to forming risks at the community level. Systemic risk is not the aggregation of individual risk but rather an emergent property of the system that arises as an amplification of any such aggregate risk

⁵ We acknowledge the existence of a discrepancy between definition of 'risk' used in economics, as the impact of uncertainty on objectives quantifiable with probabilities (following Knight), and the definition used in most other spheres of society (such as public health, engineering, or national security) e.g. the ISO risk management standard), which does not require probability to be quantifiable in order for something to be considered as a risk. For the sake of communicating with policy-makers, we adopt the latter definition, recognising that probabilities are rarely quantifiable in practice. Meanwhile, we use the term 'uncertainty' to refer to the range of possible variations in the accuracy of existing knowledge and predictions, and not in the sense used by economists meaning unquantifiable risk.

(Cont and Schaanning, 2017).

ii. Understanding dynamically rapid pervasive change

According to the UK's Green Book for policy appraisal, marginal analysis is 'generally most appropriate where the broader environment (e.g. the price of goods and services in the economy) can be assumed to be unchanged by the intervention'. By contrast, it works 'less well where there are potential non-marginal effects or changes in underlying relationships' (HM Treasury, 2018). Meanwhile, general equilibrium economic models are designed to handle marginal demand, supply and price changes, but do not handle deep structural changes in the economy, as they take the structure of the economy to be fixed.

To understand the mismatch that occurs when a marginal analysis technique is applied to a problem of non-marginal change, it is necessary to identify the relevant system dynamics and their potential path-dependence.

(1) Dynamics of economic systems

The economy is characterised by inertia against change, which implies understanding it as a dynamical system (Grübler, 1990; Mokyr, 1992; Grübler, Nakicenovic and Victor, 1999). Inertia in the economy stems from two broad processes: the long-lived nature of productive capital assets required for generating return, and the interconnectedness of agents, firms, industrial systems and supply chains/trade networks (Mercure, 2015, 2018). Production requires building physical and human capital assets, and this takes time, and such investment occurs with the expectation they will be used for an even longer period of time. Rapidly changing economic circumstances can lead to a devaluation of capital before it has paid for itself. Thus, for problems that potentially involve transformative change, dynamics should be of primary concern, where the dynamic effectiveness of policies should be analysed rather than their static efficiency (Farmer *et al.*, 2019). The static efficiency of marginal analysis is only ever true for as long as change is marginal, beyond which it loses clear meaning.

(2) Path dependence

Policy action in certain domains almost always has the outcome of changing to some degree the problem at hand, creating the need for further analysis and further policy action (Rittel and Webber, 1973). Playing the game changes the game. For example, research suggests that it was the German introduction of feed-in tariffs that created a market for solar photovoltaics, which allowed Chinese manufacturers to justify expanding production at a large scale, which subsequently resulted in substantial cost reductions and the availability of low-cost solar energy to the rest of the world (Yu, Popiolek and Geoffron, 2016). A relatively benign climate policy decision transformed the whole low-carbon industry and climate change problem, affecting the policy strategy of all nations, by opening new opportunities and closing older ones.

Path-dependence is difficult to represent in equilibrium economic analysis, because by definition the notion of equilibrium erases the impact of history, the memory that is embedded in economic structure. As time passes, each economic action reduces the range of possibilities of what the economy will not become, while it expands the range of what it could become - but neither can be exhaustively enumerated (Day, 1992; Arthur, Durlauf and Lane, 1997; Kauffman, 2000). In the language of marginal analysis, the constraints of the allocation problem that must be solved in path-dependent systems keep changing according to the solution that was reached in previous time positions. This is a difficult to solve, infinitely recursive problem when framed using economic optimisation (Way *et al.*, 2019).

iii. Addressing normatively highly differentiated and heterogeneous interests

A common criticism levelled against welfare economics is that it requires normative valuation elements to be included in an otherwise descriptive quantitative analysis (e.g. the monetary value of risk to life or the willingness to pay for beauty or pollination services, methodologies used by Bateman *et al.*, 2002; Hanley and Barbier, 2009; HSS, 2016; HM Treasury, 2018), valuation that is ultimately interpreted as objective science (Baram, 1980; Ackerman and Heinzerling, 2002). 'Moral' values (or beliefs) are quantified in monetary terms using methods that may be seen as an arbitrary choice of the analyst, since they are, strictly speaking, not reliably measurable quantities (Baram, 1980; Ackerman and Heinzerling, 2002)⁶. Aggregating the value of moral choices with real flows of economic quantities may be methodologically inconsistent as it can lead to internal philosophical contradictions and challenges.⁷

More importantly, welfare economic valuation methods ascribe value to multiple dimensions of policy impacts using only one monetary metric combining all real and moral costs and benefits, with stated interpretation that the resulting quantity represents their normative value to society as a whole. Where that quantity remains constant, society is interpreted as indifferent, but this can involve substantial underlying structural changes, with winners and losers. The normative weighting of different actors' interests is inevitably a political choice, and, where one takes a positivist view of science, this cannot be the outcome of any scientific assessment (Ackerman and Heinzerling, 2002; see also Pindyck, 2017). In other words, by including normative elements into objective analysis, welfare economics takes the value judgment, and thus agency, away from the policy-maker, and gives it to the analyst. The

⁶ One can objectively measure and cardinally organise people's actions and attitudes, under chosen objective criteria, but beliefs cannot reliably be cardinally ranked, and thus proxies of debatable reliability have to be used, such as prices, with substantial additional arbitrary interpretation and uncertainty.

⁷ For example, the Stern Review (2007) involved measuring the statistical value of life of affected people which lead to different values according to ethnicity and social background (Aldred, 2009). This is inconsistent with other widely accepted human rights-related principles, thus internally inconsistent from a normative viewpoint.

former may meanwhile be in need of guidance for policy design on how to pursue a range of goals, while the latter may end up under undue political pressure to shape the subjective component of the assessment in particular ways.

iv. Working scientifically with uncertainty

The concept of Pareto-optimal policy-making, in a strict sense, may in some instances be scientifically tenuous, since the possible outcomes of policy action cannot usually be exhaustively enumerated and ranked (Baram, 1980; Ackerman and Heinzerling, 2002; Weitzman, 2009). The aim to deliver optimality may be too restrictive as it can involve unrealistically high demands on information availability and reliability, while in practice, it frequently leads to the use of some untestable proxies for inferring missing information. Meanwhile, the role and value of uncertainty as the generator of both risk and opportunity is generally missed. By alleviating requirements for optimality, uncertainty could in fact be seen as an ally rather than as an enemy.

(1) Uncertainty is fundamental

Fundamental uncertainty is an essential characteristic of the economy (Keynes, 1921; Fontana, 2008) and is present in most policy decisions. Its sources include the development of new technologies; the intentions and investment decisions of economic agents; the outcomes of entrepreneurial ventures; the future costs and prices of all traded goods and services; and the behaviour of the economy as a whole. Possibilities are in general not exhaustively known, and therefore probability distributions around these possibilities are not knowable. Arbitrarily assigning probabilities to unknowable quantities can lead to scientific inconsistency.

That fundamental uncertainty cannot be represented using probability distributions is closely related to the degree of path-dependence inherent in the economy. For example, a range of possible values for auctioned connectivity broadcasting licences did not exist until the mobile phone was created. But moreover, many futures may either be distinctly advantageous or clearly disastrous. That probability distributions could be heavy-tailed implies that expected values – and therefore discounted costs and benefits – are generally unreliable quantities, as they involve adding up large uncertain values with small relatively well-known values.

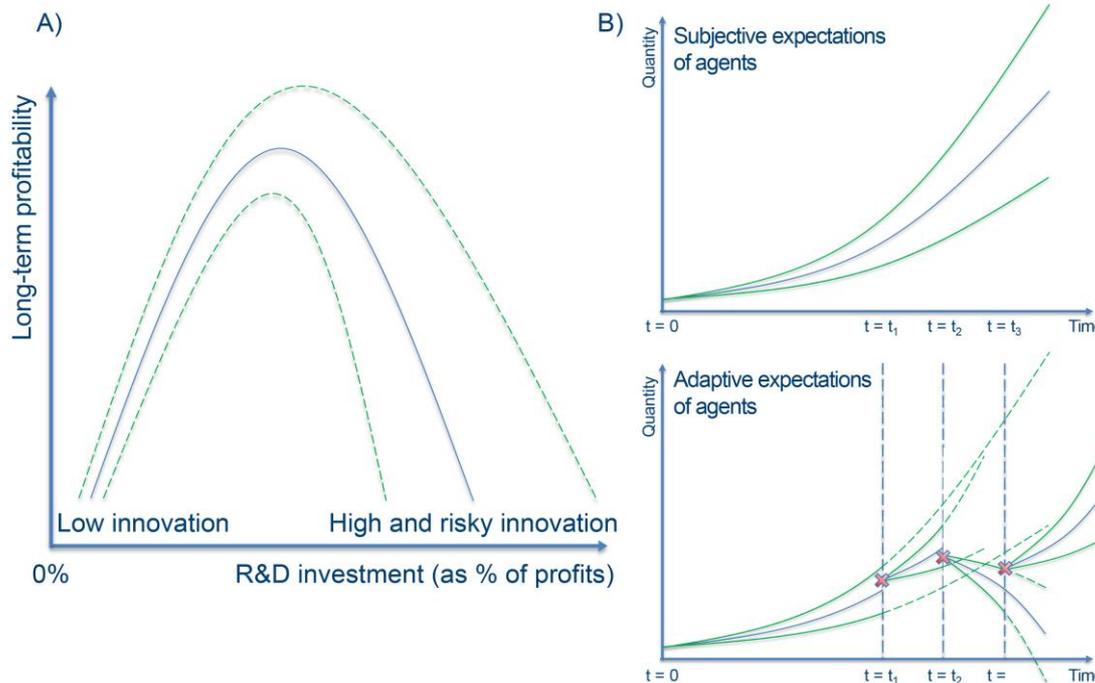


Figure 1: (Left) Illustration of the profitability of companies in relation to their degree of commitment of resources to R&D investment for the development of new products. Dashed lines illustrate degrees of uncertainty. (Right) Illustration of the process of expectations creation and readjustment by agents to capture opportunities as time passes. (Top panel) Agents in practice form subjective expectations of the future, with central scenario and limit cases. (Bottom panel) As time passes, agents re-form their expectations adaptively according to new information. Red crosses are actual realisations, while curves delimit ranges of possibilities expected by agents.

One crucial consequence of fundamental uncertainty is that knowledge about a system after a non-marginal transformation has taken place is inherently less robust than knowledge of the status quo. As a natural consequence, the valuation of the predominantly long-term direct and indirect benefits of policy action is more prone to uncertainty than the valuation of the predominantly short-term direct costs of the same policy action. Thus, mis-handling uncertainty may generate, in marginal analysis, a status quo bias if the tendency of analysts is to avoid including uncertain quantities, or a confidence bias if uncertainty is underestimated. This affects particularly innovation and regional development policy.

Experience tells us that⁸ the standard response of welfare economics analysts to fundamental uncertainty is to make proxies for missing knowledge, and impose short-tailed distributions to missing data, since marginal analysis requires users to quantify probabilistically all real and moral costs and benefits.⁹ Some of these quantities inevitably

⁸ Several authors of this article are experienced practitioners within science-policy interfaces including recent experience working inside governments.

⁹ Measuring heavy tails is by definition challenging as it requires large amounts of data and can involve long waiting times to obtain data on rare events.

have heavy-tailed or unknown probabilities, such as the social cost of carbon, or the benefits of hypothetical technologies that do not yet exist. The political pressure on analysts that results from the requirement to make proxies when data is unavailable, politicises the policy analysis process, and ultimately undermines it.

(2) Uncertainty has value

The economy naturally evolves through its attraction towards productivity increasing novelty (Schumpeter, 1939; Freeman and Louçã, 2001). Entrepreneurs and venture capitalists thrive on fundamental uncertainty, since business opportunity frequently arises through unpredictable events that allow capturing competitive advantage, for instance successful innovation. This notion contrasts with normative probability-based standard portfolio optimisation (Markowitz, 1952), which requires fully quantified risks. Venture capital would likely not exist if probabilities of entrepreneurial success were equally known by everyone, as there would be less opportunity for creating comparative advantage out of innovative industrial ventures if everybody saw it coming.

Entrepreneurs do not typically focus on single sources of cash flow (excluding monopolies), as they strive to future-proof one's enterprise by creating new products and capture new markets (Porter, 1996). Figure 1 (*left*) illustrates a typical business perception of returns on investment in research and development (R&D) at the firm level. Investing insufficient resources into innovation leads an enterprise towards obsolescence and eventual failure. Meanwhile, too high an investment of available resources into too many risky ventures is a gamble that leads to a relatively high chance of successive strategic mistakes, unproductive investments, and failure. A middle-ground thus exists.

Such a middle-ground can be seen empirically in innovation portfolio analysis, where it is observed that a combination of breadth, selectiveness and innovative intent increases return on R&D investment, due to its generation of options (Klingebiel and Rammer, 2014; Meifort, 2016). This coincides with normative portfolio analysis in the context of innovation (Way *et al.*, 2019). It may be seen as the entrepreneur's adaptive response to strong path-dependence, where strategic re-adjustment takes place as information over the future is gathered and expectations are recurrently re-formed (Figure 1 *right*). A similar logic is known empirically to apply to public innovation policy-making (Mazzucato, 2012; Mazzucato and Penna, 2016): although pressure arises for policy-makers to identify 'optimal policies', in practice not all policies succeed, while objective value exists in trial and error, investing in both high and low risk ventures.

3. RISK-OPPORTUNITY ANALYSIS FOR INFORMING POLICY-MAKING

In this section, we define a risk-opportunity assessment (ROA) framework, based on complexity science (see the Appendix), designed to inform policy-making for problems involving non-marginal change,¹⁰ that can be used within existing science-policy interfaces. ROA is a generalisation, in fact possibly the only self-consistent generalisation one can make, of CBA when in the presence of dynamics and strong path-dependence in the economy, of fundamental uncertainty and heterogeneity of stakeholders. When these are not present, CBA can be sufficient. ROA requires abandoning the use of expected values on the basis that detailed probabilities are unknowable in general, and demands appropriate treatment of uncertainty in each domain of analysis.

a. Summary of steps to take in Risk-Opportunity Analysis

Building on the standard guidelines of the Green Book for policy appraisal (HM Treasury, 2018), ROA involves the following steps:

- i. Identify the boundaries of the system considered and map out all relevant feedbacks between components, considering their magnitudes and directions. Choose or develop suitable dynamical quantitative and/or qualitative analysis models and datasets accordingly.
- ii. Estimate median¹¹ outcomes and impacts on the process and direction of evolution and on the structure of the system itself, in a chosen relevant set of qualitatively or quantitatively measurable metrics, associated with each comprehensive policy portfolio proposed, under various plausible scenarios of economic evolution through time. Establish ranges of uncertainty or degrees confidence for each outcome metric.
- iii. Carry out, using a stress test or other method, a risk assessment for each policy portfolio under study, to identify all possible *extreme unintended detrimental consequences* and worse case scenarios, estimating their severity and likelihood, under each dimension considered. This should identify notably the possibility of reaching tipping points and rapid non-linear changes, and their dependence on known variables.

¹⁰ Such as: economic, innovation and industrial strategy, regional economic development, the development of institutions, financial regulation, and some but not all types of environmental policy related or not to climate change.

¹¹ Note the key difference between using median (or e.g. quantile, percentile) as opposed to mean or expected impacts: medians can be reliably estimated even where distributions are heavy-tailed, while means and expected values are strongly dependent on the heaviness of the tail.

- iv. Carry out, using scenario variation analysis or other methods, an opportunity assessment, identifying all possible *option creation potentials* for each policy portfolio under study, under each dimension considered. Option creation potentials are elements of scenarios and systems that expand the ranges of possible desirable futures.
- v. Report to decision-makers median impacts, direction of system change feedbacks, risks and opportunities, in all dimensions considered, along with uncertainty ranges and/or confidence levels. Report both qualitative and quantitative evidence, against current regulatory norms and risk tolerances. The normative weighting or valuation of outcomes is not considered part of ROA.

b. Taking a systems perspective

The intended and unintended impacts of policy-making are typically felt across several dimensions, such as income, inequality, access to stable services, environmental quality, financial stability, health and so on. To minimise the chance of missing important impact transmission mechanisms, adopting a holistic systems view is required, identifying feedbacks between system components using multiple outcome indicators that cover the main possible intended and unintended outcomes. Furthermore, system changes can include structural changes in which the system gradually changes its mode of operation. The focus must be on the direction of whole system change in multiple domains, while assuming that the end point is uncertain. Lastly, important background changes may exist superimposed onto the outcomes of policy action, where the latter may exacerbate or synergise with existing background evolution trends.

For example, from this perspective, imposing a particular policy measure to achieve a certain objective (e.g. carbon price to reduce carbon emissions) should not be understood to lead to a new equilibrium state of society, technology and the economy, but rather, to *a new state of change* of behaviour, technology and the economy. That direction of change may suit some stakeholders and groups thereof, while others not, depending on their individual circumstances, motives, and aspirations. Particularly, some social groups may have vulnerabilities or states of resilience in various domains, which may be created, exacerbated, or mitigated by the policy initiative.

By taking a holistic systems view, the analysis encompasses the broader direction of change induced by possible policy strategies, including unintended impacts on different groups of stakeholders, as well as the wider range of possible extreme events and vulnerabilities associated with newly created systems. Thus, the use of models of complex systems by definition generates ranges of path-dependent outcomes, feedbacks and structural changes useful to populate a risk-opportunity analysis by generating both median outcome projections and tail risk analyses.

In practice this means that policy options need to be assessed in combination, rather than

individually, and assessed for a whole system, rather than limiting the analysis to a subset. Relationships between system components should be mapped and reinforcing and balancing feedbacks identified. Instead of assessing the expected outcome of a policy at a moment in time, these approaches can be used to assess whether a policy decision changes things in the appropriate direction (the direction of change), how much it changes things (the effectiveness), how quickly change happens, how confident we are that this new direction would be taken, and what the risks and opportunities are, as indicated below.

c. Generalising costs and benefits to risks and opportunities

Governments as well as other organisations are generally expected to consider tail risks, in various domains, generated by their actions, although the focus varies depending on the purpose of the policy or decision appraisal exercise. Strategic, regulatory, and budget policy and decision-making are interested in different aspects of uncertainty (Figure 2). On the strategy side, the focus is on the most likely outcome and direction of change induced by a strategic decision. However, regulatory decision-making (for example with safety, regulatory norms, compliance, quality assurance and insurance), will typically focus on ensuring that the system evolves within certain bounds away from extremes, maintaining sufficient capacity to absorb the impacts of unexpected events (e.g. based on estimates of tail events such as the likelihood of electricity black-outs, financial crashes, flooding, pandemics). Yet another category of policy action will assess whether a strategy fits within existing budgets and priorities. For the purpose of the present text, the three classes of policy-making *functions* will be denoted, respectively, '*strategy*', '*regulation*' and '*accounting*'.¹² All three functions and purposes of decision-making can make use of risk-opportunity analysis for different but related purposes.

¹² This does not mean to imply that anyone is necessarily strictly a strategist, a regulator or an accountant; we represent the *function* and *purpose*, carried out by a collective of policy-makers, as a fictional agent itself.

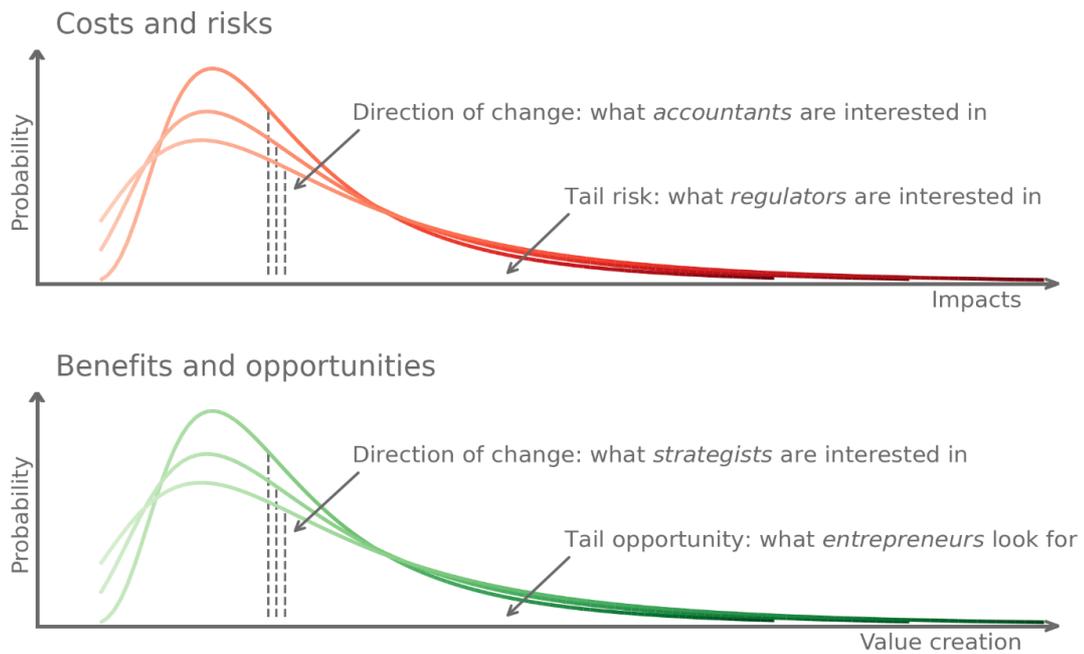


Figure 2: Illustration of heavy-tailed probability distributions for risks and opportunities. In complex systems, one can rarely accurately determine probability distributions, and thus these are shown with truncated unknown heavy tails. This suggests that expected values either do not converge or cannot be reliably calculated, but risks and opportunities can nevertheless be critically appraised.

Generalising welfare economics to complex dynamical systems, an accurate and comprehensive interpretation of non-linear dynamics and fundamental uncertainty suggests that comparing costs and benefits in fact implies a comparison of risks and opportunities. In that generalisation, the standard concept of ‘externality’ encompasses *systemic risk*, and the risk of reaching a tipping point due to collective action.¹³ Probability distributions cannot be assumed to be fully known since due to emergence in complex systems, one cannot confidently enumerate and rank all possibilities and have comprehensive knowledge, even if one can be confident about what is likely and what is less likely. Since they cannot be assumed known, due to the possible emergence of extreme events, probability distributions for costs and benefits must therefore allow for the possibility of heavy tails for any systems with moderately high degrees of complexity. *Therefore, expected values do not always exist and are not reliably calculated, and thus risk is not reliably quantifiable*¹⁴ (Figure 2). This particularly precludes the imposition of arbitrary probability distributions onto existing data, especially short-tailed distributions, since they potentially lead to wrong inferences and

¹³ In a complex networks context, some negative externalities can correspond to systemic risk (e.g. financial agents engaging in risky speculative investment impose a contribution to risk of systemic collapse onto all other financial agents) while positive externalities correspond to systemic economic opportunities that could potentially benefit everyone (the possibility of the whole system collectively functioning better). Tipping points can also be reached by other system feedbacks (e.g. climate change affecting the economy).

¹⁴ The longer the tails, the less reliable estimates of expected values are, and since probabilities often have (although not always) heavy tails, it is not possible to rely on expected values.

underestimation of real risks.

Where multiple plausible scenarios are generated but expected values are not reliable, three useful elements can be informed:

- i. The confidence that the *strategist* can have over whether a policy adoption will reach a certain outcome and send the system in movement in a desired direction that fits current objectives;
- ii. The confidence that the *regulator* can experience as to whether a system will avoid becoming prone to collapse in ways that exceed existing regulatory norms;
- iii. The *accountant* can also assess whether costs, negative outcomes, and tail risks of unintended negative consequences overshadow benefits and opportunities, and whether outcomes fit within or contribute to current fiscal priorities.

System stress tests can be used to assess risk. Indeed, as is clear in the practice of stress-testing, tail risk can be estimated without probability distributions necessarily being fully known, notably using network models (e.g. see Battiston *et al.*, 2017). This complements the estimate of *costs* with an assessment of *risks*.

However, in addition to these standard practices, the strategist, taking the role of an entrepreneur, should also assess using this analysis whether policy action is likely to open *options* for further economic and innovation opportunities. That is, without this being the main focus, some innovation strategies may offer further potential for opportunity generation and economic spillovers than others. This complements the estimate of *benefits* with an assessment of *opportunity*.

For example, a particular low-carbon transition policy strategy could have, compared to an alternate approach, different simultaneous types of outcomes: (1) it increases/decreases the likelihood of meeting stated emissions target; (2) it is more profitable/costly; (3) it makes the financial system more/less resilient (systemic risk decreases/increases); (4) it decreases/increases energy poverty; (5) as side effects, it creates/destroys, industrial capabilities with more/less potential to generate new products, markets and jobs.

In practice this means that policy options are proposed to be assessed for their broader risks and opportunities, not just their costs and benefits, and avoid aggregating outcomes over arbitrary probability distributions. Specifically, the assessment should encompass 'tail' risks and opportunities (e.g. tipping points), which may include very high impact outcomes, positive and negative. Reducing systemic risks generally implies increasing systemic resilience. The assessment must consider outcomes that can only be qualitatively assessed. The assessment is likely to rely on relevant expert knowledge and judgment; where this is the best available form of evidence it can be retained in its pure form, and not be converted to values.

d. Defining risk and opportunity

Systemic risk is well defined and managed in risk assessment methodologies (HM Treasury, 2020). Managing systemic risk is important in policy-making in order to design and shape systems in resilient ways, which allow them to withstand unexpected situations without leading to a likelihood of systemic failure. Systems typically need spare capacity to absorb such situations (e.g. during pandemics, or speculative bubbles). In many if not most systems, maximising performance may substantially increase systemic risks (e.g. see Doyle and Carlson, 2000; Carlson and Doyle, 2002).¹⁵ Underplaying heavy-tailed uncertainty, and optimising systems based on incomplete knowledge, leads strategists to design fragile systems prone to failure. Regulators, if not involved in the design, can inherit a built-in fragility challenging to manage, at potentially high costs for accountants and society. Uniting risk and cost assessments in the same policy analysis framework, including unintended consequences of design, naturally leads to improving the resilience of systems, and could open a new paradigm for policy design. It may also help better plan the direction of development of the economy in resilient ways.¹⁶ The risk-opportunity framework proposed in this article therefore encourages strategists, regulators and accountants to find ways to work closely together.

Opportunity, however, is a more diffuse concept. Whereas ‘risk’ concerns the likelihood of harm to existing components of a well-understood system (i.e. the one prevailing at decision-making time), ‘opportunity’ concerns the likelihood of decisions resulting in a system which is ‘better’ (under certain normative criteria) and/or features more option generation potential, than the prevailing one. Since a putative ‘better’ system, after transformation, is by definition less well known than the prevailing system, a ‘better’ outcome is naturally surrounded by more fundamental uncertainty than the *status quo*. However, the economy and markets are systems in continuous change, and entrepreneurs embrace that dynamism in their search for opportunities. Uncertainty is ultimately inseparable from innovation and productivity growth (Fontana, 2008; Klingebiel and Rammer, 2014).

In practice this means that, for example, policy choices with higher near-term costs and high near-term uncertainty (such as investing in innovation) can be identified in ROA for their potential to generate options to capture future opportunities with economic returns, while in comparison, other policies that have low near-term costs with low uncertainty but characterised only by moderate long-term return can be characterised as such in ROA. Similarly, policies that generate high short-term return with high confidence (such as focusing

¹⁵ This is true notably for financial networks, where reducing capital requirements accelerates investment but fragilises the whole system.

¹⁶ Notably, consider decisions regarding supporting the continued development of fossil fuel activities and infrastructure in comparison to low-carbon infrastructure (e.g. in Canada or the North Sea). A risk assessment of fossil fuel systems is likely to reveal some financial risk of stranded assets, in the context of expected rapid global decarbonisation (Carney, 2015; Bolton *et al.*, 2020), while its assessment of benefits may also reveal expectations of high returns. Whether the risks outweigh the returns is the normative choice of policy-makers, but a risk-opportunity assessment would document those as a business case is made for the choices.

on natural resource exports, or deregulating finance) but also damaging to the economy in the long run if they concurrently lead to a systemic risk build-up can be identified as risky in ROA. Such strategic insights resulting from ROA are not commonly obtained using marginal analysis.

e. Complex dynamics

Fundamental uncertainty implies that distant outcomes are uncertain, success is not guaranteed, and one can at best reliably control the direction of change, rather than the endpoint, and adaptively adjust policy over time to achieve stated outcomes. Figure 3 illustrates as an example the impact of a pricing policy for supporting the diffusion of low-carbon products (green) and the phase out of high carbon products (black) from the perspective of both static equilibrium (top row) and a dynamic complexity policy (bottom row) assessment frameworks. In the static framework, the driver is typically a tax that internalises a stated externality and changes the relationship between supply and demand accordingly. The outcome, such as the level of adoption of low-carbon technologies, is a unique static outcome of the driver, as it settles in a new equilibrium.

In the complex dynamics approach, policy shapes drivers that are themselves dynamic (e.g. vehicle prices with learning-by-doing cost reductions, which reinforce dynamic diffusion processes). Scenarios are generated in which uncertainty encompasses a range of directions of change rather than a range of static end points. Heavy-tailed uncertainty over outcomes results from the compounding effect of interactions between system components. Thus, a risk-opportunity assessment identifies central-, worst- and best-case scenarios, without giving a false sense of knowledge and certainty.

In practice this means that instead of looking for what new theoretical equilibrium is reached by a tax or subsidy, one identifies feedbacks that control the dynamics of evolution of the system, in order to look for the range of new trajectories that a system could take following the introduction of a policy portfolio. This can make use of scenario analysis: whether some or all of the scenarios achieve the stated objective; and whether opportunities can arise; and whether worst case scenarios fall within acceptable bounds of failure. Based on establishing system feedbacks and sensitive intervention points, policy space is searched until all objectives and standards are met under all dimensions of analysis.

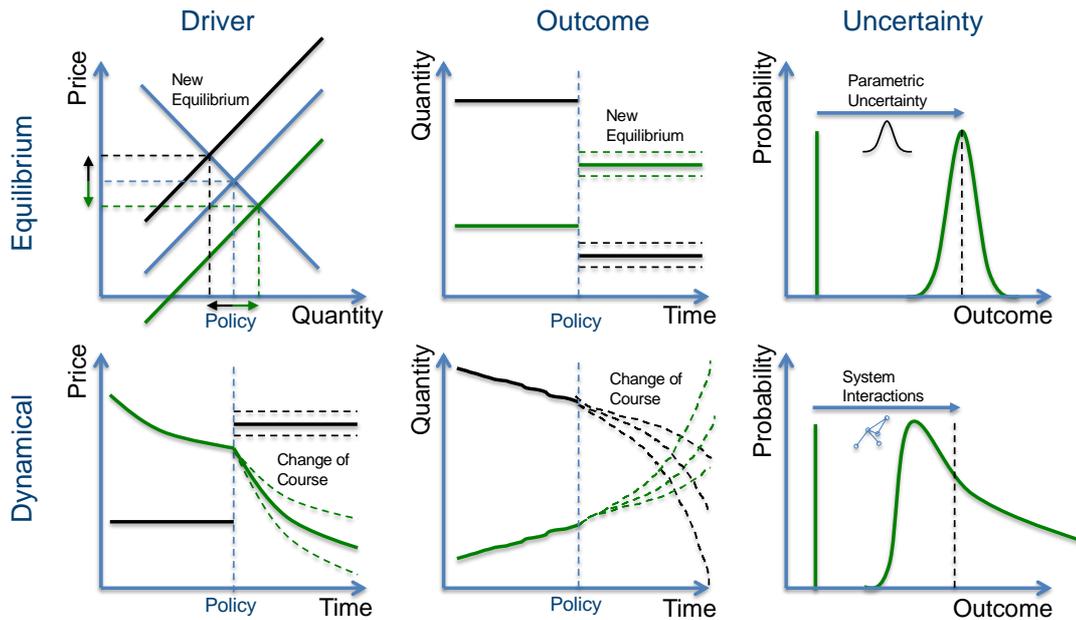


Figure 3: Comparison of the process of assessing change in policy impact assessment, between the marginal analysis framing (top row), and the complexity science framing (bottom row), in terms of its drivers (left), outcomes (middle) and uncertainty (right). This illustrates a situation of impact assessment of hypothetical policies for the diffusion of low-carbon innovations. In marginal analysis, pricing policies are typically used, which change the position of the equilibrium between supply and demand of green and brown products. The outcome is a well defined function of the driver, with assumed short-tailed probability distribution, giving a potentially false sense of knowledge and certainty. In complex systems analysis, the driver itself is dynamic, the outcome process can take a range of directions, and the true uncertainty, compounding system interactions, is frequently heavy-tailed.

f. From one-dimensional to multi-dimensional assessment

Different stakeholders value different outcomes of policy decisions, measured using different metrics, differently (e.g. GDP, health, jobs, environment), leading to political debates. In complex systems, each dimension has different degrees of uncertainty and tail lengths. Combining all metrics into one would also lead to combining their uncertainties, which could obscure uncertainty analysis unnecessarily. For example, the health impacts of reducing vehicle pollution in cities and its uncertainty is increasingly well characterised, however the economic impacts of reducing petrol and diesel use in certain countries, due to job losses, may be substantially less well characterised. Aggregating highly uncertain outcomes with relatively well-known outcomes leads to a valuation that is overall highly uncertain,

substantially undermining the analysis.

The assessment of impacts of a policy can be made individually on each metric chosen for the analysis, considering (1) intended and unintended outcomes, (2) alignment with the direction expected/desired, (3) its magnitude, (4) the degree of uncertainty or confidence in the outcome, (5) the likelihood of extreme events taking place, and (6) the option generation potential. In order to separate assessment from politics, a multidimensional analysis done independently for each relevant dimension is necessary. A relative normative valuation of policy outcomes can subsequently be carried out separately, with or without sophisticated quantitative methods, by independent actors who possess the political legitimacy to do so.¹⁷

In practice this means that analysts should report risks and opportunities in multiple dimensions relevant to the problem and leave the valuation of each of these dimensions up to policy-makers. The latter can evaluate the information and choices to be made in the context of stated multidimensional objectives and their knowledge of stakeholder needs and their diversity.

g. Principles for policymaking in a context of risk and opportunity

i. Whether to act at all

The foundational normative principle for policy-making under the Coase Theorem and market failure framework is to develop one policy response per identified market failure (Coase, 1960; Hanley, Shogren and White, 2016; Lehmann *et al.*, 2019).¹⁸ In a complex system with continuous endogenous change, or where the exogenous context changes faster than equilibrium can be reached, finding the optimal policy requires a search through an infinitely large set of possible futures branching out from one another: it cannot be identified in practice.

A foundational principle suitable for dynamical systems could instead be to act to prepare for change that is likely, to bring about options for change that is desirable, and to avoid change that is undesirable (e.g. see Marchau *et al.*, 2019). This is conceptually connected to the central principle of the 'market shaping' framework (Mazzucato and Penna, 2016), used to support the development of mission-oriented policies such as the 'Grand Challenges' in

¹⁷ Multi-criteria decision analysis used by the European Commission in its impact assessment guidelines (EC, 2015) follows more or less this spirit of analysis, which is superior to other methods as it requires a multi-dimensional policy assessment, and it allows for path-dependence in outcome scenarios. However, it does not involve estimations of uncertainty or specifically assess risks and opportunities.

¹⁸ Market failure is defined in the UK's Green Book as 'where the market mechanism alone cannot achieve economic efficiency', which itself is 'achieved when nobody can be made better off without someone else being made worse off [...] ensuring [scarce] resources are allocated and used in the most productive manner possible.' (HM Treasury, 2018).

the UK government's Industrial Strategy (UK Government, 2017), but is equally applicable as a rationale for any policy that is intended to achieve non-marginal change, or that takes place in a context of non-marginal change (or disequilibrium).

ii. How much effort to make

A principle of welfare economics is that effort to correct a market failure should be applied up to the level at which the marginal benefits of action are equal to the marginal costs of that action, thereby suggesting that this should be reliably identified. This is defensible on the basis of an idealised normative utilitarian framework of social justice but given that real world agents are not necessarily utilitarians,¹⁹ it is not necessarily what works in practice.

For non-marginal change, 'optimality' cannot reliably be identified because outcomes are heavy-tailed uncertain. The appropriate principle instead may be to apply sufficient policy effort to kick-start self-generating change over time (Farmer et al. 2019). This considers the value of policy in relation to the dynamic processes that it aims to influence. For example, if a government invests in the development of a new low carbon technology but abandons support for it before it is successfully commercialised, self-generating increasing returns may never materialise, and the investment could be wasted.²⁰

iii. Where to direct the effort

When a single marginal market failure exists, standard economic theory shows that externality pricing or compensation mechanisms can be applied after which the market can operate to allocate resources optimally. In cases where non-marginal change is possible, optimal states are not reliably identifiable, while some policies will be more effective in incentivising change towards objectives than others. The primary concern is therefore not allocative efficiency, but dynamic effectiveness (Rainer Kattel *et al.*, 2018). It may be more appropriate to act on known points of greatest leverage (Farmer *et al.*, 2019).

Applied to the pricing value of externalities, this principle implies that the most effective approach is not necessarily a uniform price across the whole economy,²¹ but prices targeted in specific sectors, set at specific levels that are likely to catalyse change (Kay *et al.*, 2012 section 8), (King et al. 2019) (Sharpe & Lenton, 2020). This principle also suggests that there is no reason to expect, *a priori*, pricing itself to be the most effective policy, and that other forms of targeted policy may be equally or more effective (notably, regulation). That policy

¹⁹ This academic debate happens notably in economic anthropology (Wilk and Cliggett, 2007), where evidence supporting utilitarianism is confronted to other evidence supporting social group responses and cultural and symbolic meaning of value and gifts (Sahlins, 1972; Douglas and Isherwood, 1979; Graeber, 2014).

²⁰ An example is offshore wind power in the UK: the initial cost of subsidies for offshore wind in the UK, required to enable initial deployment, was £140/MWh, equivalent to a cost of around £280/tCO₂e for the carbon emissions saved (using BEIS' own data for 2016). The value of emissions reduction used in UK government policy appraisal is currently £14/tCO₂e for the power sector and other sectors covered by the EU Emissions Trading Scheme, and £59/tCO₂e for sectors not covered by the EU ETS. <https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal>

²¹ For example, in UK electricity, dramatic emissions reductions have been achieved with regulations and a carbon price of about £35/tCO₂e, while in contrast, the existing petrol fuel duty, in place since 2011, is equivalent to a carbon tax of £238/tCO₂e, and has not induced since 2011 any intensified rush towards the adoption of electric vehicles.

should be 'technology neutral' does not appear to be supported by the evidence; what matters is to be effective at picking winners, not losers (Mazzucato, 2012; Klingebiel and Rammer, 2014; Carreras, 2020).

iv. Economic change, systems design and future-proofing

There is a trade-off between optimising the performance of a system under observed conditions, and maintaining its resilience to unforeseen circumstances (Doyle and Carlson, 2000; Carlson and Doyle, 2002). Take for example the Coronavirus pandemic: what may be deemed an 'optimal' level of bed capacity in the national health system, according to available resources and an assumed recurrence frequency of pandemics, could potentially have little to no resilience to actual pandemics, since these are rare events where the probabilities are not well characterised.

A second such example is technology choice in climate policy. Recent debate focused the need for substantial negative emissions occurring late century compensating for near-term emissions, scenarios developed on the basis of systems optimisation (IPCC, 2018). This may be a risky and false narrative underplaying real systemic risk, where emissions today contribute to the risk of possible future climate tipping points being triggered, a risk not mitigated by negative emissions.

4. POLICY DOMAINS WHERE ROA COULD MAKE A DIFFERENCE

In this section, we provide three examples of domains of policy that could benefit from the ROA approach in its appraisal. We explain why ROA can be applied, why it makes sense to do so, and what difference ROA makes in comparison to standard approaches.

a. Climate change mitigation and low-carbon innovation

Achieving the UK's climate target involves a deep transformation of most of its industries and systems, and a large-scale re-organisation of economic and industrial activity. This does not mean it will necessarily have negative consequences for the economy; however it will involve winners and losers. Winners will arise in new industries where high wage occupations are

created; workers in existing high-carbon industries being phased out will be at the losing end.

i. This policy objective does not meet the criteria for marginal analysis:

- *Stakeholders and their aspirations and needs are heterogenous, over several dimensions and variables: different industries, sectors, interests, perspectives.*
- *Low-carbon innovation is a non-linear process, featuring strong positive feedbacks and possible tipping points. Notably, the diffusion of innovations concurrent with learning-by-doing cost reductions have strong potential for rapid disruption.*
- *The impacts of climate change, as well as the outcomes of low-carbon innovation policy, are both characterised by heavy-tailed uncertainty and important social, financial and economic systemic risks.*

ii. Risk-Opportunity analysis can address targeted low-carbon innovation policy

Technological costs for addressing climate change are path-dependent, where the state of the technology is conditioned by the story of its development, and will be so in the future. This process is taking place with all key components of low-carbon technology, including batteries for electric vehicles. Since the costs and diffusion profiles of those technologies is highly dynamic, feedbacks must be mapped and understood, and dynamical models must be used to project the ranges of possibilities as results of deliberate policy in the UK and abroad. Notably, substantial first mover advantages exist when investing in innovation and technological change.

Opportunities of economic co-benefits from innovation policy exist, where the deployment of new technologies involves and enables the development of new capabilities nationally, which allows for the development of new industries and occupations that can become part of the makeup of the future economy and prosperity. The potential for new technologies to promote growth in key sectors can be estimated using detailed dynamical models of industrial transformation and capability on a scenario basis. This option generation potential can be assessed in ROA.

Risks emerging from a rapid low-carbon transition arise, where substantial financial value, labour and capital, invested in high-carbon industry and fossil fuel extraction, transformation, transportation and use across the economy, can become stranded, with substantial financial and socioeconomic implications. Furthermore, further investment now in high-carbon capital through lack of coordination can make the system more fragile. Estimating the accumulation of systemic risk in financial, economic and social networks is an important part of low-carbon policy appraisal, and is part of the ROA methodology.

iii. Risk-opportunity analysis reaches different conclusions to marginal analysis

Marginal analysis of climate policy first and foremost recommends pricing the carbon externality. ROA might recommend any combination of sectoral carbon pricing, targeted investment, regulation, or other measures, depending on those measures' likely effectiveness at reducing emissions in their respective contexts and their ability to generate

options for economic diversification in sectors and regions affected by post-industrial decline.

b. Multi-sector policy in response to a pandemic

Challenges encountered during the COVID-19 pandemic, and through the government response, have highlighted key salient issues in the need for and use of scientific information for guiding policy decisions. Challenges include determining the level of preparedness that society should continuously maintain, the structure of the health system response, the structure of the economic response and the structure of the stimulus package post-crisis.

i. Preparedness and response to pandemics do not meet marginal analysis criteria:

- *The likelihood and frequency of pandemics is not a well-known distribution, has a probability tail (most likely a heavy tail) that is not well characterised.*
- *The propagation of diseases is highly non-linear, such that delays in acting result in higher than proportional impacts, damages and loss of life.*
- *The economy falls so far under full-employment equilibrium that the impact of the economic response and stimulus is not well described by equilibrium economic theory.*

ii. Risk-Opportunity Analysis can address preparedness, response and economic stimulus

Preparedness. The frequency and magnitude of pandemic events is not known, which makes choosing a suitable level of preparations complex. ROA can help determine the balance between what is excessive and likely never to be used, and what is necessary to avoid a serious breakdown of the health system, including the adaptive capacity of the existing system. A system that is highly economical is also highly brittle, breaking down at every shock.

Lockdown response. The propagation of diseases is highly non-linear, reflecting the fact that the more people are ill and contagious, the more people are at risk of contracting the disease, and different response timings lead to radically different outcomes. ROA, which is arguably what has in effect been used in the UK, offers a suitable framework to integrate outcome data from non-linear epidemiological models, such as those that were used in the UK,²² to predict the outcomes and assess the direction of change of contagion in various scenarios of lockdown and social distancing policy.

Economic response. Offering no economic support would have led to systemic loss of aggregate demand and further job losses, which can lead to widespread insolvencies. Excessive support leads to accumulation of public debt that can have an impact on foreign

²² See <https://post.parliament.uk/models-of-covid-19-part-1/>

investor confidence and the economy's ability to service debt in the future. ROA could integrate a dynamic economic and financial analysis, under different dynamic scenarios of contagion and response, to evaluate suitable levels of support.

Post-crisis stimulus. How to prioritise the allocation of resources post-crisis should be addressed using dynamical modelling. Some sectors may face higher systemic economic and financial risk than others, notably the energy-intensive and heavy industries as well as transport (e.g. aviation). ROA can help determine whether reviving these sectors helps contribute to aggregate demand and restart the economy or leads to stranded investments due to rapid obsolescence or lack of sustained demand.

iii. Risk-opportunity analysis reaches different conclusions to marginal analysis

An extensive review of cost-benefit methods to determine pandemic preparedness revealed that none of 34 studies included non-marginal system transformations (Kellerborg, Brouwer and van Baal, 2020). Studies of the CBA of lockdown response typically compare the value of lost life against lost GDP, but indicate that the methodology critically depend on the value assigned to quality-adjusted life years, without consensus on the strategy to follow (Broughel, 2020; Miles, Stedman and Heald, 2020; Schonberger *et al.*, 2020). ROA however offers a deeper sense of the system dynamics at play. For example, due to the non-linearity of disease propagation, early and brief lockdown intervention may have widely different impacts on GDP and contagion than delayed action of the same or longer duration, analysis that can be done using detailed dynamical modelling over a wide range of possible strategies.

c. Regional development policy

Regional development is highly path-dependent, since local industrial, innovation and development capabilities build, to first order, on existing local capabilities. Just as success breeds success, regional development allows the creation of ever higher wage occupations and living standards, which attract further highly skilled labour, which helps fuel development further. Wages typically follow steep spatial gradients between highly and less developed regions across and within countries. Assessing regional development policies based on comparing local productivity, wages and prices can inadvertently exacerbate the typical winner-take-all positive feedback that already exists in the process of development.

i. Levelling-up policy does not meet the criteria for marginal analysis:

- *Positive feedbacks exist between the level of development of a region, and its ability to attract resources necessary for further development*
- *Reverse negative feedbacks exist where slowdown in regional development drives highly skilled labour away, reinforcing economic decline*
- *Regional development policy and infrastructure investment affects wages, which attracts new workers and change the fundamental economy in a path-dependent way*
- *Stakeholders are heterogenous and many dimensions are involved, notably inequality*

ii. Risk-Opportunity Analysis can address regional development policy

Targeted investment can catalyse and crowd-in private investment. ROA can analyse whether public authorities can signal a direction of travel to the private sector through local infrastructure investment that may or may not crowd-in further private sector investment. Leadership signals can help companies decide where to locate and access the skills they require. ROA with systems dynamics models can simulate local capability accumulation investment through cumulative causation.

Path-dependence and heavy-tailed uncertainty. The winner-takes-all nature of regional development implies that the outcome of intervention is uncertain, depends on history and the way in which it is carried out, and is therefore heavy-tailed uncertain. In ROA, scenarios of development are developed focusing on best and worse case scenarios to determine clearly the bounds of the problem and where the risks lie.

Maximising option generation instead of near-term income. Investing where expected return is highest does not necessarily mean investing where opportunities are highest, since some strategies with lower near-term direct returns can increase the potential for business creation generating higher longer-term indirect returns, compared to strategies with high direct near-term returns but low option generation potential. This is particularly true for the spontaneous emergence of new industry clusters following infrastructure developments or investment in innovation and higher education.

iii. Risk-opportunity analysis reaches different conclusions to marginal analysis

Infrastructure investment policy appraisal based on static CBA frameworks can identify near-term direct costs and benefits, but indirect, longer-term dynamical outcomes are not identified. Urban simulation models, for example, can help identify indirect, path-dependent impacts and offer a sense of urban planning strategy, while non-equilibrium regional economic models can track the development of capabilities and supply chains in wide ranges of policy strategies.

5. CONCLUSION

The next steps in proposing a risk-opportunity analysis framework to replace welfare economics-based policy assessment lie in laying out a framework development roadmap. This roadmap should be co-created in close collaboration with stakeholders and users of the framework. Ideally, this should include actors involved in purposes such as *regulating*, *accounting* and *strategizing*. Indeed, such a framework must respond to existing needs in existing science-policy interfaces which must be identified using an expansive engagement program between scientists and decision-makers.

A first part of the roadmap must involve an intensive dissemination program for concepts of complexity science applied to decision-making (dynamics, heterogeneity, uncertainty). A second part should involve developing clear context-dependent guidelines on how to use this framework under diverse situations and problems. The risk-opportunity assessment framework proposed here is as defensible on grounds of social justice as are cost-benefit analyses, multi-criteria assessments and other welfare-economics based policy assessments. However, it makes better and more honest use of available information and uncertainty.

It may be argued that welfare economics and equilibrium-based analysis and decision-making methods have not helped governments see clearly the best opportunities to drive the rapid, structural economic change that is needed to meet climate change goals. As Stern (2018) writes, *'The economic response [to climate change] has to be very large, involve dynamic increasing returns, changed economic and urban organisation and design, and the avoidance of potential lock-ins'* but *'we have seen models predominate where these elements, the guts of the story, are essentially assumed away.'* When society faces great challenges, economic analysis that assumes away the most important considerations can lead to unease and distrust of economics and economists on the part of policy-makers (Mercure, 2019) and the public (Haldane and Turrell, 2018). A stronger science-based decision framework may be an important part of the solution.

ACKNOWLEDGEMENTS

The authors thank UK BEIS and Treasury policy officers for support, direction and insights, as well as A. Roventini, F. Lamperti, G. Dosi, A. Jones and D. Farmer for insightful discussions. This work was funded by the UK's Department for Business, Energy and Industrial Strategy (BEIS), and by the Children's Investment Fund Foundation, under the Economics of Energy Innovation and System Transition (EEIST) program. JFM and SS jointly formulated the general framework and principle, and wrote the text. All authors contributed to developing the

framework, to the material and insights, and to writing the text. JFM and FJMMN developed the graphics. The authors declare no competing interests.

APPENDIX: COMPLEXITY SCIENCE FOR ECONOMIC GOVERNANCE

a. Properties of complex systems

Tools of complexity science are given in this section. The economy, as a complex system, is made up of many mutually interacting agents, subsystems, institutions, technologies and regulatory and political systems (Anderson, Pines and Arrow, 1989; Arthur, 2014). Complexity theory is the study of systems with interacting internal elements, and of the emergence of macro structure stemming from these interactions. Humans interact with one another and form social groups, fads and fashions, institutions, markets and technologies, which all have their own dynamical behaviour such as collective booms and crashes.

Complexity economics treats the economy as a perpetually evolving system. Agents are seen to make decisions using processes that can make use of use of plausibly available information. Decisions influence economic outcomes, which feedback to alter decisions. This sometimes leads the economy to a steady state,²³ but most of the time it leads to more complex endogenous dynamics. This makes it possible to understand path-dependence and the emergence of unknown unknowns and extreme events, considering the concepts in **Table 1**. These elements allow us to identify key properties missing in marginal analysis that matter for analysing non-marginal economic change.

b. Disequilibrium dynamics in complexity economics

In physical systems, if a stable equilibrium exists, a timescale to get to equilibrium also exists, which can be compared to the frequency of measurement and the rate of change of the environment. When equilibrium timescales are much shorter than the latter two, physicists assume equilibrium in every situation. But many systems have no equilibrium, or it is never reached as the time required to reach equilibrium is longer than the time it takes for the context to change. In the economy, inertia due to the long lifetimes of productive capital (Mercure, 2015) and the connectivity of economic networks (Hidalgo and Hausmann, 2009), economic evolution can be understood as constantly disturbed away from a steady state circular economic flow by non-ergodic innovative activity (Mercure, 2018).²⁴ Innovative activity (or evolution) creates order in the economic system (self-organisation), which continuously increases its efficiency of resource use. The combinatorial implications of

²³ Steady states can arise, but are not assumed to necessarily happen – see Mercure *et al.*, (2019) for a classification of theory and methods.

²⁴ Concept originating with Schumpeter (1934).

evolution and self-organisation suggest that the economy will not have had time to explore all of its possible states even over the age of the universe (Kauffman, 2000) (Beinhocker, 2005).

In practice, there exist different timescales and length-scales over which non-equilibrium systems may exhibit properties closer or further away from equilibrium, or more or less volatile and uncertain. Some quantities can be predicted with relative ease for longer periods than others (e.g. employment in comparison to financial asset prices).

c. Path-dependence and the direction of change in complex economic systems

Systems that are strongly path-dependent (with memory of the past, i.e. not in equilibrium) exhibit different behaviour than systems that are not (without memory of the past, i.e. in equilibrium). Most systems touching environmental policy are path-dependent: the climate, ecosystems, and the economy. This does not mean that they are not stable; it means that they cannot be described as having no memory, and the order in which events take place matters for describing the future.

For example, take the diffusion of innovations (Arthur, 1989; Arthur and Lane, 1993; Rogers, 2010; Mercure, 2018), innovation itself (Arthur and Polak, 2006) and the development of industrial clusters and regional economic development (Arthur, 1986). These are typically self-reinforcing (path-dependent) phenomena in that the more innovation is made visible/available, the more it is adopted, and the more it becomes visible/available. Similarly, the development of new capabilities enables the development of yet more capabilities. Every element along the path of diffusion affects the subsequent path of diffusion. The same happens for industry clusters: since industries typically save on operational costs by locating in the vicinity of other related industries, industry location is determined by contingent, early historical events (e.g. where the first plant was built).

Table 1: Key properties of complex economic systems.

Disequilibrium	In dynamical systems theory, the equilibrium steady state is a special state, and one that is not necessarily likely to emerge or to last, depending on stability conditions that must be established. Persistent and accelerating creation of novelty and increasing product diversity, continuously revolutionising industrial systems is a defining characteristic economic evolution (Freeman and Louçã, 2001), with some parallels to natural systems (Lenton and Watson, 2011) .
Heterogeneity of actors' interests and expectations	The aspirations and motives of actors in the economy are heterogenous (Mercure et al., 2016), and cannot always be reliably replaced by averages. Agents are not all accurately described as utilitarians (Wilk and Cliggett, 2007), while beliefs, morals, aspirations and motives are not cardinally measurable with any certainty.
Emergence	Emergence is the appearance of system behaviour that is qualitatively different from the behaviour of components of the system. Where this property exists, the behaviour of the system cannot be extrapolated from the behaviour of an individual component or agent within it. In the economy, emergent phenomena arise from the interactions between economic agents, and include financial crashes, fashions, the diffusion of innovations and the formation of social groups.
Disproportionality of cause and effect	The frequent existence of reinforcing feedbacks in complex systems creates the possibility, and likelihood, of non-linear change where small input changes can lead to larger than proportional outcomes (the 'butterfly effect'), hysteresis, inertia and additional dynamics.
Non-ergodicity and path-dependence	An ergodic system has the same statistical behaviour averaged over time as over its entire set of possible states, and therefore has no memory of its past. The economy is not ergodic, since the more states the economy explores, the more states it becomes able to explore, which grows faster than the number of possibilities it eliminates, the range of explorable future states being shaped by the system's past history (Kauffman, 2000). This implies that future scenarios necessarily diverge from one another as small differences in trajectory cumulate over time (Lyapunov, 1892).
Fundamental uncertainty	The reliability of predictions in complex systems away from stable equilibria generally declines with the length of the projection time span, where nearer term projections are more reliable than longer term ones. Furthermore, possible futures can frequently not be exhaustively enumerated with confidence, while long-heavy-tailed probabilities frequently arise. Both render the use of expected values unreliable. ²⁵

²⁵ Notably, power-law frequency distributions is a frequent emergent observation, of which the first moment diverges if the distribution exponent is lower than 2, or its estimation is unreliable where it does not diverge, requiring very large datasets to suitably sample low frequency events. This arises notably with financial data.

It follows that change in the economy has a direction, and a momentum (Mazzucato, 2013; Mazzucato and Penna, 2016). Clearly, it is not the sole result of policy action, but such action can catalyse momentum. The economy is in constant movement, and the role of policy is to help re-direct its course towards desired outcomes. Much like the climate system: it sees endogenous change from within, currents, turbulence, and occasional extreme events.

In response to path-dependence, economic agents and decision-makers become adaptive by continuously re-assessing their positions over time, and as they do so, near-term uncertainty is reduced by performing new observations (Figure 1 *Right*). This illustrates how opportunity can be conceived: uncertainty generates an increasing variety of possible good and bad futures over time in comparison to earlier projections made by agents when investment decisions have been made. As time passes, agents validate their past investment decisions (Minsky 1986), reinforcing their future ones. This awareness of the wide range of possibilities is what entrepreneurs use for hedging risks and capturing passing opportunities of higher than expected returns.²⁶

d. The structure of uncertainty in complex economic systems

Complex dynamics and fundamental uncertainty can arise in systems in which many elements strongly interact with other elements, even if each of these may have perfectly well-known behaviour rules or economic return when isolated from others. They collectively behave differently when interacting (Arthur, 2014).

Many systems with meaningful interrelations between components are also prone to emergent extreme events characterised by heavy probability tails. Examples of such events that are well described by complexity theory include the failure of transport, water or power networks, financial crashes, disruption in industrial supply chains, or many other types of cascading events (Bak, 1996; Gallos *et al.*, 2005; Kishore, Santhanam and Amritkar, 2011; Vespignani, 2012). The higher-than-normal likelihood of extreme events is in many cases driven by the combination of the properties of 'contingency' and 'fluctuations' (Bak, Tang and Wiesenfeld, 1987; Watkins *et al.*, 2016). Since in complex systems, variations trigger variations, just like earthquakes trigger earthquakes, and financial fluctuations trigger financial fluctuations, it is often the study of variations in complex systems that reveal information about their propensity to produce extreme events (Bak, 1996), and to possess tipping points (Lenton *et al.*, 2008; Lenton, 2020).

²⁶ This is not to say that path-dependence is a generator of normative principles, as it is merely a description of reality and agents behaving within their cognitive space.

Table 2: Strands of economic theory compatible with principles of complexity economics.

Theory branch	Focus	Seminal contributions	Model examples
Complexity	Emergent economic phenomena	Anderson, Pines and Arrow, (1989); Arthur, (2014); Beinhocker, (2005)	Agent-based
Evolutionary	Innovation, finance, business cycles	Schumpeter (1934); Nelson and Winter (1982); Freeman and Perez (1988); Perez (2001)	Networks, agent-based, systems dynamics
	Socio-technical transitions	Geels (2002)	Qualitative
Post-Keynesian	Macroeconomics, money, finance	Keynes (1936); Minsky (1986); Lavoie (2014); Wray (2016); Pollitt and Mercure (2017)	Macroeconometric, stock-flow consistent simulations
Ecological	Resource use, economic metabolism	Georgescu-Roegen (1971)	Systems dynamics
Econophysics	Financial markets, systemic risk	Hidalgo and Hausmann (2009); Battiston <i>et al.</i> , (2012); Sornette (2017)	Network models

Take a domino chain standing idle in a noisy environment: while one domino has a well-defined likelihood of falling over on its own due to the noise, estimating its likelihood of falling over due to its neighbours falling is complex as it depends on the likelihood of its neighbours' neighbours falling over, which depends on their respective neighbours, and so on. These tele-connections generate a compounding effect that spans as far as the whole chain of dominoes. The main characteristic of the problem is that the likelihood of a domino falling due to its neighbours is much higher than that of falling over due to the noise, and the likelihood of the whole chain falling over collectively (the systemic risk of an extreme event) is many orders of magnitude higher than the likelihood of all individual dominoes falling over on their own independently due to the noise. Thus, the fact that elements are chain-linked

means that this system has a high likelihood of extreme events (collective collapse), the likelihood of systemic collapse is heavy-tailed but the exact probability function is not straightforward to determine. In fact, the compounding of uncertainty across the chain means that estimates of likelihood of systemic collapse are themselves more uncertain than for individual dominoes. Assuming normal probability distributions, such as those that may describe the noise, leads to vastly wrong predictions (e.g. Adams and Thornton, 2013).

The various strands of economic theory that can fit under complexity economics as an umbrella term are given in **Table 2**.

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