Evaluation of economic approaches under high-end scenarios

Deliverable D5.1

February 2015

Rob Tinch[1], Cindy Schoumacher[1], Marco Grasso[2], Marco Ettore Grasso[2], Antoine Mandel[3], Francesco Lamperti[4], Mauro Napoletano[4], Andrea Roventini[4], Alessandro Sapio[4], Jill Jäger[5], J. David Tabara[6]

[1]Iodine, Belgium
[2]UNIMIB, Italy
[3]CNRS, France
[4]SSSA, Italy
[5] Independent Scholar, Austria
[6] Independent Scholar, Spain

IMPRESSIONS – Impacts and Risks from High-End Scenarios: Strategies for Innovative Solutions (www.impressions-project.eu)

Prepared under contract from the European Commission

Contract n° 603416
Collaborative project
FP7 Environment

Project acronym:	**IMPRESSIONS**
Project full title:	**Impacts and Risks from High-end Scenarios: Strategies for Innovative Solutions**
Start of the project:	01 November 2013
Duration:	60 months
Project coordinator:	University of Oxford
Project website	www.impressions-project.eu

Deliverable title:	Evaluation of economic approaches under high-end scenarios
Deliverable n°:	D5.1
Nature of the deliverable:	Report
Dissemination level:	Public
WP responsible:	WP5
Lead beneficiary:	Iodine sprl
Citation:	Tinch, R., Schoumacher, C., Grasso, M., Grasso, M.E., Mandel, A., Lamperti, F., Napoletano, M., Roventini, A., Sapio, A., Jäger, J., Tabara, J.D. (2015). *Evaluation of economic approaches under high-end scenarios*. EU FP7 IMPRESSIONS Project Deliverable D5.1.
Due date of deliverable:	Month 16 (February 2015)
Actual submission date:	Month 16 (February 2015)

Deliverable status:

Version	Status	Date	Author(s)
1.0	Draft/plan	September 2014	Rob Tinch, Cindy Schoumacher
2.0	Draft	13 November 2014	Rob Tinch, Cindy Schoumacher
3.0	Draft	17 December 2014	Rob Tinch, Cindy Schoumacher, Marco Grasso, Marco Ettore Grasso, Antoine Mandel, Francesco Lamperti, Mauro Napoletano, Andrea Roventini, Alessandro Sapio, Jill Jäger, J. David Tabara.
4.0	Review	15 January 2015	“”
5.0	Draft	16 February 2015	“”
6.0	Final	25 February 2015	“”

Table of contents

Preface 5
Summary 5
1. Introduction 7
2. Climate change adaptation and mitigation under HES 8
   2.1. Policy context for studying HES 9
   2.2. Specific issues for HES 10
      2.2.1. Dealing with future generations 11
      2.2.2. Uncertainties and risks 12
      2.2.3. Temporal and spatial scale mismatches 15
      2.2.4. Tipping points, irreversible risks and non-substitutability 16
   2.3. Link to the IMPRESSIONS workplan 16
3. Conventional appraisal methods 17
   3.1. Cost-benefit analysis (CBA) 18
   3.2. Cost-effectiveness analysis (CEA) 19
   3.3. Real option analysis (ROA) 20
   3.4. Portfolio analysis 21
   3.5. Iterative risk management (IRM) 22
   3.6. Robust decision-making (RDM) 23
   3.7. Multi-Criteria Analysis (MCA) 25
   3.8. Critique of conventional methods for use with HES 26
4. Alternative methods 30
   4.1. Indicators of well-being and development 30
   4.2. Capacity-based approaches 32
   4.3. Threshold-based decision-rules 33
      4.3.1. Maximin method and minimax regret 34
      4.3.2. Safe Minimum Standards (SMS) 34
      4.3.3. Critical natural capital 35
      4.3.4. No net loss 36
   4.4. Complexity and agent-based methods 37
      4.4.1. Complexity and HES 37
      4.4.2. The potential of Agent-Based Modelling 39
      4.4.3. Climate issues and ABMs 40
   4.5. Summary for IMPRESSIONS 42
5. Conclusions: methods to apply in IMPRESSIONS 45
   5.1. Criteria to choose the best methods 46
   5.2. Selecting indicator methods in step with scenario, vision and model development 48
6. Acknowledgements 49
7. References 50

List of abbreviations

ABM: Agent-based model

CBA: Cost-benefit analysis

CEA: Cost-effectiveness analysis

DICE: Dynamic Integrated model of Climate and the Economy

EEA: European Environment Agency

EU: European Union

FP: Framework Programme

GDP: Gross domestic product

GHG: Greenhouse gas

HDI: Human Development Index

HES: High-End Scenarios

IAM: Integrated Assessment Model

IHDI: Inequality-adjusted Human Development Index

IPCC: Intergovernmental Panel on Climate Change

MACC: Marginal Abatement Cost curves

MCA: Multi criteria analysis

NNL: No Net Loss

OECD: Organisation for Economic Co-operation and Development

PDF: Probability Distribution Function

ROA: Real option analysis

SMS: Safe Minimum Standards

TEV: Total Economic Value

UNECE: United Nations Economic Commission for Europe

UNFCCC: United Nations Framework Convention on Climate Change

WP: Work Package

WTP: Willingness to pay

Preface

IMPRESSIONS WP5 aims to use information gathered in WP1-4 to analyse the synergies and trade-offs between adaptation and mitigation pathways. The focus is mainly on the level and distribution of societal and economic risks, vulnerabilities, opportunities, costs and benefits within the context of high-end scenarios (HES). This report considers the specific challenges related to appraising policy options under HES. It provides a review of methods for assessing the impacts of adaptation and mitigation pathways, and evaluates the applicability of these methods under the specific context of HES. The report concludes with recommendations for integrating the process of method selection in the IMPRESSIONS workplan, and in particular the stakeholder workshops.

Summary

Climate change adaptation and mitigation policies have been a focus of research for many years, driven by increasing weight of evidence and growing concerns about possible impacts, risks and vulnerabilities. However, relatively few studies have focused on "high-end scenarios" (HES) with potentially extreme and disruptive consequences.

This can be partly explained by reluctance to accept that the 2^{o}C target set by the EU and the UNFCCC is unlikely to be achieved. However, policy-makers are increasingly interested in evidence concerning these scenarios, and research into HES is gradually expanding to meet this need. The IMPRESSIONS project is advancing knowledge on HES by describing the features and consequences of such scenarios, and by proposing innovative solutions for adaptation and mitigation which effectively respond to high-end climate change.

One particular challenge that a project like IMPRESSIONS has to face is the assessment of different ensembles of climate change policies under HES. Conventional appraisal methods face severe limitations for assessing the impact of adaption and mitigation in complex and non-linear frameworks characterised by tipping points, irreversible thresholds, and extreme endogenous shocks. New alternative approaches and tools are needed.

Conventional economic methods depend heavily on the ability to estimate future market and non-market values. These methods face many ethical and practical criticisms that are mostly exacerbated in the context of climate change, and especially HES. They require monetary expressions of all costs and benefits, based on the assumption that income-dependent expressions of preferences are stable and good indicators of welfare. Data gaps are extensive, due to imperfect understanding of ecosystem processes and human behaviour, which leads to an under-weighting of non-monetised impacts in evaluations and potentially in decision processes. Even when partial-equilibrium estimates are present, they are not reliable for very different long-term projections and scenarios analyses, as non-linearity and threshold effects limit the range of service provision over which such estimates are informative. More generally, standard evaluation analysis based on the theory of rational choice under uncertainty cannot be employed in HES, where the probability distribution of future events is unknown and can change over time.

Therefore, there is a need for innovative methods to evaluate adaptation and mitigation policies under HES. Alternative approaches focusing on sustainability and associated indicators of well-being may be more appropriate and informative. There are many candidate indicators relating to broad definitions of wealth and welfare, capabilities and capacities, and specific outcomes such as mortality or vulnerability indicators. Options for using these indicators include maximin criteria, setting vulnerability thresholds and estimating the costs of meeting them across all scenarios, or linking policy appraisal closely to the modelling of the evolution of capacities over time.

Alternative methods generally present a less clear-cut 'bottom line' appraisal result than classical economic methods. However, given the radical uncertainties and the purpose of the modelling, this is not a disadvantage. Presenting policy appraisal in simple numerical terms risks giving a spurious and ultimately unhelpful, even dangerous, illusion of confidence or certainty. Especially in the context of HES, where the future is highly unpredictable, we are less interested in 'optimal' policy and more interested in aiding a process of reflection about the possible consequences of climate change and possible robust adaptation options for dealing with them. In this respect, IMPRESSIONS aims to explore possible pathways consistent with achieving desirable outcomes, or avoiding vulnerabilities, under HES. Furthermore, the radical uncertainties and transformative changes that are likely to be associated with the IMPRESSIONS scenarios suggest that keeping track of capacities to adapt and cope with uncertain climate change may be more practical and policy-relevant than attempts to predict (unreliable) numerical values for specific outcomes.

There are two distinct, but closely linked, purposes for evaluating the impact of adaptation and mitigation policies under HES. Firstly, there is a need to develop ways in which the impacts of near-term policies and decisions can be assessed, in terms of their long-term consequences. Secondly, there is a need to provide a structure that will help stakeholders and researchers compare radically different future scenarios and assess opinions regarding desirable and undesirable futures. These purposes are closely linked through the search for robust policy options – adaptation and mitigation choices that perform well under all scenarios. The same indicators and methods can be adapted to each purpose. In developing this assessment, there are several choices to make, including:

- Focusing attention at the level of individual welfare, or focusing on societal indicators.
- Focusing on measures of outcomes (for example average income, income distribution, agricultural and labour productivity, unemployment, health outcomes …) or on measures of opportunities (capitals, capabilities).
- Pre-judging the goal and automating the trade-offs or adopting a more flexible approach to trade-offs.
- Restricting choice to a small number of indicators, or providing a diversity of indicators and tools for selecting or weighting.

In such an assessment, agent-based models (ABMs) are very useful tools to inform researchers, stakeholders and policy-makers about the possible impact of different climate change policies. They model the environmental and economic framework as a set of heterogeneous, boundedly-rational agents (e.g. firms, households, governments, stakeholders…). A crucial aspect of ABMs is that they can represent learning (e.g. of decision rules of agents over time) which is central to adaptation strategies under HES. ABM simulations can be employed to design and test the impact of different ensembles of policies under evolving climate and socio-economic scenarios, and in particular assessing interactions between systems of solutions and pathways aimed at supporting transformation. In this respect, ABMs are a valuable tool for transformative science, as they can be employed as artificial policy laboratories where researchers and policy-makers can interact, informing the ranking of different policy solutions and the testing of their robustness under HES.

The final decisions on the methods and indicators to be used in IMPRESSIONS, are dependent on the work being developed in other areas of the project. In particular, this includes the stakeholder-led scenario and vision development, as well as work on developing indicators of adaptive/coping capacities and modelling their evolution in the scenarios, taking account of adaptation policies. In the conclusion to this report, we set out criteria for selecting methods, and explain how the work will be taken forward in step with the scenario and vision development and other IMPRESSIONS work streams.

1. Introduction

'High-end' scenarios (HES) are those that describe climate change levels at the upper end of the range of possible futures. Whilst a target to limit climate change to 2°C above pre-industrial levels has been agreed by the EU and subsequently by the UNFCCC, HES are considered in IMPRESSIONS as those beyond this target, including, for example, a scenario consistent with a potential revised policy target of +3°C, and worlds of +4°C and higher. HES include the underlying socio-economic storylines, both as the drivers of emissions (and other contextual factors) and as narratives that capture a range of plausible societal challenges to adaptation and mitigation, as well as the ability of society to cope with the impacts of climate change.

HES have received relatively little attention in the impact assessment literature. One reason for this could be a perceived need for conservatism in communicating the need for climate action, and fear that discussing HES implies a politically-unacceptable recognition that the 2°C target is unlikely to be reached. It is also possible that since HES are perceived to be less likely, they are less central in the scientific literature. Alternatively, the consequences of HES may be perceived to be so extreme that their "cost-benefit analysis" has been performed implicitly and consensus on avoiding them requires no further public debate. More controversially, one could argue that the lack of focus on HES stems from the inadequacy of standard cost-benefit methods for their analysis or the unwillingness of human societies to consider extreme outcomes.

In any event, it now appears increasingly clear that global increases in mean temperatures are likely to be over 2°C (IPCC, 2013; IPCC, 2014a). This could have important environmental and human consequences, in particular because many impacts are expected to increase non-linearly with temperatures. The requirements of adapting to 4°C warming are not a simple extrapolation of adaptation to 2°C (Smith et al., 2011). The IMPRESSIONS project is one of a growing number of research initiatives based on the idea that it is essential to consider HES in order to foster stronger action on mitigation, to develop an understanding of possible early warning signals and to catalyse the transition towards a low-carbon society.

IMPRESSIONS aims to quantify and explain the consequences of HES, taking into account uncertainties and strong non-linear changes related to these scenarios and those with intermediate warming levels. High-end climate and socio-economic scenarios will be created at multiple scales and applied to impact, adaptation and vulnerability models to produce time and path-dependant transition pathways, enhance synergies between adaptation and mitigation and develop resilience regarding uncertainties. IMPRESSIONS also aims to involve stakeholders within several case studies to develop HES and adaptation and mitigation pathways, so that their understanding of the risks, opportunities, costs and benefits regarding these pathways under HES will be improved.

This recognition of the decreasing likelihood of achieving the 2°C target must not lead to the trap of 'self-inflicted irrelevance' (Geden, 2012, p. 20), reducing the credibility and momentum of attempts to reduce emissions. On the contrary, it should increase the sense of urgency and motivation to act given the potentially dramatic consequences of the outcomes associated with HES. Stern (2006) argues that a "business-as-usual" trend in emissions would lead to +2-3°C by the end of the century and perhaps +5-6°C next century. Impacts are difficult to assess, but would be extensive: Stern cites 5-10% loss in global GDP, though poorer countries could lose much more, and changes could more fundamentally threaten human well-being, health and the environment. The possible consequences are also likely to occur faster than in less extreme scenarios, and, given the presence of non-linearity and tipping points, we would no longer face marginal changes (as in conventional cost-benefit work), but radical and potentially discontinuous shifts.

This gives rise to the question of the relevance and practicability of attempts to assess "costs and benefits" in the context of HES. The complexity, non-linearity and possible thresholds associated with HES raise several challenges that cannot be addressed easily with classical economic methods. This report seeks to consider these specific challenges, to assess the applicability of existing methods, and to define innovative solutions and recommendations about the methods and tools to be used for the analysis of alternative pathways within IMPRESSIONS.

To achieve these aims, this report undertakes a review of existing tools and methods. The aim is to define whether, and under what conditions, we can consider some of these approaches for analysis of adaptation and mitigation pathways related to HES. We consider a wide range of methods, from classical economic methods such as cost-benefit or portfolio analysis, to approaches focusing on satisfaction instead of optimality. We also consider novel approaches, such as using agent-based models, which integrate the notion of complexity, derive indicators of performance or value and identify key system interdependencies and vulnerability nodes in systems interactions and configurations.

The outcomes of the research have been discussed and validated with a selected set of experts to consolidate the results. The conclusions present recommendations for the methods to be developed and implemented within the IMPRESSIONS project to evaluate alternative climate change policies under HES.

The next section of this report focuses on background issues and requirements for assessing adaptation and mitigation pathways under HES. The third section focuses on conventional approaches to policy appraisal, and develops a critique of their applicability in the context of HES. The fourth section examines alternative approaches based on non-monetary indicators, capacities and threshold-based decision rules, and discusses the potential applications of agent-based models as a means of dealing with the complexity of HES. The fifth section then concludes briefly on the next steps in IMPRESSIONS, explaining how the upcoming work on scenario and vision development, in particular the stakeholder workshops and work on developing capacity indicators, will shape the final selection of indicators for assessing pathways and the methods of their analysis and presentation in the IMPRESSIONS project. To evaluate the approaches, we develop criteria that can be used to assess the suitability of the methods under HES.

2. Climate change adaptation and mitigation under HES

The future is highly uncertain: we do not know which of many different possible climate and socio-economic scenarios will be realised. This is partly dependent on the decisions and actions of humans, and partly on biophysical relationships. Both are complex and imperfectly understood. The consequences of climate change, and the risks it poses to society, vary greatly across different scenarios and may be irreversible. This should be considered when deciding adaptation and mitigation policy. For example, while around 20 to 30% of species assessed so far are likely to be at increased risk of extinction if rises in global average temperatures exceed 1.5 to 2.5°C, 40 to 70% of species assessed would be at risk of extinction if global average temperatures exceed about 3.5°C warming (IPCC, 2007: 54). Consideration of such uncertainties and possible irreversible damages is particularly important under HES. Research to better understand and capture the uncertainties associated with HES could therefore inform the development of adaptation and mitigation strategies to offset these risks. This may lead us to radically revise our ways of understanding and planning for the future in view of such severe challenges.

However, HES are under-researched. The IPCC's WGII 5th Assessment Report (IPCC, 2014b; IPCC, 2014c) reveals much thinner evidence on the outcomes of HES than evidence for impacts of other scenarios. There is a gap between the information that can be provided by existing climate models and what policy-makers really need in terms of assessing the risks and consequences of HES.[1] This is partly because standard models cannot deal well with HES, and partly because information is not communicated effectively or in 'usable' forms to policy-makers, for instance because the distinction between "high-end scenarios" and "catastrophic scenarios" is blurred (many HES may be catastrophic, but some might not be, and not all possible catastrophes are associated with HES).

2.1. Policy context for studying HES

Climate change is a long-term process, but important policy decisions must be made in the short-term. Although the literature focusing on HES is not yet well-developed, demand for policy-relevant knowledge about them is present – as evidenced by the FP7 call under which IMPRESSIONS and its sister projects (HELIX and RISES-AM) were funded. At the EU level, we carried out interviews with three policy officers at DG CLIMA. They expressed an interest in having more information on a range of possible scenarios for mid- and long-time horizons, citing 2030-2050-2080-2100, with a view to comparing intermediate with extreme scenarios. Demand for mid-term scenarios (2020-2025-2030) was also emphasised in interviews with two policy officers at DG Research, where mid-term scenarios were considered to be more 'realistic' than long-term scenarios for decision-making.

The precautionary principle is a strong policy driver for the consideration of HES. This is a key principle of environmental governance that applies to *'situations of scientific complexity, uncertainty and ignorance, where there may be a need to act in order to avoid, or reduce, potentially serious or irreversible threats to health and/or the environment, using an appropriate strength of scientific evidence, and taking into account the pros and cons of action and inaction and their distribution'*[2]. It features prominently in many international environmental policy processes, texts and treaties and in national strategies and laws of many countries. It is one of the four environment principles in the Treaty of the European Union, in which article 191,§2 states that Union policy on the environment *"shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay"* (European Commission, 2012). The potential negative outcomes of HES could be very severe, so the high uncertainty associated with these scenarios is not a good reason for ignoring them.

The key decisions can be split into two broad areas, mitigation and adaptation. Mitigation seeks to tackle the root causes of climate change, while adaptation focuses on adjustments to economies, technologies and the human-environment system that can reduce the impacts and damages of climate change, or take advantage of opportunities that may arise. In the case of HES, conventional adaptation and mitigation together might not be enough to respond to the (potential) impacts of climate change: we may require transformative change in many of our current institutions and cultural frames. Methods are needed for analysing the risks and opportunities of different strategies for adaptation, mitigation and transformation under HES.

---

[1] Conferences at the European Commission (Brussels, Belgium) on the 06/05/14 about "Climate change adaptation and mitigation: key messages from IPCC's 5th Assessment Report and implications for policy and decision-making and at AgroParisTech (Paris, France) 19/06/14 "Economie et attenuation/adaptation face au changement climatique: Enseignements du GIEC pour les entreprises et les pouvoirs publics"

[2] See: working definition of the precautionary principle proposed by the European Environment Agency – EEA 2013, p. 649. Also Principle 15 of the Rio declaration (1992) http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

Appropriate climate policy will involve some balance of mitigation, adaptation, transformation and residual damages. Debates about these policies have different requirements: mitigation is driven by the politics of controlling emissions sufficiently to meet certain climate targets (so tighter targets could motivate greater action), whereas adaptation is driven by the need to foresee and adjust to future climate impacts and vulnerabilities (so higher warming estimates or projected impacts could motivate greater action). This is a source of friction and policy advisors often disagree regarding the appropriate way to act (Bretteville Froyn, 2005; Kates, 1997). Some argue that because of uncertainties, measures should be delayed pending better knowledge of potential impacts (meanwhile, we can invest in diverse projects to enhance the innate ability of systems to adapt to changes), whereas others think that mitigation measures must be put in place now, following the precautionary principle (Aaheim et al., 2001). In practice, the overwhelming focus of policy at the international level is mitigation to meet the agreed strategic aim not to exceed a 2°C increase in global mean temperatures. But focusing too strongly on achieving the 2°C target could prevent us from putting in place measures that would deal with higher increases in temperature, perhaps until it is too late.

One approach to walking this line is to adopt different figures for different debates: "mitigate for 2°C but adapt for 4°C" (New et al., 2009) or the ABC approach of **A**im to stay below 2°C; **B**uild and **B**udget assuming 3-4°C; **C**ontingency plan for 5-7°C (Mabey et al., 2011). There are various strategic and political considerations here (see Jordan et al., 2013), including the risk that planning for 5-7°C could hamper mitigation efforts. However, it is clear that it is valid and even important to consider HES. There is a non-negligible possibility that high-end conditions could arise, so the robustness of adaptation policy to these possibilities should at least be considered and the potential for transformative solutions should be explored. Studying HES to convey an image of extreme outcomes can foster action by providing the image of what has to be avoided by all means. HES analysis can also provide early warning signals that the "danger zone" is close.

2.2. Specific issues for HES

HES involve greater complexity and uncertainty, and generally longer time horizons, than assessments focused on the consequences of 2°C warming or intermediate scenarios. There is pervasive and substantial uncertainty and a strong possibility of encountering thresholds and tipping points.

Evaluating the impacts of policy options is extremely challenging, involving environmental and social conditions that are further removed from the current situation. This can have consequences for the metrics and valuation methods that can be used. HES present a number of specific challenges that make the problem of measuring performance qualitatively different from current-day applications such as standard cost-benefit analysis for project appraisal:

- Long-time horizons:
    - different people;
    - different preferences;
    - different social and economic structures;
    - technological change;
    - strong impact of discounting if calculating net present values from today.
- Extreme scenarios:
    - high uncertainty about outcomes;
    - extrapolation outside current experience;
    - unknown tipping points, thresholds;
    - multiple irreversibilities and feedbacks.

These features all have important implications for the suitability and feasibility of different evaluation methods.

2.2.1. Dealing with future generations

Managing the risks of climate change involves adaptation and mitigation decisions with implications for future generations, socio-economic systems and the environment. Measures of outcomes (incomes, services) and of opportunities to act (available capitals, capabilities), and their distribution across people/groups in future societies and over time, are central to the evaluation of adaptation and mitigation policy. HES necessarily deal with future generations – the longer time horizons involve almost exclusively people not yet born – and scenarios often involve radically different social and economic structures. This raises ethical issues and also practical problems in terms of assessing preferences and values for potentially very different societies. These issues impact on the choice of indicators or tools to assess climate change adaptation and mitigation.

Since mitigation actions put in place today will be effective only in the long-term, the temporal aggregation of costs, damages and benefits plays an important role in economic evaluations. In particular, the definition of a discount rate with which to aggregate damages and benefits that will occur at different moments in time plays a central role in the determination of the aggregate economic impact in classical economic methods. Standard economic methods define the discount rate as a function of pure time preference and consumption growth, via the Ramsey formula, $\rho_t = \delta + \eta \cdot g_t$. This defines the discount rate at time t (ρ_t) as the sum of the utility rate of discount (δ) and the rate of growth in consumption between the present and t (g_t), weighted by the elasticity of marginal utility of consumption (η).

A recent USEPA expert panel of 12 economists (Arrow et al., 2012) unanimously agreed that “the Ramsey formula provides a useful framework for thinking about intergenerational discounting.” However, they did not reach agreement on “how the parameters of the Ramsey formula might be determined empirically”, let alone on actual values. They explain this with reference to a long-running debate between a “descriptive” approach (based on behaviour observed in markets) and a “prescriptive” approach (focusing on ethical considerations to set parameters).

So despite its importance, there is no universally accepted way of calculating a discount rate, resulting in a multiplicity of estimates. Discount rates of a few percent, standard for short-term policy appraisal, result in huge discounting of long-term impacts – applying these rates for climate policy would justify a “wait and see” approach. Some authors advocate declining or hyperbolic discount rates (Kirby, 1997) to combat this problem. Others use a low constant rate - the Stern Report, for instance, has been criticised (Nordhaus, 2007) for using a very low discount rate (0.1%), a factor of ten or more less than conventional studies (e.g. 4% average in DICE model, Nordhaus 2008).

Faced with this indeterminacy, different authors draw different conclusions. Pindyck (2013) argues that integrated assessment models are “close to useless as tools for policy analysis” in part because the discount rate is essentially arbitrary but has a huge impact on estimates of the social cost of carbon. Heal & Millner (2014) argue that there are no objectively correct discount rates, just different ethical positions that should all be taken into account: they argue that climate policy analysis “becomes an exercise in social choice” that requires aggregating “the diverse preferences of individuals into a representative discount rate”. Against this, however, one could argue that there is no way to know the preferences of most of the individuals involved, namely future generations. Weitzman (2007) instead recasts the debate by stressing that expenditures to combat climate change “should perhaps not be conceptualised primarily as being about consumption smoothing as much as being about how much insurance to buy to offset the small change of a ruinous catastrophe that is difficult to compensate by ordinary savings."

The standard approach can also be criticised for failing to account for different attitudes to growth and decline. There is an underlying assumption in most policy/economic circles of continuous economic growth, but HES can include scenarios of substantial economic decline or collapse. Moxnes (2014) reports evidence that, when very long-term sustainability of well-being is threatened, most people's implicit discount rates actually resemble the low estimates used by the Stern Review. Moxnes also reports that standard social welfare functions represent people's choices well only along steadily increasing consumption paths, but are not able to capture people's aversion to overshoots and fluctuations. Zuber & Asheim (2012) argue for an extended rank-discounted utilitarian (ERDU) criterion in which discounting becomes a simple expression of intergenerational inequality aversion: it discounts the wealthier generations, making it a strong ethical choice, while being equivalent to discounted utilitarianism on non-decreasing consumption paths. Moxnes (2014) proposes the discounted utility of relative growth in per capita consumption, giving a welfare function that is averse to fluctuations and overshoots in the consumption path.

This brief overview of a large and diverse literature suggests that discounting is likely to be particularly controversial for HES. Dietz (2011) argues that, although welfare estimates strongly depend on tail risks, for a set of plausible assumptions time preference still matters. These assumptions include, in particular, capping the maximum losses and the assumption that tail risks are both unlikely and distant: these may be appropriate assumptions for general analysis, but do not apply to the particular case of assessing HES. The scenarios in IMPRESSIONS are likely to involve some situations of declining incomes or welfare, and some of the outcomes to be assessed may involve extreme losses or collapses. Evidence suggests that standard approaches to discounting do not reflect people's choices when faced with such situations; where collapse is possible, discounting is ethically very dubious, at best. Certainly, we cannot expect widespread agreement on the 'best' approach – even amongst top economists, this is not possible (Arrow et al., 2012). Moxnes (2014) poses the question "could one do without welfare functions and discounting when choosing between policies?", and reports that people presented with graphs of policy consequences over time are indeed able to make consistent choices.

This would suggest that there is no particular need in a project like IMPRESSIONS focused on HES to use discounting to reduce evidence on future welfare paths to a single present value figure: the discounting process involves loss of information about intertemporal distributions; there is no reliable way to determine the parameters and functions that 'should' be applied; and stakeholders and decision-makers are quite capable of considering the whole paths anyway. We conclude that consideration of the pros and cons of different adaptation pathways should consider the whole pathways, rather than aggregated versions that collapse the time dimension via discounting.

2.2.2. Uncertainties and risks

Uncertainty can be defined as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" (Walker et al., 2003; Lourenço et al., 2013). Knight (1921:19) made a more subtle distinction between measurable risk and immeasurable uncertainty, arguing that "it will appear that a measurable uncertainty, or 'risk' proper… is so far different from an immeasurable one that it is not in effect an uncertainty at all. We ... accordingly restrict the term 'uncertainty' to cases of the non-quantitative type." This distinction is maintained in much of the economics literature. However, the recent Fifth Assessment Report of WGII of the IPCC (IPCC, 2014a) defined 'risk' more generally, as "the potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values." and as resulting from "the interaction of vulnerability, exposure, and hazard". We suggest that it is important to maintain the distinction between measurable risk, where the underlying probability distribution is known and stable, and immeasurable uncertainty, where the probability distribution is unknown, or does not even exist, because for the most part in HES we are considering rather fundamental uncertainties that defy precise quantification in probabilistic terms.

Even where occurrence probabilities can be estimated for specific events, this information alone is not sufficient for decision-making. Policy-makers also need to know the magnitude of the impact. The translation to social and economic effects introduces further uncertainties to the chain. Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are therefore large, and understanding them is challenging due to the number of interacting social, economic, and cultural factors.[3] International issues such as trade and relations among states are also important for understanding the risks of climate change at the regional and global scales. Felgenhauer et al. (2013) distinguish two main sources of uncertainties which are true for climate change in general, and are even more exacerbated in the case of HES:

- Climate change uncertainty:
  - o we are not sure of the future emissions of greenhouse gases;
  - o our knowledge of the climate system is limited;
  - o there is unavoidable natural variability (the global climate variables have specific dynamics which are related to the chaotic behaviour of the climate system).
- Technological uncertainty, because damages depend on:
  - o future technologies, preferences and socio-economic structures;
  - o effectiveness of mitigation and adaptation technologies to reduce damages.

In addition, it is not sufficient to consider impacts/damages individually, because the combined effects of many different impacts of climate change could be greater than the sum of the parts. The probabilities of individual impacts are neither independent nor perfectly correlated: the events depend partly on the same uncertainty (climate sensitivity)[4] and partly on uncertainty specific to how climate influences the impact.

So although there is no longer any scientific doubt that anthropogenic climate change is taking place, there remains substantial uncertainty about specific key aspects of it, and in particular about the precise extent of warming associated with particular emissions trajectories, and the associated social and economic consequences. The distributions of possible outcomes are often very wide, and even though we cannot define precise probabilities for extreme outcomes, proper consideration of options must include attention to the lower probability high-end tail risks of extreme damages, which is a strong justification for studying HES.

---

[3] These factors include wealth and its distribution across societies, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutions to resolve conflicts.

[4] The IPCC (2007) defines the equilibrium climate sensitivity as "a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is likely to be in the range 2°C to 4.5°C with a best estimate of 3°C, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values." The climate sensitivity parameter also should take into account possible feedbacks, such as the self-amplification potential related to the possible release of GHGs from the arctic permafrost and offshore deposits of methane as hydrates.

Greater uncertainty associated with recognition of high-end and long-term outcomes (rather than analysing consequences of 2°C) may motivate greater precautionary behaviour. More uncertainty about models increases the scale of the distribution of outcomes, hence thickens the tails and increases the chance of catastrophic or extreme damages. Weitzman (2009) analysed "fat-tailed" probability density functions for climate damages, showing that failure to consider the full range of uncertainty about future climate change underestimates the benefits of aggressive policies against future risk. In particular, a combination of a heavy-tailed, unbounded distribution for temperature change and a common model of risk aversion implies that the risk premium for avoiding climate change is infinite. Newbold & Daigneault (2009) evaluated the risk premium under different (bounded) scenarios, finding that non-linearities in utility damage functions make the risk premium rise for greater levels of uncertainty. Taleb et al. (2014; see Figure 1) demonstrate how this increased risk of 'ruin' should motivate more precautionary policies. In particular, they explain the (perhaps counterintuitive) implication that greater scepticism about the accuracy of climate modelling makes us less confident of predictions and should therefore motivate more precautionary action, not less. The increased chance of ruinous outcomes (thicker left tail) is much more policy-relevant than the increased chance of happy surprises (thicker right tail). Millner et al. (2010) go further and demonstrate that ambiguity about climate change knowledge precludes the definition of a single probability distribution, and aversion to this ambiguity motivates even greater efforts to avoid climate change damages.

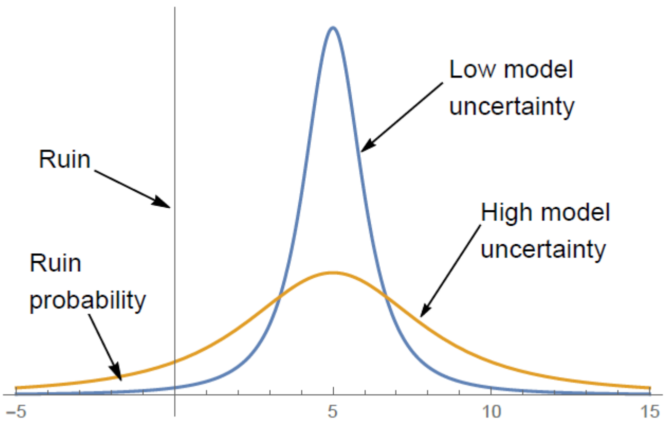

Figure 1: Greater precaution under conditions of increased model uncertainty (source: Taleb et al., 2014:8)

We can also distinguish between reducible and irreducible risks/uncertainties, i.e. those that could be resolved with better data or models *versus* those that are fundamentally due to random influences. In some cases we may be able to estimate risks, but often the distributions will be unknown, and there is also the potential for true 'surprise' outcomes: "unknown unknowns". Furthermore, there is often a 'hidden' assumption of stationarity in the stochastic processes generating outcomes: even if we can today estimate probability distributions for future outcomes, our decisions would make sense only if probabilities are stable, or we know in advance how they change. If probabilities of disaster change unpredictably over time, decisions which seem 'optimal' today may be completely inconsistent tomorrow. So while better science may lead to narrower distributions to consider, this is not always the case, and some fundamental uncertainties will remain, in particular for longer-term and higher-end scenarios.

These features pose a particular challenge for analysing policy options under HES. In IMPRESSIONS, 'impact response surfaces' will be developed to investigate the strength and direction of impact responses within and across regions, assessing the risks for probabilistic projections. However, the probabilistic component of the analysis will focus on a limited range of variables, such as temperature, precipitation and population, as defining PDFs for other social and economic variables is extremely challenging. The fact that probabilities often cannot be derived for most relevant impacts means that many classical methods for risk analysis, and in particular calculations of expected values and variances of outcomes, cannot be applied. Recognising that we are faced with uncertainty, not risk, therefore entails recognition that we cannot choose assessment tools that rely on probability distributions. This is a problem for any classical utility-based assessment under HES, except for the most extreme forms of non-expected utility preferences (e.g. maximin or multiplicative intertemporal preferences) which are rather close to simple binary decision criteria. These issues are discussed further in section 3 below.

2.2.3. Temporal and spatial scale mismatches

There are very different temporal and spatial scales for benefits, costs, and the observation of effectiveness, as well as different levels of uncertainty, for different policy options. It can therefore be difficult to find a compromise between adaptation and mitigation solutions because we do not consider the same stakeholders nor the same temporal and spatial scales. However, recent attention to green growth and circular economy policies have stressed (Jaeger et al., 2012) that mitigation also yields local and short-term benefits, for example, increasing competiveness, welfare and jobs, and reducing poverty. Such policies hold promise for partially overcoming trade-offs between adaptation and mitigation, and between short- and long-term policies.

Some economic sectors such as forestry or energy production have more or less the same time scales as that of climate change. These sectors have a high degree of inertia that can be technical, institutional, regulatory and cultural. Socio-economic inertia, through the implementation of adaptation measures with actions ahead of time, makes the process more complex and can lead to maladaptation (Hallegatte et al., 2011a).

Furthermore, through mitigation policy, the need to adapt could decrease. Thus, if we put in place an adaptation policy now related to the projected climate in 2050 (for example), this policy might turn out to be over-ambitious if mitigation efforts (or uncertainties) make the climate change less significant than anticipated. There can also be ancillary benefits to adaptation and win-win solutions. Strategies for reducing vulnerability and exposure to present climate variability can include actions with co-benefits for other objectives, for example improving human health and livelihoods, and for enhancing longer term resilience (IPCC, 2014a). For instance, new strategies of urban planning more attentive to green areas can both reduce the danger of, and therefore the necessity to adapt to, heatwaves, and increase the capacities of carbon sequestration (Grasso, 2010).

The way societies and ecosystems will react to modifications in local climate is uncertain, but this is an important factor in defining an effective adaptation strategy (Hallegatte et al., 2011a). Climate change involves many other important sources of risk and uncertainty, in particular relating to the timing and magnitude of climate change due to GHG emissions; the ecological, economic and social impacts; and the effectiveness and costs of adaptation and mitigation policies (Bretteville Froyn, 2005). It may take considerable time before uncertainties about the effectiveness of adaptation and mitigation strategies, and the implications for climate damages, are resolved.

Ideally, therefore, we need to develop adaptation measures that are robust regarding uncertainties, and/or that are flexible and can be modified when better information is obtained. Analysing the relative performance of pathways in the context of HES therefore needs to take into account the high uncertainty about damages and the effectiveness of adaptation, and also consider the flexibility retained in the system. Considering conditions under which the uncertainties about adaptation's effectiveness will be less important, and seeking robust strategies and win-win approaches to both adaptation and mitigation, will represent an effective way to respond to diverse scenarios.

2.2.4. Tipping points, irreversible risks and non-substitutability

Particularly in the case of HES, more extreme forms of uncertainty need to be considered. The problem is not only the possibility of facing huge damages in the future, but also the fact that damages may be irreversible: no policy will then be able to restore previous conditions. Tipping points are thresholds for abrupt and irreversible changes in the human-environment system. As warming increases, some ecosystems may be at risk of abrupt and irreversible changes, and there is increasing likelihood of some systems entering irreversible trajectories. The precise levels of climate change sufficient to trigger any particular tipping point remain uncertain, but the risk associated with crossing multiple tipping points in the Earth system or in interlinked human and natural systems increases with rising temperatures. Risks associated with such tipping points are already in evidence, with early warning signs that both warm-water coral reef and Arctic ecosystems may be experiencing irreversible regime shifts, and the number of threatened systems at risk of severe effects grows rapidly with additional warming of 1-2°C (IPCC, 2014a:12).

Loss[5] estimates associated with disasters or catastrophic changes (IPCC, 2014a) based on hypothesised tipping points can be considered lower bound estimates because many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetise, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy as well as indirect economic effects can be very important in some areas and sectors, but are generally not counted in reported estimates of losses.

2.3. Link to the IMPRESSIONS workplan

In IMPRESSIONS, WP1 is working with decision-makers to better understand their knowledge needs for incorporating uncertain scientific information within adaptation decision-making. WP2 is also working closely with stakeholders in the five IMPRESSIONS case studies to develop participatory socio-economic scenarios which will be integrated with intermediate and high-end climate scenarios. These scenarios are then being applied to a wide range of models of impacts and adaptation in WP3 to assess risks and opportunities. WP4 will then work with stakeholders in each case study to develop adaptation and mitigation pathways which will be tested with the impact models. Finally, WP5 will synthesise the outputs of all the research areas to develop recommendations on robust new policy strategies and pathways, including the costs and benefits of different policy options, in order to provide integrated and transformative solutions that help society plan for the long-term under high-end climate change.

[5] "Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable. Furthermore, many estimates do not account for catastrophic changes, tipping points, and other non-easily predictable factors. With these recognised limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2 °C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (medium evidence, medium agreement). Losses are more likely than not to be greater, rather than smaller, than this range (limited evidence, high agreement). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (limited evidence, high agreement), but few quantitative estimates have been completed for additional warming around 3 °C or above" (IPCC, 2014a: 19).

This report focuses on approaches for analysing the adaptation and mitigation pathways in the context of HES. The impacts and adaptation modelling in WP3 will provide quantitative projections of changes in biophysical and some socio-economic indicators for the HES. However, understanding the full implications of these futures requires assessment of their impacts on human welfare.

A conventional approach to this problem would focus on developing ways in which the benefits of adaptation and mitigation can be compared with the (opportunity) costs in commensurable metrics. In many cases the costs could arise earlier than the benefits, leading to issues associated with intertemporal comparisons as discussed above. However, especially in HES, costs paid in the short-run can lead to huge benefits in the long-run – potentially 'infinite', if the result is avoiding 'ruinous' collapse. A narrow focus on short-run cost could lead to irreversible commitment to catastrophic scenarios with enormous costs and no possibility for adaptation policies.

The whole approach of trading-off costs and benefits may therefore be misleading under HES: the objective is rather to establish policies and pathways that avoid disaster loops and keep socio-ecological systems on "sustainable" trajectories. While we need to explore metrics for assessing these pathways, it may not be possible to quantify costs and benefits in commensurable terms, or even at all, due to the many problems discussed in this report. For example, we may be able to estimate short-term costs in monetary terms but be unable to do this for long-term benefits. It may be impossible to develop metrics at all for some outcomes, with quantification limited to measurements of capabilities, or simple disaster-avoidance decision rules. The different metrics (monetary, quantitative, or qualitative) will need to be carefully selected and explained to provide the clearest and most useful information to stakeholders.

Partly, the question is what minimal system conditions need to be considered (in economic, social and biophysical terms) to keep the social-ecological system running, and able to produce a certain quality of life, even if a lot of options are lost along the way. More generally, this task seeks ways in which the survivability, robustness, desirability or 'value' of possible future states of the world can be evaluated. In particular, the aim is to be able to map out important vulnerabilities for specific groups of people (whether spatially, economically or culturally defined) and examine ways in which adaptation, mitigation and transformation could address these problems.

The outputs from this task and the description of suitable methods for the analysis of costs and benefits under HES will feed into the Information Hub, one of IMPRESSIONS's products, and will be further developed and used in modelling and assessing options in the case studies. In particular, this task will provide information for later stakeholder workshops, during which questions will be resolved about indicator choices and methods for assessing costs and benefits in ways stakeholders consider comprehensible, justifiable and useful.

3. Conventional appraisal methods

This section discusses the different approaches that could be used to assess climate change policies under HES, and the lessons learnt from past projects relating to assessment of costs and benefits for different climate change scenarios. Seven methods considered as conventional are presented (cost-benefit analysis, cost-effectiveness analysis, real option analysis, portfolio analysis, iterative risk management, robust decision making and multi-criteria methods). A conclusion based on their potential usefulness for HES -related studies is then provided.

3.1. Cost-benefit analysis (CBA)

CBA aims to estimate net present values of projects or policies. The method depends on being able to quantify all the impacts of project options (states of the world with and without the option) and on being able to ascribe robust monetary values to each impact (Watkiss et al., 2014). In practice, CBA rarely (never) covers all impacts in monetary terms, with non-monetised items being reported separately. For this reason, and because monetary valuation does not capture everything of importance to society, CBA should be seen as a tool for structuring information and for supporting decisions, not as a substitute for deliberation or a decision-making tool. CBA has been widely used and is common in public sector policy appraisal. There is a substantial literature on the subject, and many applications to climate change in general and to climate adaptation (e.g. see review by UNFCCC, 2011; Leary et al., 2007; European Commission, 2007). In the context of HES, Table 1 presents a summary of relevant information about CBA.

Table 1: Summary of issues for using CBA for HES.

Issue	Considerations
Data requirements	Predicted time series of all costs (fixed and variable) and benefits related to a strategy/option. Monetary values for these impacts, via value transfer requiring: (a) contemporary studies, preferably meta-analyses; and (b) appropriate variables for projecting values to future scenarios.
Credibility / legitimacy / relevance for stakeholders	Provides results in metrics that are easily understandable by stakeholders. But can be rejected due to monetary treatment of non-market impacts.
Treatment of uncertainty	Uncertainties are usually limited to probabilistic risks, using expected values. Through the introduction of a risk premium or welfare function, risk aversion can be taken into account. Sensitivity testing for uncertainty about key parameters or to create low-high value scenarios is common. Can be used with Monte Carlo techniques.
Strengths	Allows comparison of all impacts, and all options, using a common metric. Use of discounting to make future and present values comparable. A CBA assesses separately external costs and benefits, and weighs the costs against benefits which is helpful for decision-makers. A well-known and widely applied method that - where applicable - provides a direct analysis of economic benefits (Watkiss et al., 2012).
Weaknesses	Lack of monetary data for non-market impacts (Watkiss et al., 2012). Some services are not directly included in a CBA because they do not have a monetary value. Stakeholder unease at reducing all impacts to a single figure - loss of wider picture of impacts. Dependence on discounting - can raise particular issues for very long-term studies. Distributional consequences are generally ignored. If using expected values across uncertain futures, provides low importance to scenarios with low probabilities.
Summary	**CBA is used for traditional decision support and includes only economic metrics. It is not suited to situations of high uncertainty or transformative changes in social and economic structures, where estimating monetary values is difficult or impossible.**

Risk can be dealt with formally by summing expected values using a probability distribution of outcomes. Defining such a PDF is often problematic, and the expected value approach can also be criticised for giving inadequate weight to high-consequence, low-probability outcomes. The assumption of risk aversion can partly address this criticism, but only where it is possible to define a PDF for outcomes (i.e. risk rather than uncertainty). Another option is to modify the decision-rule away from a focus on maximisation of net present value. Sequential analysis, for example, modifies

CBA by focusing on minimising the cost of conserving the possibility to reach a target under uncertainty in the future. The present decision rule seeks to minimise the expected cost of error, which requires subjective probabilities for each scenario (Hallegatte et al., 2011a). Non-probabilistic methods could instead focus on maximin strategies or other approaches to robust policy development, while still drawing on estimates of costs and benefits under different scenarios.

3.2. Cost-effectiveness analysis (CEA)

CEA is in effect a variant of CBA that compares the costs of several ways of producing the same results. This reveals the most efficient (cheapest) method of achieving a pre-determined result, but does not say whether or not this target is cost-beneficial overall. The advantage is that it is not necessary to value the benefits, which is often the most challenging aspect of CBA. However, ancillary benefits that vary across options should in principle be included. For example, Eory et al. (2013) present marginal abatement cost curves (MACCs) for GHG mitigation measures in the UK agricultural sector. They show how including values for additional external effects related to nitrate, ammonia, phosphorous and sediment pollution enables calculation of social MACCs, and alters the ranking of options compared to private MACCs. Uncertainty can be dealt with in similar ways to CBA: in practice, full probability distributions are often lacking, and qualitative analysis may be used to highlight different sources of uncertainty and develop scenarios; quantitative analysis can then be applied to each scenario and results compared (see e.g. Eory et al., 2014).

CEA is widespread in climate change economics, because it is very difficult to estimate the benefits of mitigation, but easy to derive a common metric of it. We can directly compare mitigation options across all countries and sectors with a single globally comparable common metric of €/tCO2e, and this enables cost-efficient mitigation planning through the definition of MACCs which identify the most cost-effective options and the least-cost cumulative abatement.

However, applicability is more limited in the case of adaptation, since this is a response to specific local, regional or national level impacts. The benefits are location- and technology-specific, and time-dependent. This makes it impossible (or extremely challenging) to define a single, globally-applicable metric of adaptation. Nevertheless, sector-based measures could be possible. In the context of HES, Table 2 presents a summary of relevant information about CEA.

Table 2: Summary of issues for using CEA for HES.

Issues	Considerations
Data requirements	Data on the costs and effects of particular options. Monetary values for impacts other than the primary target. Probability distributions or ranges where outcomes are uncertain.
Credibility / legitimacy / relevance for stakeholders	The focus on comparison of different options in a particular sector (if a metric of adaptation can be derived) and constructing MACCs can be highly relevant for stakeholders.
Treatment of uncertainty	Can be included via sampling (multiple cost curves) considering several socio-economic and climate model projections, or by comparing scenarios.
Strengths	The main advantage is not having to estimate the headline benefits in monetary terms. The method in terms of the ranking of options and building a MACC are easy to understand. Especially applicable when there is a clear headline indicator and a dominant impact, and when the uncertainty is low (Watkiss et al., 2012).
Weaknesses	Less applicable in the case of cross-sectoral studies and complex risks because it uses only one metric. The method is more useful for technical options, whilst capacity building and soft measures are often not considered because the costs and/or effects are difficult to define (Watkiss et al., 2012).
Summary	**CEA is used for traditional decision support and includes only economic metrics, except for one target variable. CEA is not suited to situations of high uncertainty or transformative changes in social and economic structures, where estimating monetary values is difficult or impossible, and where it is not feasible to define a single target variable for 'adaptation' or 'transformation'.**

3.3. Real option analysis (ROA)

ROA is inspired by financial analysis methods combining classic decision analysis and financial theory. A financial option gives an investor the option to buy a financial asset in the future, at a specified price, if conditions are such that he/she wants to. Applied to decision-making under uncertainty more generally, the focus is on explicit recognition of uncertainties and flexibilities in options. A "real option" is the ability (but not the obligation) to carry out some action such as investing in, delaying, abandoning, expanding, staging… some adaptation project. This method is useful in the adaptation context for the analysis of flexibility, learning and future information, in the presence of significant uncertainty. Analysis that ignores the fact that the future exercising of options can be contingent on the resolution of uncertainties can give misleading results: ROA takes explicit account of these contingencies. ROA will tend to favour adaptation projects with important near-term benefits, quite a small variance in outcome scenarios, and/or a long period of waiting for information that could have an impact on the investment decision (Watkiss et al., 2014). In the context of HES, Table 3 presents a summary of relevant information about ROA.

Table 3: Summary of issues for using ROA for HES.

Issues	Considerations
Data requirements	Similar to a CBA but also needs information on when/how uncertainties can be resolved.
Credibility / legitimacy / relevance for stakeholders	It provides outputs in a metric which is understandable for stakeholders. It also considers future possible options which might provide higher benefits. Stakeholders can be involved in defining options (etc.) which can enhance buy-in.
Treatment of uncertainty	Explicit aim of the method is to take full account of different options, uncertainties and their future resolution. Data to achieve this may be difficult to derive, or require strong assumptions.
Strengths	Assesses in quantitative and monetary terms the costs and benefits of different decision options: implementing the decision now or waiting, incorporating the value of flexibility and learning. The method also provides decision trees which explain the context of adaptive management.
Weaknesses	The decision trees can only be built if we first define probabilities. The poorer the estimates are, the less accurate will be the outcomes. All elements of costs and benefits also need to be quantified and valued, as in CBA, with the same problems. Moreover the method is quite data and resource intensive, complex and requires many expert inputs.
Summary	**The method improves on CBA by accounting for learning possibilities. However, the other criticisms of CBA remain, notably regarding the need to express future costs and benefits in monetary terms, and derive PDFs for outcomes. Therefore the method is unlikely to be useful for assessing adaptive and transformative pathways under HES.**

3.4. Portfolio analysis

Portfolio analysis also draws on financial techniques, with a focus on defining a portfolio of policies/options to decrease risks and hedge against uncertain future scenarios. A hedge in this context is “a position established in one area in an attempt to offset exposure to the price risk in another area” (Means III et al., 2010). The analysis relies on estimates of probability distributions and seeks to minimise the portfolio variance, a weighted function of the variances and covariances of ‘assets’ in the portfolio. Alternatively, Monte Carlo simulations may be used to assess overall risks, and strategies for minimising them through hedging.

Applied to adaptation, a portfolio is comprised of many different specific policies or projects – generally any given option will be suitable for one or more, but not all, possible scenarios. In simple terms, portfolio analysis aims to define a robust set of these strategies that, together, would be suitable for any kind of future. In general, the more diversified the portfolio will be, the more robust it will be (Means III et al., 2010), or more technically, portfolio variance can be reduced by choosing options with a low or negative correlation across different future scenarios. A relatively straightforward example is crop choice, where it makes sense to grow different crops and multiple cultivars as a hedge against problems associated with specific crop failures, diseases and growing conditions, rather than planting a monoculture of the single most profitable crop.

Where uncertainty cannot be specified in probability distributions, the method could be applied under the assumption that all future scenarios/outcomes considered are equally probable and cover all possible future developments. In principle this can help to identify robust solutions regarding the deep uncertainty we face when considering HES, though this depends on finding a sufficient range of scenarios to 'bracket' possible outcomes. In the context of HES, Table 4 presents a summary of relevant information about portfolio analysis.

Table 4: Summary of issues for using Portfolio analysis for HES.

Issues	**Considerations**
Data requirements	Data for assessing outcomes (values, indicators…), including the proportion of the selected asset (adaptation option/strategy), the performance under different scenarios, and the covariance across all options (Crowe et al., 2007).
Credibility / legitimacy / relevance for stakeholders	Institutional investors are familiar with these techniques. They could be particularly relevant for policy-makers with business/finance background and for policy options relying on leveraging private sector investments (such as the Natural Capital Finance Facility).
Treatment of uncertainty	Key focus on risk is the main strength of this approach. Uses probabilities and Monte Carlo simulation to deal with risks, which are then minimised through hedging. Requires determination of probabilities of outcomes under different scenarios for all portfolio elements (Means III et al., 2010).
Strengths	Relevant for adaptation (selection of a set of options which are effective together regarding several possible future climates). IPCC Third assessment report concludes that this method could be applied to deal with uncertainties (Means III et al., 2010). Several metrics could be used including both physical and monetary values (Watkiss et al., 2012).
Weaknesses	Issues regarding interdependence of options, since it may not be possible to assess separately each option of the portfolio (Means III et al., 2010). The method is resource intensive (expert knowledge). Data need to be quantified and we need probabilistic climate information (or the likelihood equivalence) (Watkiss et al., 2012). But could be applied under the assumption that future (combinations of climate and socio-economic) scenarios are equally likely.
Summary	**Has the advantages of the potential to use both physical and monetary values and to consider uncertain scenarios (by treating them as equally probable). However, requires clear metrics of performance for the scenarios as well as estimates of covariances. Aimed at hedging expected returns for uncertainty rather than development of robust policies which is the aim of IMPRESSIONS.**

3.5. Iterative risk management (IRM)

IRM aims to improve future management strategies, while using a monitoring, research, evaluation and learning process cycle (Watkiss et al., 2014):

- Understanding the current climate variability and existing adaptation issues;
- Identifying the main future risks from climate change;
- Building of future risk scenarios ;
- Identifying indicators and vulnerability or impact thresholds;
- Identifying adaptation options or portfolios which are effective enough regarding different threshold levels;
- Developing these options;
- Confrontation of the options with economic and other criteria; and
- Describing the best feasible pathway and key monitoring variables.

The iterative risk management process can use either qualitative (MCA) or economic (CBA) tools including uncertainty (Watkiss et al., 2012). Consequences can be dealt with in terms of general welfare metrics that may vary according to outcomes. For example, with risk aversion, a higher value may be given to marginal changes in a bad outcome than to the same marginal change in a good outcome. Considering uncertainties associated with climate change and especially HES through a risk-management method encourages short-term measures that hedge against all types of future climate risk (considered with monetary or different indicators). From an economic point of view, measures should be applied now to minimise the expected costs of reaching long-term aims (Yohe, 2010). The method favours building adaptive capacity, while focusing on both short-term no-regret options and areas of long-term concern that justify early action, so that flexibility can be taken into account, risks of lock-in could be avoided and future options are still considered (Watkiss et al., 2014). The identification of risk thresholds can be a challenge, as can issues of scale and geographic aggregation, and dependencies between options within a pathway. Multiple risks acting together can make option analysis more complex. In the context of HES, Table 5 presents a summary of relevant information about IRM.

Table 5: Summary of issues for using IRM for HES.

Issues	Considerations
Data requirements	Quite variable, depending on exactly how the approach is applied: cyclical process of monitoring, research, evaluation and learning.
Credibility / legitimacy / relevance for stakeholders	Method designed for ongoing involvement of stakeholders in a process of monitoring and a cycle of review. This would need some adjustment for application in a research-focused study.
Treatment of uncertainty	Proposes a portfolio of actions to decrease the risks associated with a large set of climate futures. The method reviews the response over time once more information is available (which corresponds with a way of dealing with uncertainties).
Strengths	Useful for building adaptive capacity. The advantage of this method is that decisions are adjusted over time when more information is available. Thus the method is based on monitoring, research, evaluation and learning. The scenarios are not used to predict the future but to define uncertainties. The method is also more policy-oriented. Finally, it involves stakeholders to discuss changes and indicators (Watkiss et al., 2012).
Weaknesses	The identification of risk thresholds is an issue for several sectors. Thus, this method has been rarely applied in the agriculture area for example because of the complex combination of climatic parameters, several impact risks, and complex socio-economic and institutional baselines (Watkiss et al., 2014).
Summary	**The method is focused on iterative adaptation and learning. This general approach is in some respects suitable for IMPRESSIONS work with stakeholders, and many of the steps identified above are present in the IMPRESSIONS workplan. However, overall IRM is more of an applied short-term decision-support tool than an approach to research into long-term consequences of HES.**

3.6. Robust decision-making (RDM)

RDM includes elements of classical decision analysis and traditional scenario planning. The aim is to find strategies robust enough over several scenarios describing different possible futures. Contrary to traditional scenario planning, this method uses simulation models. RDM assesses robust strategies against objectives, but, contrary to classic decision analysis, does not use a single set of probability distributions for its scenarios. RDM assesses the performance of strategies according to whether a strategy provides bad results. This can then be used to build more robust strategies. Strategies are tested against vulnerabilities to seek out a robust strategy. Steps in RDM include: (i) defining the decision analysis; (ii) applying models to assess strategies regarding different scenarios; (iii) taking into account uncertainties within the scenarios and describing a set of candidate policies; (iv) testing strategies according to different scenarios; (v) describing conditions leading to bad performance of the best performing strategies; (vi) assessing performance trade-offs for the strategies in the key vulnerabilities; (vii) improving the strategies according to these vulnerabilities; and (viii) selecting a robust strategy (Means III et al., 2010).

This method presents some advantages when the set of strategies is not fully known at the beginning of the study, the uncertainties are highly important, and the decision-makers cannot come to an agreement about the valuation of the strategy's potential outcomes. The method also helps to define which measures should be put in place in the near future and which should be delayed pending better information. RDM can take into account a wide range of futures and can thus be relevant for HES. RDM can inform on the quality and performance of scenarios according to the futures we consider. The vulnerabilities of the strategies are highlighted and solutions are proposed to reduce them. RDM can also assist decision-makers about their investments in research to reduce uncertainties or develop options. However, this method requires specific computing and analytic knowledge, and is more difficult to understand and explain. This method, when it is used, needs to be well explained and precise to be efficient. For example, a precise definition of robustness needs to be developed. An RDM will be successful if it finds robust strategies (Means III et al., 2010). In the context of HES, Table 6 presents a summary of relevant information about RDM.

Table 6: Summary of issues for using RDM for HES.

Issues	Considerations
Data requirements	Requires specific computing and analytic knowledge. Needs quite precise information on the plans/strategies and scenarios. Data mining algorithms are needed to develop vulnerability and-response-option analysis.
Credibility / legitimacy / relevance for stakeholders	Often applied to water management. Method presents different solutions to stakeholders who can then observe their robustness. Participatory processes can be used to define a strategy.
Treatment of uncertainty	One of the strengths of the method is the treatment of large uncertainties when defining scenarios and a set of possible policies.
Strengths	Can consider a wide range of futures and uncertainties, and provides solutions when decision-makers cannot reach an agreement about the valuation of potential outcomes. Can also provide recommendations for action (now or later) and highlights the vulnerabilities of the strategies. Strength/weakness of "pessimism" and sensitivity to worst-case scenarios and focus on robustness over optimality.
Weaknesses	High data and analysis requirements. Strength/weakness of "pessimism" and sensitivity to worst-case scenarios and focus on robustness over optimality.
Summary	**This method enables identification of robust strategies for diverse futures. It is suited to cases of deep uncertainties and when short-term decisions are needed, with long-term, uncertain consequences. For long-term and HES in IMPRESSIONS, full application is likely to demand more data than would be feasible, but the general principles/ideas could be useful.**

3.7. Multi-Criteria Analysis (MCA)

MCA or multi-metric decision-making takes a broader approach to evaluating different outcomes, using a range of weighting methods to include a full range of social, environmental, technical and economic criteria, with a focus on quantifying and exploring trade-offs (Chambwera et al., 2014). This approach deals with the situation where efficiency and benefit are only two criteria among others, such as cultural or ecological criteria, which are difficult to quantify. Criteria are identified and weighted, and the different solutions that should be compared are assessed following these criteria, making the comparison possible. Criteria may be clustered, for example, a MCA for sustainability might group criteria under the 3 pillars of sustainability (economic, social, and environmental). Typical steps in MCA include: (i) definition of options; (ii) selection of criteria; (iii) scoring options against the criteria; (iv) defining weights for the criteria; (v) assessing the weighted sum; and (vi) ranking the options (de Bruin, 2013).

The approach can integrate both quantitative and qualitative data in the ranking of alternative options, one of the main strengths of this method, making it applicable where quantification and valuation in monetary terms of costs and/or benefits is not possible (UNFCCC, 2002). However, the weightings lack the theoretical underpinning of preference-based valuation, and can be arbitrary, lacking robustness. They are potentially open to manipulation (favouring particular views/ stakeholders) and/or introducing assumptions and consequences that are not fully understood or intended by stakeholders. Sensitivity analysis can partly address these problems. In the context of HES, Table 7 presents a summary of relevant information about MCA.

Table 7: Summary of issues for using MCA for HES.

Issues	Considerations
Data requirements	Measures of impacts of options. These need not be in monetary terms, other quantitative or qualitative indices can be used. Weights for criteria must also be derived (generally using stakeholder involvement).
Credibility / legitimacy / relevance for stakeholders	Transparent and simple method, which often involves stakeholders. The importance of the different criteria considered in this method are defined by decision-makers and stakeholders.
Treatment of uncertainty	When treated, often done qualitatively and subjectively.
Strengths	Very useful if the considered criteria cannot be assessed by a CBA or if the valuation of benefits is impossible. Takes into account both quantitative and qualitative data, monetary and non-monetary values. Possibility to compare and rank options. Quite low cost/time requirement. Generally used with stakeholder involvement to determine weights, etc.
Weaknesses	Lack of robustness. Quite subjective approach. Requires a lot of information from stakeholders.
Summary	**MCA is used for decision-support and can include qualitative, quantitative and economic values. Monetary valuation is not needed, which is a substantial advantage over classical economic methods, but projection and weighting of different outcomes is nevertheless required. MCA techniques are very flexible and certainly could be applied to HES, including applications using alternative indicators sets described in later sections of this report.**

This method has been applied to adaptation issues such as urban flood risk (Nasra Haque, 2012; Viguie et al., 2012; Kubal et al., 2009), agricultural vulnerability (Julius and Scheraga, 2000) and choice of adaptation options in the Netherlands (de Bruin et al., 2009; de Bruin, 2013). The use of

MCA has also been suggested by UNFCCC (2002), which developed guidelines for the adaptation assessment process in developing countries.

3.8. Critique of conventional methods for use with HES

It is increasingly common to measure and interpret the ways in which ecosystems and their human uses and management underpin personal and societal well-being via an ecosystem services framework, often overlaid with assessment of economic value in total economic value (TEV) terms. The "classical" economic theory behind monetary valuation methods is grounded in individual utility and preference satisfaction (Wegner & Pascual, 2011). These standard economic methods are however controversial, in particular when they are extended outside areas traditionally managed through markets.

Expected utility theory (EUT; von Neumann & Morgenstern, 1944) and its subsequent developments can be viewed as a well-structured analytical framework that is used to explain people's decisions under uncertainty, grounded in the assumption that decisions stem from individuals' preferences. According to neoclassical economics, for an individual, TEV represents all the ways that goods/services influence utility, as reflected through the preferences of the individual, acting under a budget constraint, expressed as their 'willingness to pay' (WTP). At a societal level, TEV represents the sum of these individual values aggregated following some criteria. Applied to a particular ecosystem or natural 'asset', TEV is the sum of all the ways the ecosystem functions and ecosystem services and goods influence the utility of individual humans. Integrating these values over time and using discounting to convert future values to present equivalents gives the net present value of these flows. Assuming calculable risk about future flows, these values are often expressed as expected values, though other statistical treatments are also possible.

Leaving aside issues associated with expressions of preferences through markets, utility theory does not necessarily provide a reliable descriptive guide to human behaviour, especially in complex settings - such as those climate change, and HES in particular, impose. Different studies have shown that EUT fails to explain people's behaviour even in simple environments (Lichtenstein & Slovic, 1971; Kahneman & Tversky, 1979; Camerer, 1992). Moreover, when the complexity of decision environments increases, for example trading in a financial market, people rarely behave as EUT would predict (Benartzi & Thaler, 1993; Barberis & Thaler, 2003). Moving from a micro to a macro perspective, models based on the EUT framework do not reliably predict the evolution of economies (Colander et al., 2009). This entails a substantial failure of the so-called "as-if" argument (Friedman, 1953) according to which the economic system behaves "as if" economic agents behave as rational utility maximisers operating under the assumptions of EUT. The lack of predictive accuracy is likely to be exacerbated under HES conditions. This places serious doubt on the suitability of neoclassical methods for evaluating outcomes under HES.

Even if the "as if" assumption is maintained, treating aggregated TEV as an index of social welfare is problematic in two main ways: (i) it assumes the inter-personal comparability of utility (without which, there is no obvious way to aggregate preferences at the societal level); and (ii) it assumes that the underlying income distribution is socially optimal, or at least an issue that is adequately dealt with via existing policies (notably taxation and benefits). This is generally overlooked (though in some cases income weights are used to adjust values). It can be argued that this is a reasonable approximation in the context of valuing current market exchanges, since our economic and political structures actually use these values, and tax/welfare policies act to redistribute incomes as a result of democratic processes. However, extending valuation outside the market (for environmental goods and services) is ethically contentious and could support policies that are regressive. For example, it appears more 'efficient' to cluster environmental 'bads' where people are poorer, because their willingness to pay (constrained by ability to pay) is lower than that of wealthier people. Extending it forwards in time to distant future markets under very different or transformed social, economic and ecological systems is also controversial. Seven main problems can be identified.

Firstly, basing a system of value on preferences assumes that individuals are the best judges of their own welfare. This is demonstrably untrue in some cases (e.g. drug addiction) but by and large, for many classes of activity, democratic societies basically reflect this view and allow wide freedom of choice within a framework of rules and regulations to curb any excesses (for example, to regulate pollution and antisocial behaviour).

Secondly, accepting individual behaviour/statement as the indicator of preference assumes that individuals are capable of expressing values in this way, and that such preferences are stable. Again, institutions in democratic societies are generally consistent with this view, within certain limits including restrictions on advertising and requirements for trade descriptions and product labelling. However, this does not necessarily imply that people are well able to express market-style values for goods and services that are not actually traded in markets, and indeed stated preference methods in particular are often criticised on these grounds.

Thirdly, values expressed through market behaviour are constrained by incomes / ability to pay. This means that, in effect, the use of this behaviour to derive estimates of social value assumes that existing income distributions are desirable, or at least fair. Again, democratic societies generally follow rules consistent with this approach, including policies to redistribute incomes via taxes and benefits such that actual distributions can be deemed at least in part a reflection of democratic decisions. However, this does not necessarily imply that WTP-based values for goods and services that are actually provided *outside* markets should be considered valid measures of their social value.

Fourthly, there are inevitably data gaps, either in the ecological/scientific understanding of the ecosystem processes, and/or in the valuation evidence base. Full analysis must devote considerable attention to discussion of the items that could not be valued, and their possible significance in the context of the overall balance, as well as to sensitivity analysis for the key uncertainties in the assessments. Despite such efforts, there is always the concern that drawing attention to the ‘bottom line’ figures of cost-benefit assessments results in under-weighting of non-monetised impacts.

Fifthly, optimism bias refers to the tendency of any assessment of future projected impacts to underestimate costs and overestimate benefits. Optimism is not specific to economic valuation methods, in fact, it is more about physical outcomes and timings than about costs/values *per se* (e.g. the problem is the assumption that something can be achieved in 5 years and will be 80% effective, when in fact it takes 8 years and is 50% effective, more than about the assumed value per unit change). Simple rules can be applied to attempt to deal with optimism bias. Nevertheless, it remains a significant concern, especially for very long-term and high uncertainty assessments.

Sixthly, non-linearities, threshold effects and areas of highly inelastic demand / rapidly changing values all have consequences for valuation, both within individual studies, and in particular for attempts to transfer values across studies, for grossing-up across spatial scales, or to construct meta-analysis functions. More generally, they may suggest the need to move to safe minimum standards or precautionary approaches when dealing with decisions about critical natural capital. This may imply setting limits to the applicability of cost-benefit methods where catastrophic changes are plausible.

Seventh, Weaver et al. (2006) argue that the partial-equilibrium focus of CBA, CEA and risk analysis make them too narrow and static for assessing and mainstreaming climate policy options. The nature of climate change, including wide spatial scales and long temporal scales, and features of the ecological and human systems that are impacted by, and respond to, climate change, make the situation highly complex and uncertain. In particular, these systems involve several "dimensions" (environmental, economic, social, institutional), and metrics can be found for some but not all of them. The systems also exhibit non-linearity, threshold effects, contingency, irreversibility, recursivity, and the potential existence of multiple quasi-stable states. In addition, there are multiple stakeholders and values, high stakes, and diverse perspectives. And there are pervasive uncertainties related to all of these features.

Thus, while the use of market values to account for goods and services actually traded in markets, including ecosystem services such as food or timber production, is *relatively* uncontroversial, use of economic values for services such as clean air provision or biodiversity protection can evoke strong responses from different perspectives.

These reservations apply *a fortiori* to the case of valuation under HES. Firstly, predicting the preferences of future generations is difficult. This is especially true for socio-economic scenarios that are radically different from today, because we cannot assume that preferences are independent of society and culture. In fact, they are heavily dependent, inter alia, on cultural, religious and traditional factors. The realised future scenarios will also depend on these same features – in a process of co-evolution – and we would expect future preferences to be somehow co-related to other scenario variables. This implies that values for the same goods/services would not be the same across scenarios.

Secondly, incomes are likely to vary substantially across scenarios, and from todays. Values based on WTP are constrained by ability to pay, and therefore depend heavily on the distribution of incomes and property rights. Both levels and distributions are likely to be very different across scenarios, and this will result in major differences in values. It means that comparisons across scenarios, or from today to the future, would be difficult to interpret in value terms (although such comparisons may not be the main purpose of the exercise).

In fact similar points arise today when considering differences in values across countries. Values are commonly transferred from one situation to another (for expedience, and due to the high cost and time requirements for carrying out primary valuation studies) and this often involves (a) the search for comparable social/institutional settings, such that preferences can be assumed to be similar and (b) correction for differences in incomes, generally using conversion at purchasing power parity, sometimes corrected for the estimated income elasticity of demand for the good/service under consideration. So one option for adapting valuation for scenario analysis is to apply value transfer procedures to seek out current value estimates from societies/situations that resemble those of the scenarios, and to correct for changes in incomes.

However, in the case of HES, the changes are quite likely to be outside the range of current estimates available. Non-linearities, highly inelastic demand/rapidly changing values, and threshold effects become problems for evaluations, because we are unlikely to have a smooth, linear increase from values in the baseline. In policy terms, this would motivate the use of safe minimum standards or precautionary approaches, in particular when dealing with decisions about critical natural capital. From the perspective of analysis, this may imply that cost-benefit methods cannot be applied where catastrophic changes are a concrete risk: in some low probability scenarios, the costs could be almost infinite.

The theoretical and practical problems outlined above can motivate extended versions of economic techniques, such as multi-criteria analysis, though these methods are not mutually exclusive (CBA can be combined with MCA, as in Stern 2007). Nevertheless, the main conclusion above still stands, because MCA suffers from many of the same problems, plus some new ones. Classical decision analysis techniques remain grounded in the analysis and ranking of decisions considering several decision objectives. The purpose is to simplify complex issues, breaking them down into clear steps, distinct alternatives, and structured information. Uncertainties are considered as probabilities.

In the case of complex and highly uncertain situations, this kind of methodology is difficult to put in place. Classical methods are focused on identifying preferred options, rely on accurate estimates of probabilities, and do not deal well with data gaps. HES are likely to be characterised by severe impacts and vulnerabilities that are not easily predictable, since the extent of change is much higher than most impact models are designed to deal with and there are probably thresholds beyond which non-linear changes occur. The IPCC 5th Assessment Report notes that "it may be impossible to define (or to agree upon) probabilities for alternative outcomes, or even to identify the set of possible futures (including highly improbable events)" (Chambwera et al., 2014). Where this is the case, the applicability of the economic methods outlined above is severely limited; though *ad-hoc* approaches can be used (such as considering all modelled outcomes to be equally likely), this involves abandoning any attempt to optimise policy on the basis of actual distributions. In itself this is not really a problem – if distributions are unknown, then formal optimisation is not possible and seeking robust policy is the best we can hope for. However, the economic methods are designed for optimisation, and for exploring robustness, alternative methods may be preferable (Kunreuther et al., 2012).

The overall conclusion from these critiques is that classical methods do not provide suitable tools to assess policies and pathways in the highly complex and uncertain long-term scenarios represented by HES. Weitzman (2007) argued that for situations with fat-tails and "potentially unlimited downside exposure", presenting cost-benefit estimates as if they were accurate and objective is unhelpful; rather, economists need to explain to decision-makers that the crisp results of conventional IAM-based CBA are "especially and unusually misleading". IMPRESSIONS will best serve its stakeholders by exploring alternatives to classical methods that respect the limitations of current knowledge and techniques, and do not seek simple numerical answers to complex and irreducibly uncertain questions.

In the case of HES, therefore, it may be more appropriate to maintain sets of alternatives, and to focus on criteria other than optimality, such as robustness and fairness across a wide range of possible scenarios. A traditional scenario planning approach aims to develop future scenarios taking into account several possible future situations, using a strategic approach to evaluating outcomes under uncertainty and guiding robust decisions (Schwartz, 1991). Scenarios are defined as possible situations, but are not predictions. Where probabilistic methods focus on statistical properties of outcomes across all scenarios (the expected costs/benefits, and sometimes higher moments), non-probabilistic methods do not attempt to aggregate/average across future possible scenarios. Instead, the aim is to assess scenario by scenario, and seek policies that are in some way robust, for example, by staying above an acceptable level of benefits in all possible scenarios. These approaches are therefore independent of the probabilities of the results. However, they do assume that all possible outcomes are known (i.e. there are no genuine surprises or 'unknown unknowns').

In the next section, we therefore focus on a range of non-risk-based approaches for dealing with phenomena such as tipping-points and non-linear changes associated with HES. Such approaches work with concepts of thresholds, capabilities and responsibilities, operationalised for example through consideration of safe minimum standards, levels of insurance, disasters prevention and preparedness, the use of casualties from climate change as a measure of climate impacts, and human security overall.

4. Alternative methods

The considerations set out in the previous section can motivate the use of other indicators to assess different climate policies under HES, outside economic appraisal techniques. Instead of looking at assessment of value based on preference satisfaction and willingness-to-pay, we could consider indicators that are less subjective and less liable to change. These could focus on outcomes, or on capacities, or on thresholds related to these.

Outcome indicators would examine levels and distributions of certain variables, without going to the step of converting these measurements to estimates of preference-based values. For example, the availability of food could be assessed in calories per capita per day, rather than in monetary terms. This would have the advantage of being directly comparable across scenarios and with absolute estimates of dietary needs. At the same time, there is a disadvantage of losing the intra-scenario comparability across different output categories that is afforded by measuring all values in monetary units.

Capacity indicators go one step further back by focusing not on outputs but on options. Rather than estimating, for example, the levels of outdoor recreation services under a given scenario (in terms of number of visits, or their monetary value) we could measure the capacity for this service (in terms of natural areas available for recreation). Again this would be comparable across scenarios. The further advantage here is that we do not need to make assumptions about future preferences and decisions, rather, we are ascribing value to the options presented to future societies. This is a model that accepts that we cannot know 100 years in advance exactly what people will want to do, but that we can understand that keeping options open for them is a 'good thing'.

Threshold-based indicators do not attempt to evaluate scenarios against continuous (outcome or capacity) metrics, but instead establish minimum standards for sustainability or acceptability, and assess how likely these are to be respected. Vulnerability analysis falls largely in this category, by establishing thresholds for impacts and assessing the number of people vulnerable to them by being exposed to the impact and unable to cope with it.

These observations do not necessarily rule out economic methods for option appraisal, as discussed below. Some of the economic methods are strongly focused on decisions under risk/uncertainty, which is potentially a significant strength from the perspective of HES. Although these are designed for use with outcomes for which monetary values can be estimated, some other indicators could also be analysed using these methods.

4.1. Indicators of well-being and development

Although growth in gross domestic product (GDP) is the best known, and most widely used, indicator of economic progress, it is widely recognised that GDP is not a suitable indicator for development, welfare or wealth. It is not adequate for assessing the results of adaptation nor the capacity to undertake it ("Beyond GDP" Conference 2007; EC Communication "GDP and beyond: Measuring progress in a changing world" (European Commission, 2009); Stiglitz et al., 2009). Meadows (1998) notes that "Indicators arise from values (we measure what we care about) and they create values (we care about what we measure)." This stresses the central role of indicators, the fact that they can come to shape policy more than the underlying features, and the pitfalls of choosing indicators poorly. She argues that while different indicators are needed for different purposes and worldviews, there may be "overarching purposes that transcend nations and cultures, and therefore there may be overarching indicators" and that "indicators may help narrow the differences between worldviews". Indicators of sustainable development must go beyond simple environmental indicators and economic growth - they must take account of dynamic processes and thresholds, efficiency, sufficiency, equity, and quality of life (Meadows, 1998).

Over time, several indicators of sustainable development have been developed. Recently, the United Nations (2007) provided guidelines and methodologies for indicator development. Massetti & Merola (2009) reviewed several indicators of quality of life and sustainable human development. Adelle & Pallemaerts (2009) reviewed FP6 and FP7 projects working on sustainable development indicators to identify trends and gaps.

Sustainable development can be represented in terms of non-declining per capita wealth over time (where wealth represents opportunities for well-being), or non-declining (realised) well-being (UNECE, 2009). Wealth, in turn, can be represented in terms of capital stocks that support the opportunities for well-being. There are many possible conceptual models, including a popular division into 5 stocks of natural, manufactured, human, social and financial capital (Porritt, 2006). UNECE (2009) proposed several extensions to total wealth indicators, including separate monetary indicators of financial, produced, human, natural and social capitals and determination of "critical" capitals. However, not all of the indicators set out by UNECE can actually be measured with current techniques.

Various sets of indicators aim to measure quality of life at the aggregate scale. The human development index (HDI) comprises indicators of three key aspects of human development (life expectancy, education and living standards) combined as a geometric mean. However, it fails to take account of social parameters such as inequalities, poverty, and human security[6], or any environmental feature. The Inequality-adjusted Human Development Index (IHDI)[7] modifies the component indices based on the level of inequality across society: this gives quite a different ranking of nations. The Global Footprint Network (2010) associated the HDI with national ecological footprints (Figure 2) in a cross-sectional analysis; for comparing different HES pathways, a similar time-series approach might be considered.

OECD (2011) identified 11 parameters essential for well-being in the Better Life Index[8]. This captures a broader range of economic, social and environmental concerns; equality/distribution is not directly included[9], though some indicators reflect related concerns (e.g. long-term unemployment rate) and the interface allows reporting of 'high' and 'low' bands, as well as splitting by gender. Eurostat published work on measuring quality of life in the EU[10] based on "8 + 1" quality of life dimensions to be considered jointly. Data can be found for each dimension for every EU28 country in 2012 (although some data are missing).

[6] http://hdr.undp.org/en/content/human-development-index-hdi

[7] http://hdr.undp.org/en/content/inequality-adjusted-human-development-index-ihdi

[8] http://www.oecdbetterlifeindex.org/

[9] Income distribution and poverty are treated in detail in a separate part of the 'social protection and wellbeing' statistics.

[10] http://ec.europa.eu/eurostat/web/gdp-and-beyond/quality-of-life/data/overview

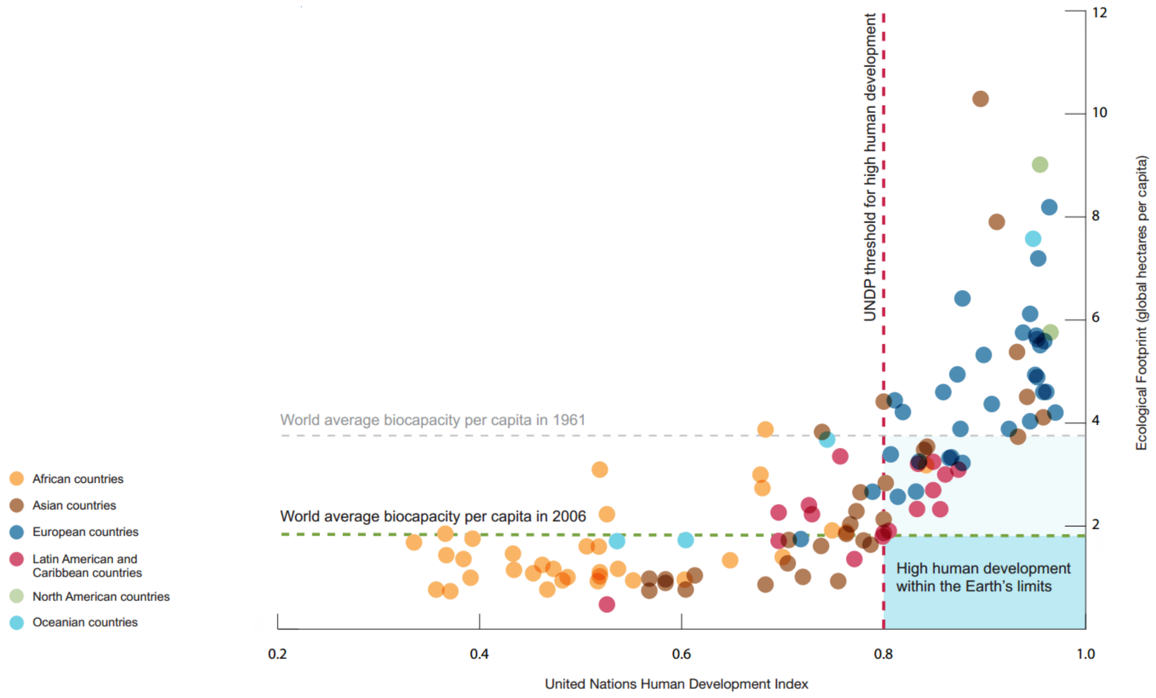

Figure 2: Human development index and ecological footprint 2006 (source: Global footprint network, 2010).

Other approaches focus on specific subsets of impacts on human welfare. Alkire (2003:2) views the notion of human security as the protection and promotion of a limited number of aspects of well-being which constitute its "vital core" – the "central component of human well-being" (UNU, 2007, p. 6). King & Murray (2002) and Brklacich et al. (2010) propose a number of indicators to cover the economic, social, institutional and environmental dimensions of human security. Attention can also be limited to fatalities or loss of disability-adjusted life years. DARA (2012) puts the current annual death toll from climate change at 400,000 (nearly all in the developing world) and projects that by 2030 it will rise to nearly 700,000. Broome (2012) points out that climate change will cause tens of millions of deaths by the end of this century. Although richer nations do not experience fewer natural disasters than poorer states, these nations observed less death from disasters (Nolt, 2014), suggesting that measures of fatalities also capture underlying vulnerabilities and coping capacities. Grasso & Redclift (2013) divide Mediterranean countries with regard to human security, distinguishing nations with sufficient/higher levels of human security from those that require support to enhance security.

4.2. Capacity-based approaches

Focusing on welfare outcomes supposes that we can measure and project related indicators under HES. This can be challenging, and one alternative is to focus instead on capacities or capabilities to achieve welfare. The capability approach (see Rauschmayer et al., 2012) is the most generalised of these approaches, focused on capabilities to live a 'good life'. The theoretical framework rests on two claims: the freedom to achieve well-being is defined as of primary moral importance, and this freedom is represented via human capabilities, i.e. their real opportunities to do and be what is of high value for them.[11] This rejects the focus on preference-based or utilitarian views of well-being,

[11] http://plato.stanford.edu/entries/capability-approach/

and also the use of monetary indicators of well-being (Polishchuk et al., 2011). Sen (1992) proposes an approach based on human functionings and their capabilities: "the ability to satisfy certain elementary and crucially important functionings (achievements of a person) up to certain levels". The approach is very flexible, since capabilities can be selected and weighted according to people's judgements, though some aspects such as notions of justice and social development require non-individual considerations such as efficiency or economic growth (Clark, 2005).

The capability approach focuses social and political attention on the basic needs of humans (at individual and community level), and considers local vulnerabilities of these needs, through the functioning of both human and non-human systems. Applying the capabilities approach to adaptation enables assessment of location-dependant vulnerability, aiding definition of adaptation needs and goals. It is strongly oriented towards the integration of stakeholders/the public in decision processes.

Other approaches to capacity modelling have been developed, including the capitals models noted above (Porritt, 2006; World Bank, 2005, 2011). The CLIMSAVE project used a model of capital stocks to define adaptive and coping capacity indicators (see Tinch et al., 2015; Dunford et al., 2015). Similarly, Norris et al. (2008) present a theory of resilience in which community resilience emerges from four primary sets of adaptive capacities - Economic Development, Social Capital, Information and Communication, and Community Competence - that together provide a strategy for disaster readiness. IMPRESSIONS plans to use a similar approach to assessing adaptive and coping capacities.

One option for assessing the impacts of different ensembles of climate change policies is therefore to consider these in terms of changes in capital stocks. In other words, rather than attempting to evaluate outcomes directly, benefits could be assessed via future changes in capital stocks. Costs could be assessed in terms of current (and ongoing) consumption of capital stocks. In principle, net present values could be assessed by applying discount rates to flows to and from capital stocks (compared with a baseline), though as noted above there are serious ethical and practical concerns with discounting – an alternative approach would be to present and consider dynamic paths of capital stocks. Several issues would need to be addressed, including issues relating to trade-offs across capital stocks (do we define critical capitals, do we allow trade-offs and if so, at what exchange rate?), dealing with uncertainty, and so on. Depending on the solutions to these issues, the approach could be combined with different option appraisal methods – allowing full exchange across capitals at a fixed exchange rate would in effect become a form of cost-benefit; setting strict limits to be respected could combine with robust decision analysis, and so on. As argued above, methods based on cost-benefit approaches are of extremely limited use in the highly uncertain context of evaluating policies under HES: many of these issues would also apply to appraisals using capitals, suggesting that attempts to derive net present values or allow full exchange across capital stocks would not be useful. One advantage of using capitals as indicators would be linking the policy assessment work closely to the vulnerability assessment being undertaken in IMPRESSIONS WP3. This would help to compare quite different adaptation options: some allow direct modelling of vulnerability (via different types of models in IMPRESSIONS) while others can be represented only indirectly, via impacts on coping capacity.

4.3. Threshold-based decision-rules

Several methods for policy setting and evaluation rely on the definition of thresholds, with a specific activity, or development in general, deemed 'sustainable' provided these thresholds are not breached. These approaches are particularly relevant where there is significant uncertainty regarding adverse outcomes, as in the case of HES.

4.3.1. Maximin method and minimax regret

The maximin principle focuses on the worst outcome that might be obtained through any given option. The chosen option will be the one which has the best (most preferred) worst outcome (Chambwera et al., 2014): maximin maximises the welfare in the worst case scenario. It can be understood as a corner-case of decision-theoretic approaches: a utility maximisation framework tends to maximin when there is maximal aversion towards ambiguity (Gilboa & Schmeidler 1989; Klibanoff et al., 2005)

The trouble with maximin is that it places most weight on outcomes that are actually highly unlikely; the most likely outcomes are effectively ignored. This is highly precautionary, but is equivalent to infinite ambiguity aversion, so in many cases, this method could be considered 'irrational': strict application of maximin would rule out crossing the street or getting out of bed in the morning. This relates to a broader problem with the precautionary principle, in which weaker versions are effectively useless while stronger versions can lead to paralysis. The maximin criterion can be used as a basis for a limited version of the precautionary principle applied in a limited number of cases, and can be argued to be rational if three conditions hold: strong uncertainty/veil of ignorance (we do not know the probabilities of the possible outcomes of our choices); the minimum outcome is 'acceptable' (it is not imperative to do better than the minimum); the alternatives have potentially very bad outcomes (Bognar, 2011). Even under these conditions maximin might not necessarily be the only rational decision-making rule but can be an appropriate alternative if other candidate rules do not adequately take extreme risks into account (ibid.).

The alternative 'minimax regret' criterion aims to minimise the worse-case regret, and thus choose the decision with the smallest deviation from optimality across all scenarios. In other words, it minimises the difference between the best that could happen and what really happens, thus minimising the regret of not making the best choice (Bretteville Froyn, 1999; Chambwera et al., 2014). The generalised maximin/maximax approach, or the pessimism-optimism index criterion, chooses the level of abatement to maximise a weighted average of the social welfare in both best and worst cases (Hurwicz, 1951; Aaheim et al., 2001; Bretteville Froyn, 2005; Heltberg et al., 2009).

4.3.2. Safe Minimum Standards (SMS)

This approach has been developed to take into account uncertainty and irreversibility within natural resources management. It has been applied, for example, to water quality, agricultural land use and endangered species conservation (Crowards, 1996). The basic principle behind SMS is to take account of uncertainty regarding future environmental impacts and associated costs by setting mandatory thresholds that should not be breached. These standards are considered 'safe' in the sense of avoiding possible serious damages, and 'minimum' in the sense that they do not rule out more stringent control efforts. The approach is closely related to the Precautionary Principle and to the 'maximin' rule (i.e. setting policy so as to maximise the benefits of the 'worst case' scenario). Great emphasis is given to the long-term benefits of preserving nature, compared to any current benefits of development. The safe minimum standard approach is thus a conservative, risk-averse method.

For HES, there are many possible serious damages to natural resources that could arise. Applying SMS could be done in three slightly different ways:

- Setting minimum thresholds for various future outcomes or indicators (and selecting adaptation options such that these thresholds would not be breached, even under worst case conditions);

- Setting minimum thresholds for adaptation actions (with consideration of the implications for possible worst-case outcomes);
- Setting minimum thresholds for future capacities to deal with possible shocks (such that the worst case shocks could be coped with 'acceptably').

In practice, the SMS approach generally involves trade-offs between ecological and economical concerns, because the costs of action are also considered, and it does not provide clear solutions in case of disagreement. The failure to respect the 2°C target is a case in point, and the failure to reach the 2010 biodiversity target is another – leading to the redefinition of the standard, or the time frame for its achievement. The SMS should encourage discussions on the notion of sustainability (Toman, 1992) but also risks creating hostages to fortune ('crying wolf') and the risk that targets are paid lip-service but not respected. However, these criticisms of SMS as a policy tool are not especially relevant to the present potential use as an indicator of 'success' or 'failure' of adaptation policy for future scenarios.

4.3.3. Critical natural capital

'Weak' sustainability assumes that the components of wealth are completely substitutable, and in particular that the services of ecosystems are perfectly substitutable by human-made capital. Under this interpretation, human use of the environment is essentially an economic problem, and the costs of environmental degradation can be compensated through building up man-made capital. Strong sustainability rejects this substitutability, and considers different capitals as being separately essential to well-being. This makes human use of the environment a jointly economic and environmental issue, and focuses concern on the preservation of important and non-substitutable environmental outputs and services (Davies, 2013).

Critical natural capital is usually defined as that part of the natural environment that performs important and unique functions, and therefore ought to be maintained in any circumstances for present and future generations. In policy terms this represents a form of SMS: the idea of critical natural capital reflects the view that there is some level of natural capital that is 'essential' and provides important ecosystem services that cannot be substituted by other forms of capital, such as human or social capital (de Groot et al., 2003; Dietz & Neumayer, 2007). Depending on the scale, this could mean globally essential, e.g. to continuing human life on the planet, to locally essential, e.g. a minimum level of accessible green space for psychological well-being, and anything in between. Typical examples include essential ecosystem services, such as freshwater resources, climate regulation and fertile soils (Ekins et al., 2003).

In economic terms, this can be conceptualised as an area of perfectly inelastic demand for natural capital below a certain level of provision; it is a natural extension to consider gradually increasing demand elasticity above the absolute threshold (Figure 3, Farley 2008). There are limits to the use of economic methods where marginal values rise steeply, and a recognition that critical natural capital cannot be traded-off. Identifying critical natural capital is partly outside the remit of economics (a matter of biophysical science) but can also depend on ethical deliberation and how minimum thresholds of acceptable outcomes are defined. For example, it is possible to argue on cultural/ethical grounds that particular sacred sites should be accorded critical status, and excluded from trade-off, though this has nothing to do with ecology or natural functions. This can go some way to addressing the concerns relating to incommensurability of values, by setting 'hands off' areas where trade-off is not permitted.

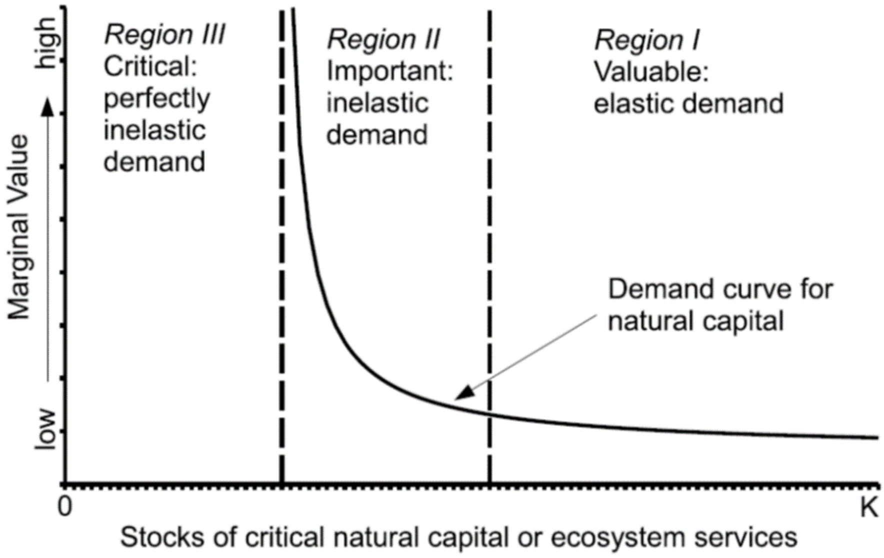

Figure 3: The demand curve for natural capital (Farley, 2008:3).

4.3.4. No net loss

No Net Loss (NNL) is a particular form of SMS, defined with respect to a baseline rather than with an evaluation of likely consequences. This is appropriate where uncertainty is high, loss is ongoing and it is recognised that serious impacts or thresholds could be reached without knowing it. NNL has been developed primarily in the context of biodiversity conservation, but could be given wider application in scenario modelling. The EU biodiversity strategy to 2020 aims to ensure "no net loss of biodiversity and ecosystem services" (target 2, action 7), with the intention to propose by 2015 a supporting initiative, perhaps using compensation or offsetting schemes[12].

In IMPRESSIONS, we could adopt a NNL approach for biodiversity and ecosystem services within the HES impact modelling in just this way – in effect, setting a safe minimum standard for biodiversity in comparison with today. This is not as straightforward as it may sound, since the 'net' part allows for trade-off: we would need to determine sets of habitats and services to which NNL would apply, and determine whether (and at what exchange rates) any trade-off would be permitted across these sets. However, there is likely to be further guidance from DG Environment on this over the next year.

The NNL approach could also be applied to various capitals or capabilities relevant to coping with climate change and associated impacts and shocks. There is a close link here to definitions of sustainability in terms of the capital stocks available to society. Furthermore, the question of trade-off across stocks reflects the difference between 'weak' and 'strong' sustainability criteria and the notions of critical (natural) capital, and 'strategic assets'.

A strategic asset is an asset that is needed by an entity to be able to maintain its ability to achieve future outcomes. Without this asset the future well-being of the entity could be in jeopardy[13]. In the case of climate change, a strategic asset would be any asset which is essential for the functioning of the whole socio-ecological system – if this is an ecosystem component for which there are no

---

[12] http://ec.europa.eu/environment/nature/biodiversity/nnl/index_en.htm

[13] http://www.businessdictionary.com/definition/strategic-assets.html

(affordable) human-made substitutes, this then overlaps with the definition of critical natural capital. Vulnerability analysis in IMPRESSIONS should enable the identification of (some) strategic assets, with implications for the development of adaptation pathways.

4.4. Complexity and agent-based methods

HES emphasise two major long-term challenges faced by our societies: the possibility of catastrophic climate impacts and the need to eventually achieve the transition to a carbon-free economy.

Research on complex systems provides models and methods which are able to analyse the mechanisms of propagation and amplification that are key both to catastrophic failures and to large shifts in socio-economic regimes. They also provide tools for evaluating the resilience, vulnerability or adaptability of a system and, hence, can help assess the adequacy of climate policies with respect to the objectives of avoiding (or reducing the probability of) catastrophic climate impacts and of fostering the transition to a carbon-free economy. It should, however, be accepted that, in the highly non-linear and uncertain setting of HES, it is completely illusory to expect precise quantitative estimates and to consider that socio-economic systems can be controlled. They can at best be partially understood and influenced. With this caveat in mind, we review below the insights that complexity science and agent-based modelling can offer for the evaluation of, first, catastrophic climate impacts and, second, "transformative" policies.

4.4.1. Complexity and HES

There is a lively debate in the literature about the relevance of conventional integrated assessment models (IAMs) given the possibility of catastrophic climate outcomes that may be likely under HES (see in particular Tol, 2003; the dismal theorem by Weitzman, 2009; and comments by Nordhaus, 2011 and Pindyck, 2011). There is, however, a consensus about the fact that conventional IAMs cannot provide any insight about the likelihood or the impacts of such catastrophic climate outcomes (e.g. Pindyck, 2013). By contrast, complex systems models are tailored to analyse the dynamics of abrupt changes. They provide models of the transmission and amplification of shocks in a variety of networked systems: production networks (e.g. Battiston et al., 2007; Mandel et al., forthcoming), financial systems (Haldane & May, 2011; Battiston et al., 2012), trade networks (Fagiolo et al., 2009), disease propagation (Pastor-Satorras & Vespignani, 2001) or food webs (Dunne et al., 2002).

These models can help understand the propagation of climate-related shocks, and hence actually characterise what catastrophic climate outcomes would be, by answering questions such as "which climate shocks can induce a major downfall in global food production?" or "which climate-related shocks can lead to a large decrease in international trade?" In addition, such models can be used to assess the resilience of existing socio-economic networks and provide policy insights into the design of more robust ones. This involves addressing questions such as: "what are the most vulnerable sectors in production networks?"; "how can international trade agreements lead to more resilient international trade networks?" and "can the global food supply network survive a massive decrease in water resources in specific part of the world?" Recent advances in the theory of networks (see D'Agostino & Scala, 2014) could also lead to the development of meta-models of socio-economic systems which could characterise safe-operating boundaries in the socio-economic sphere akin to the biophysical ones put forward in Rockström et al. (2009).

In addition, complex system models can offer a complementary perspective to that of conventional general equilibrium or macro-econometric models for the evaluation of the benefits of climate policy. The latter types of models provide a very precise quantitative assessment of climate policy, but rely on very strong assumptions, which are not reliable under HES. They assume that the economy has a unique equilibrium and can be represented by a single agent in the case of general equilibrium models, and that the economy can be described as a stationary process in the case of macro-econometric models. Complex system models are less precise quantitatively, but better account for the uncertainty and self-organising features of socio-economic systems. In particular, they do not rule out the possibility of crisis and disequilibrium, generally have multiple equilibria, and allow researchers to investigate the transitions between different equilibria.

Accounting for disequilibrium and inefficiency allows the failures of climate policy to be better understood, for example, the existence of negative-cost mitigation opportunities that are not seized. More broadly, one of the crucial issues for mitigation policy seems to be the permanence of the gap between the large investments needed for the energy transition and the almost equally large pledges by financial actors to invest in climate-friendly funds. Developing network-based models of climate finance can help understand the permanence of these structural holes and help design policies that overcome them.

Another crucial aspect of mitigation policy is the diffusion of climate friendly technologies. Complex systems can be used to gain further insights on this issue. For example, the pioneering work of Hidalgo & Hausmann (2009) sheds light on the technological networks that are structuring international trade. Also, network-based models of technological diffusion have recently been developed that account for the actual socio-economic complexity of the technological diffusion process and clarify the influence of the network's topology on its dynamics (see e.g. Montanari & Saberi, 2010). Building on these recent advances, network-based models which are tailored for analysing the diffusion of selected climate-friendly technologies and the impact climate policy can have on this process can be developed.

At the macro-economic level, the main advance brought about by complex systems is the possibility to investigate transitions between different regimes and different equilibria (e.g. Jaeger et al., 2011; in van den Bergh, 2013). There is large uncertainty about the possibility of decoupling economic growth from environmental impacts (van den Bergh, 2013) and, hence, a need to investigate transitions both towards green growth and degrowth. Yet, both are possible only in models that actually represent out-of-equilibrium dynamics.

At the aggregate level, system dynamics models (e.g. Fiddaman, 2002; Weber et al., 2005) provide a concise framework to investigate technologically feasible trajectories while taking into account feedback effects, stock-flow consistency and energy constraints. At the micro-level, complex systems have been used to gain a better understanding of opinion and expectation formation processes (e.g. Lorenz, 2007; Hommes, 2013), the evolution of social norms (in line with the insights put forward by Ostrom, 2000) or the dynamics of technological change (starting from the seminal contribution by Nelson & Winter, 1982). These insights can be integrated into agent-based models in order to provide better founded macro-models for assessing climate-change policies under HES. They can above all inform policy about the measures that can be put in place in order to foster the transition to a more sustainable economic regime. Indeed, key roles of policy in this respect will be to foster innovation, diffusion and adoption of climate friendly technologies, to let environmentally-friendly social norms and preferences emerge and more broadly to coordinate expectations on a new growth path (see Tàbara et al., 2013).

Hence a number of tools are available, but their integration into policy relevant insights is a tremendous challenge for research because of the multiple spatial and temporal scales (see Cash et al., 2006), the heterogeneity of actors and global nature of the problem. Agent-based modelling is a promising avenue for this integration. In this respect, climate policy might require going beyond complex systems theory *per se* and towards the development of a global systems science.

4.4.2. The potential of Agent-Based Modelling

Understanding the complex, dynamic and non-linear relationships between humans and the environment is a difficult problem (Millennium Ecosystem Assessment, 2005), especially under HES, where the reductionist approach of conventional methods may break down. The description of the behaviour of the system requires laws that are qualitatively different from those describing its units, as interactions among agents and the heterogeneous feedbacks from the system to agents play a non-trivial role (Anderson, 1972). In the context of climate change, the impact of a given policy cannot be easily forecast, as the very future is often not foreseeable in a tractable way (Moss et al., 2001), so most conventional methods for climate policy evaluation are of very limited use (see Pindyck, 2013 and Scrieciu, 2007). Standard methods are developed on the underlying assumption that the systems evolve in a stable way, along equilibrium-oriented trajectories that are, at most, exogenously shocked. However, in HES, equilibrium might not be unique, or might not even exist. Therefore, it is important to account for behaviours that might be nearly stable for a long time, but then change dramatically, stochastically and irreversibly in time and space, as tipping points can be triggered by small changes in conditions.

In light of the above considerations, agent-based modelling (ABM) is a well-suited tool for studying the impact of policies on socio-ecological systems under HES. More specifically ABMs are developed to study systems composed of heterogeneous agents, whose repeated interactions give rise to the emergence of properties which cannot be simply deduced by aggregating their individual ones. Heterogeneity stems from different initial resource endowments, but more importantly from differences in the “models of the world” that guide the agents’ adaptation decisions. When interactions occur among bounded rational agents, engaged in heterogeneous learning processes, adapting their behaviours to their past experiences in a complex evolving environment, the dynamic properties of the system cannot be studied analytically, and the identification of causal mechanisms is not always possible. In such a case, ABMs might be the only practical method of analysis (Tesfatsion & Judd, 2006).

The last two decades have seen a rapid growth in agent-based modelling in all the social sciences, partially due to the increasing availability of computing power. For instance, the survey of Ballot & Weisbuch (2000) found studies from sociology, demography, politics and economics employing ABMs. Focusing on economics, the emergence of ABM approaches has been discussed since the early 1990s (Lane, 1993; Tesfatsion, 2006, and more recently Fagiolo & Roventini, 2012). The result has been an increasing number of agent-based applications to the study of networks (Wilhite, 2001; Fagiolo et al., 2007), organisational and industrial dynamics (Dosi et al., 1995, Axtell, 1999; Malerba et al., 1999; Marengo & Dosi, 2005; Chang & Harrington, 2006), technical change (Dawid, 2006 and references therein) and macroeconomic issues (Colander, 1996; Delli Gatti et al., 2005; Dosi et al., 2010). The recent financial crisis and its aftermath have clearly pointed out the inadequateness of standard approaches to the description of our economic system (Gaffard & Napoletano, 2012) and it has sparked a new generation of ABMs dealing with tipping points, contagion dynamics, and rare events (e.g. Delli Gatti et al., 2011; Dosi et al. 2013, 2014; Lengnick, 2013; Riccetti et al., 2013; Salle et al., 2013; Raberto et al., 2014; Dawid et al., 2014).

The potential of ABMs as an adequate tool for analysing socio-ecological systems in the context of climate change is illustrated by Moss et al. (2001), who also provide a sound critique of cost and benefit approaches à la Nordhaus (1992, 1994, 1999, 2001). There are, indeed, several limitations to cost-benefit analysis as described in Section 3.1. As claimed by Moss et al. (2001), the expected benefits of a policy action are conditional on the validity of the underlying theoretical model. The costs of validating the theory should be detracted from the expected net benefits of the policy, but the very implementation of a policy derived from an incorrect model can give rise to further costs.

Validation and implementation costs can be prohibitive, in light of the complexity of causal chains in socio-economic and environmental systems. It may be further argued that not all costs of climate change can easily be quantified (e.g. the extinction of a species), nor the avoidance thereof. ABMs are built upon empirically validated assumptions, and are better suited to dealing with complexity. In this regard, Smajgl et al. (2011) provide guidelines for characterising human behaviour in complex socio-ecosystems composed by heterogeneous interacting agents. Patt & Siebenhüner (2005) focus on the relevance of agent-based approaches for modelling the ability (or inability) of a society to adapt to a changing climate. In particular, they stress that ABMs are almost the only way to account for adaption, considered as an aggregate property stemming from the joint decisions of many separate agents. Indeed, in a complex evolving system framework, adaptation is an emergent property. Kelly et al. (2013) have recently proposed an analysis of five different modelling approaches for integrated assessment and policy decision support. Within the range of the instruments considered, the ABM framework was found to be a useful and flexible laboratory for policy experimentation, as it allows various requirements of environmental management modelling to be embedded (Hare and Deadman, 2004) more naturally than standard approaches. Even though there is a strong case for using the ABM approach in climate policy analysis, the number of ABM applications in this field is still far below the number of models based on standard assumptions (e.g. the DICE family, Nordhaus 1992; the FUND family, Tol 1995; the WiTCH family, Bosetti et al., 2006). However, the gap is rapidly narrowing.

4.4.3. Climate issues and ABMs

Agent-based contributions in the field of climate change can be broadly divided into four categories: land-use modelling, empirical field studies, common resources management, and macroeconomic oriented models. The application of ABMs in land use seems to be well established in the literature, with a plethora of models and accompanying empirical exercises (Brown et al., 2005; Matthews et al., 2007; Robinson et al., 2007). By contrast, there is a scant number of ABMs involved in the study of the macroeconomic impact of climate change (Balbi & Giupponi, 2009; Kelly et al., 2013), even if this area of research displays the highest growth potential and relevance for policy analysis at the national and international levels (e.g. EU level policy in support of climate negotiations).

<u>Land use modelling</u>

In the realm of land use, ABMs deal explicitly with climate change issues and, particularly, adaptation mechanisms (e.g. Dean et al., 2000; Werner & McNamara, 2007; Entwisle et al., 2008; Filatova, 2009; Filatova et al., 2011). Dean et al. (2000) is an early example of an ABM of local socio-ecosystems, which includes climate change elements in order to simulate human responses and the outcome of adaptation. The model represents the behaviour of culturally relevant agents on a defined landscape in order to test hypotheses concerning past agricultural development and settlement patterns. Werner & McNamara (2007) investigate how economic, social and cultural factors surrounding human response to river floods, hurricanes and wetlands degradation affect a city landscape. Entwisle et al. (2008) focus on responses to floods and drought at a regional level in terms of agricultural land use and migration, explicitly taking into account social networks. Filatova (2009) incorporates climate change related risks in an agent-based land market for coastal cities, which simulates the emergence of urban land patterns and land prices as a result of micro scale interactions between buyers and sellers. Filatova et al. (2011) draw on a similar model to assess land tax policies and find that agents' interactions are fundamental in shaping policy outcomes. Interestingly, they contrast ABM results with those obtained using a representative agent and welfare maximising analysis of the same policy, and show how the latter might lead to detrimental conclusions when heterogeneity is overlooked.

Empirical field studies

Empirically calibrated and locally focused ABM analysis of socio-ecosystems is found, among others, in Berman et al. (2004) and Bharwani et al. (2005). These contributions are generally concerned with the investigation of adaptation mechanisms in small, but well-defined, societies. Berman et al. (2004) assess how scenarios associated with economic and climate change might affect a local economy, resource harvest and the wellbeing of a small arctic community. Alternatively, Bharwani et al. (2005) focus on whether individuals belonging to a South African village, gradually adapting to annual climate variability, are better equipped to respond to longer-term climate variability and change in a sustainable manner.

Common resource management

The third classical area where ABMs contribute to understanding the effects of climate change on socio-ecological systems is common resource management. Moss (2002) proposes a simple example of an agent-based participatory model for climate impact assessment in the context of water management. In particular, relying on UK data, the author builds up a model composed of a hydrological box, used to determine soil-water content, and a social architecture to capture the effects of the latter on policy agencies and household consumption. In a similar context, Barthel et al. (2008) develop an ABM framework for the construction of future water demand and supply scenarios, where the socio-ecosystem is enabled to react and to adapt to climate change. Janssen (2002), and references therein, provide a more extensive review of multi-agent approaches to ecosystem management.

Macroeconomic-oriented models

Finally, a new generation of ABMs studying the multifaceted links between growth and climate change at the regional, national and global level has been growing rapidly over recent years. The first ABM which attempted to link the (co)evolution of climate and the economy was proposed by Janssen & de Vries (1998), who developed an economy-energy-climate model where international negotiators are allowed to change their view about the system's functioning and to modify it. Even if the economy is described at the aggregate level as in Nordhaus (1994), the model was the first attempt to introduce some degree of heterogeneity in the study of aggregate economies under a warming climate. Weber et al. (2005), and successively Hasselmann (2008) and Hasselmann & Kovalevsky (2013), introduced a few representative actors in macroeconomic models of coupled climate and socio-economic systems employing a system dynamics approach. The focus is on the evolution of the system given the behaviour of the agents, who pursue different goals while jointly striving to limit global warming to an acceptable level. These models, despite the claim of being multi-actor based, use a single representative agent in each compartment of the economy (financial sector, public sector, production and consumption) and, in many aspects, appear similar to standard general equilibrium models. However, in contrast to the latter, the authors model explicitly non-linear dynamics through feedback cycles, out-of-equilibrium paths and non-rational beliefs. Mandel et al. (2009) developed an ABM of a growing economy where growth is triggered by increases in labour productivity proportional to investments. A more recent version of the model (Wolf et al., 2013b) adds the possibility of specifying different interacting economic areas and to study the properties of economic growth as emerging from a spatially explicit production network. Beckenbach & Briegel (2011) investigated the relationship between innovations, economic growth and carbon emissions. The same issue is addressed in detail by Gerst et al. (2013) who, drawing on Dosi et al. (2010), model a complex economy composed by two vertically related industrial sectors and an energy production module, and test the effects of different carbon tax recycling schemes. Safarzyńska et al. (2013) discuss the shortcomings of standard macroeconomic modelling for the analysis of large-scale flood events, which, like in the case of Fukushima for instance, might have enormous impacts at the aggregate level, and explicitly refers to agent-based micro to macro approaches to conveniently study public policies aimed at reducing flood risks.

4.5. Summary for IMPRESSIONS

Conventional tools, especially those grounded in neoclassical economics, have important limits, in particular when applied to HES of climate change. The criticisms largely relate to serious problems in estimating monetary values and probability distributions for outcomes, and, more generally, in the descriptive reasonableness of utility theory. Traditional appraisal methods such as CBA might be suitable when probability distributions for most of the costs and benefits are known with acceptable confidence, can be monetised in widely agreed ways, and do not include risks of extreme or disastrous outcomes. However, this is not the case for climate change, and in particular for the analysis of HES, because of uncertainties associated with high stakes and disputed values.

One response to these problems is to modify traditional approaches, using monetary valuation where possible, and falling back on multi-criteria methods for other impacts (Figure 4). However, MCA approaches do not avoid all the problems of CBA, in particular relating to uncertainties about outcome distributions and issues around using weights (albeit non-monetary ones) to combine diverse impacts.

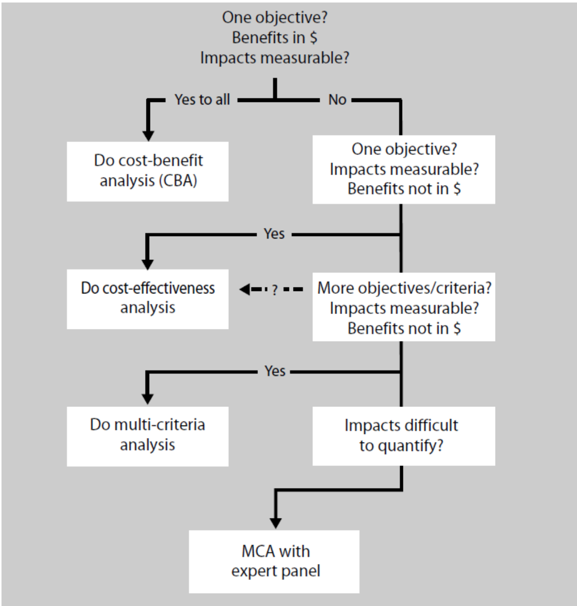

Figure 4: The choice between CBA, CEA and MCA (UNFCCC, 2002:34).

Accepting that appraisal leading to 'optimal' policies may not be feasible, an alternative is to seek robust policies using non-probabilistic approaches. If we do not know in advance which scenario holds, and have to adapt before this uncertainty is resolved but can model the outcomes under each of the possible future scenarios, we can seek policies that perform 'acceptably' across all scenarios. Deliverable 5.3 on 'stress-testing' of policies (due in August 2017) will provide more details on this topic. It is worth highlighting that, although IMPRESSIONS is considering only a relatively small number of scenarios, these include some quite extreme outcomes, augmented by 'wildcard' shocks. Although we cannot assume that these cover all the worst possible outcomes, the scenarios and wildcards will cover a very broad range. However, they are far from a probabilistic description of possible futures - in fact, the most likely outcomes may not be included as we focus only on intermediate and HES. This means that any approach based on averaging across future outcomes can effectively be ruled out. For most non-probabilistic methods, this is not necessarily a problem, provided we can assume that the 'worst' cases do not occur in any of the milder scenarios we do not cover. However, for methods such as 'minimax regret', this is more of an issue.

With the more flexible versions of non-probabilistic approaches, the aim is to limit the number of scenarios with unacceptable outcomes. In this case, the scenario-based analysis aims to implement measures efficient enough across a wide range of scenarios (under all levels of uncertainty regarding outcomes), or flexible measures that can be modified or deleted when more information is gathered (Hallegatte et al., 2011a – see also real options analysis and iterative risk management in Section 3). The scenarios will include both optimistic and pessimistic scenarios (Hallegatte et al., 2011b). This method has been commonly used in climate change impact and adaptation studies using IPCC SRES scenarios (Carter et al., 2007; Hallegatte et al., 2011a).

Threshold approaches are generally presented and used in the context of policy-making, i.e. setting actual thresholds and targets, such as No Net Loss, in the face of uncertainty, to guide sustainable policies. For IMPRESSIONS, the need is different, to assess adaptation options and policies. For this purpose, the binary nature of the indicator is an important shortcoming: either the threshold is breached, or it is not. To counter the binary nature of threshold methods, the research question can be cast in the terms 'how much will it cost to respect this policy target':

- determine a threshold;
- examine options for just achieving it:
    - under a given scenario; or
    - in a robust fashion across a suite of scenarios; and
- compare options to determine the most cost-effective way of achieving the target.

This approach is closely related to vulnerability analysis – in effect, defining a population as 'vulnerable' to a particular shock is close to stating that the safe minimum standard has been (or could be) breached. Determination of thresholds would require consideration of various possible impacts, social values and requirements, similar to the setting of vulnerability thresholds. This approach was adopted successfully in the CLIMSAVE project, with thresholds determined through expert judgement (see Dunford et al., 2015).

However, these approaches still limit the extent to which trade-offs across different objectives can be taken into account. A 'capabilities' approach could allow more flexible setting of limits, and could be implemented in a non-threshold manner by allowing multiple different levels of capabilities, or a continuity. For application to HES, the main issue here is how much we allow trade-offs across capitals or capabilities. Is it acceptable to run down (say) natural capital, provided (say) produced capital increases commensurately? This is 'weak' sustainability. Or on the contrary, do we define minimum levels of each type of capital? This is 'strong' sustainability.

As noted before, the answers to these questions would have important implications for what we try to measure, and how we measure it. In particular, if we reject substitutability across capital types (via a strong sustainability criterion) and/or if we recognise, estimate or (in the face of uncertainty) arbitrarily set thresholds for capitals (via critical capital constraints), there is limited scope for trade-off, and therefore limited scope for monetary valuation (upper left cell, Table 8).

Table 8: Approaches to conceptualising benefits.

	Relationship between capital stock and human welfare		
	Threshold	**Inelastic**	**Elastic**
Strong sustainability	Individual critical capitals: No substitutes	No substitution, rapid changes in welfare for small changes in stocks	Smooth transition, for each indicator separately
Weak sustainability	Composite threshold: minimum wealth	Substitutable but large compensations needed for small changes	Perfect substitutes. Single metric possible

ABMs are a promising tool for policy analysis in the context of climate change, especially when HES are explicitly taken into account. The new generation of macroeconomic-oriented ABMs being developed in IMPRESSIONS has especially strong potentiality for policy analyses under HES. They allow policy-makers to design different climate change and macroeconomic policies (e.g. innovation, industrial, monetary, fiscal policies) and test their short- and long-term impact on economic performance and environmental conditions (e.g. GHG emissions, temperature), taking into account that the latter can endogenously change and co-evolve with the structural transformation of the economy. In such a framework, tipping points and irreversibilities can be taken into account by linking the frequency and size of environmental disasters (e.g. huge shocks to productivity, stock of capital, population, etc.) to the temperature and the stock of GHGs in a non-linear and time-varying way. In such stylised economy, the assessment of different policies can be performed employing indicators such as GDP, unemployment and productivity. Given the pervasive uncertainty related to technical change and HES, the values of the quantitative indicators generated by the model cannot be considered precise. Nonetheless, policy-makers can employ them to rank alternative suites of policies.

ABMs can also facilitate the discovery of combinations of policies which lead to win-win pathways. Such policies are likely to be ‘transformative’, going beyond the classical mitigation and adaptation dichotomy. For example, ABMs could be used to test whether macroeconomic policies supporting a green transition of the economy can allow Europe to exit the uncertain and stagnating aftermath of the Great Recession, with enhanced growth potential and reduced likelihood of suffering extreme consequences under HES. ABMs in IMPRESSIONS will therefore help us:

- to study the properties of systems in disequilibrium and the transitions between different regimes;
- to study how agents and groups adapt and react to changing environments;
- to explore learning, for example in decision rules and cooperation of agents over time, a component which is central in representing both adaptation and adaptation strategies under HES and in particular in assessing pathways aimed at supporting transformation;
- to improve understanding of cumulative aggregate effects of agents’ behaviour on systems structural change dynamics, hence linking microeconomic decisions not necessarily triggered or led by explicit public policies (e.g. changes in dietary habits) to macro-structural effects (which then become represented as emergent properties);
- to study the endogenous co-evolution of the environmental and socio-economy systems;
- to detect tipping points in the dynamics of the system and to check the effects of alternative policy pathways on the possible occurrence and location of such points;
- to test adaptation and mitigation policies together with ‘transformative’ ones;
- to analyse the distributional effects of different ensembles of policies together with their economic and environmental impact over different time horizons; and,
- to rank alternative combinations of policies and implement robustness policy tests.

However, the development of ABMs represents only one strand of the IMPRESSIONS research. We will also need to develop methods for appraising policy options for the outputs of other IMPRESSIONS models. The following section draws some conclusions on the requirements of these methods and the approach to be taken in selecting them within the IMPRESSIONS work programme.

5. Conclusions: methods to apply in IMPRESSIONS

"Valuation is about assessing trade-offs toward achieving a goal" (Farber et al., 2002). Conversely, all decisions that involve trade-offs involve either explicit or implicit valuation (Costanza et al., 2011). Thus valuation and trade-off are inextricably linked. The key point is that "when assessing trade-offs, one must be clear about the goal" (Costanza et al., 2014). Whatever approach is adopted in IMPRESSIONS – whether trade-offs are made implicit or explicit, numerical or categorical – the purpose of 'analysing costs and benefits' is to allow people to examine the possible consequences of different courses of action.

Different methods of sustainability assessment and appraisal can be distinguished according to their purpose as well as the tools used. These distinctions are not identical, since the same tools can be used in different ways for different purposes, leading to different types of assessments. Evaluation of assessments needs to reflect "fitness for purpose" criteria. A broad distinction can be drawn between pragmatic approaches seeking to demonstrate suitability of policy initiatives within the prevailing policy paradigm and its definition of sustainable development, and more strategic approaches that focus on robustness of policies under radical uncertainty, issues relating to unsustainable development paths, and stakeholder attitudes to these dangers and associated policy paradigms. The latter are less well developed, but highly relevant to HES analysis of long-term, highly uncertain futures and potentially transformative scenarios (Weaver et al., 2006). In IMPRESSIONS, WP1 is making a related distinction between 'predictive top-down' or 'science-first' approaches based on seeking optimal policies under risk, and 'resilience bottom-up' or 'decision-first' approaches that seek robust policies under uncertainty (see Deliverable D1.1; Capela-Lourenço et al., 2015).

Most analysis to date follows the pragmatic approach, in particular via conventional cost-benefit analysis, or related toolsets, leading to relatively minor policy decisions (such as quite insignificant carbon taxes), dubious estimates of marginal abatement cost/benefit curves (that do not fully reflect uncertainty and endogeneity of future technological change) and decisions to delay action until more knowledge is available and/or the costs of response/action are lowered (Barker, 2008). However, increasing attention to analysis reflecting the major uncertainties and 'fat'-tail risks (Stern, 2007; Weitzman, 2009; Taleb et al., 2014) and to complexity-based models that do not make *a priori* assumptions about probability distributions (Wolf et al. 2013a,b; Ballot et al. 2014) promotes action without delay, so that dangerous scenarios of climate change can be avoided, and to implement cost-effective and equitable policies to accelerate the decarbonisation of the world economy.

This report has set out the advantages and disadvantages of different approaches for evaluating climate change policies under HES. There is a fundamental choice between a focus on selection of the 'best' policies (generally through optimisation of expected outcomes), or a focus on robustness over a wide range of possible scenarios, including climate futures, socio-economic trends, and other factors. Where uncertainties are important – as in HES – seeking robust strategies is preferable to criteria base on optimisation (Lempert & Collins, 2007; Matrosov et al., 2013). As IMPRESSIONS is adopting a HES approach, there is no scope for formal optimisation across scenarios, so the choice is between optimisation for each scenario individually and seeking robust policies across all scenarios together. To assess robustness, we need to define indicators that can be assessed and compared across the scenarios. ABMs offer a flexible tool to test robustness of a wide range of policies under endogenously evolving scenarios. However, the final decisions on the methods and indicators to be used in IMPRESSIONS are partly dependent on the developing work in other areas of the project, in particular the stakeholder-led scenario development. Below, we set out criteria for selecting methods, and explain how the work will be taken forward in step with the scenario and vision development and other IMPRESSIONS workstreams.

5.1. Criteria to choose the best methods

In the scope of this work there are various choices to make. We have the option of pre-judging what the goal is and automating the trade-offs (which CBA essentially does, through aggregation of externally-derived values) or we could be more flexible and offer different indicators and allow stakeholders to decide which ones are relevant to them. In any event, we should be clear that any attempt to reduce complex, long-term implications of adaptation, mitigation and transformative options under HES to single numerical 'answers' would be misleading and ultimately unhelpful.

Similarly, we can focus attention at the level of individual welfare, and how it is distributed among individuals within and across generations, or focus rather on societal indicators. Finally, we can focus on measures of outcomes (for example particular incomes, services, health outcomes …) or on measures of opportunities (capitals, capabilities…). Questions of distributions across people/groups are also relevant.

The answers to these questions will have an impact on the choice of indicators or tools to assess the costs and benefits of climate change adaptation and mitigation in the context of HES. Monetary data and valuation are often proposed because they have the great advantage of using a common metric. This allows comparison of sources of value that otherwise are expressed in totally incommensurable terms. This is particularly useful for decision support and scenario analysis - but *if and only if* the estimated monetary values are reasonably complete and accurate, and good indicators of welfare. Physical data do not give this generalised comparability, but do keep the focus on absolutes. They are more useful for thinking about biophysical thresholds, for example. For many purposes, physical data are better suited for comparing across time or space, because monetary values change with changing incomes and prices.

In any case it is not necessarily a matter of selecting one or the other – both types of data have their uses, and IMPRESSIONS could decide to have a diversity of indicators. Similarly, both stock and flow measures are useful for different purposes, for example, it is important to consider both the current flow of services supporting human welfare and changes in the stock of service-generating assets that will support future welfare. In the UN System of Environmental Economic Accounting, for example, both physical and monetary tables are presented, covering both current flows and asset stocks.

For IMPRESSIONS, stakeholders could have the opportunity to select or weight the indicators they find most relevant. Any pre-selection of methods by researchers, and final determination of methods, should be carried out transparently on the basis of clear criteria. These can be based on existing methods, as discussed below. However, it should be clear that the purpose of setting out criteria is not to dissolve the complexity of such a choice into an apparently objective procedure: we do not seek to reduce the different logics and assumptions of very different methods into a single 'best choice'. Rather, the aim is to provide guidance on the multiple features that different methods have in varying proportions, to help researchers and stakeholders consider the trade-offs in selecting from among the options available.

The European Statistical System defines quality criteria for statistical data, but while relevant they are retrospective in application (i.e. relate to the performance of actual statistics[14]). We require a more prospective set of criteria, focused on selecting indicators that we will use within the project. For this, we draw on Heink & Kowarik (2010) who present a comprehensive list of criteria (Table 9)[15].

Table 9: Criteria for the selection of indicators for assessing the costs and benefits of climate change adaptation and mitigation in the context of HES; colour coded with respect to their relevance for IMPRESSIONS (green = most relevant; red = least relevant; yellow = intermediate relevance).

Criterion	Interpretation for IMPRESSIONS	Decision on relevance
Feasibility:		
Knowledge	How well is the category understood?	Essential that both researchers and stakeholder understand clearly what the indicators mean.
Portability	Wider relevance outside IMPRESSIONS framework	Desirable but not of primary interest.
Suitability for statistical analysis	Low random variation at relevant scales	Changes in the figures must have some interpretative validity: wide random fluctuations.
Existence of reference values	For comparison with base case	Desirable, but not essential, to be able to compare across scenarios.
Efficiency of indicators:		
Feasibility of data collection	Is the information available in IMPRESSIONS models/scenarios/outputs?	Essential to link indicators to modelling work and outputs of stakeholder workshops.
Universality	Widely applicable, i.e. relevance is not scenario-dependent	Indicators must be comparable across scenarios, and relevant to all.
Parsimony	Particularly important for communicating results, i.e. ability to assess outcomes without too many indicators to present/graph/understand	Desirable, but IMPRESSIONS can cover multiple maps and indicators, and develop composite ones as required.
Relation between indicator and indicandum:		
Precision of correlation	For example if we want to measure "happiness" the Easterlin paradox would suggest that GDP is not a good choice	Desirable, but again multiple indicators can be used, and interpreted as appropriate.
Validation	Can the relationship be tested/validated using available data?	Desirable, but could be acceptable to base indicators on theoretical justification.
Construct validity	Is the indicator theoretically justified?	Need a clear justification for relating indicator to human wellbeing or other impacts of interest.

[14] http://ec.europa.eu/eurostat/web/social-protection/quality

[15] These criteria were originally developed for biodiversity indicators, but can be adapted for IMPRESSIONS. The criteria listed in the first column have been modified from the Heink & Kowarik (2010) with additions and deletions appropriate to the changed context.

Criterion	Interpretation for IMPRESSIONS	Decision on relevance
Aggregation of a substantial amount of information	Single measure that is closely related to a wide range of features	Desirable, in particular in the sense of aggregating impacts across multiple sources of threats/impacts (although this aggregation involves loss of information).
Information to be provided by the indicator:		
Relevance	In context of overall purpose, see also 'acceptance'	Indicators must be clearly relevant to assessing human welfare in the context of HES.
Speed of response to change	Responsive to changes in the fundamental aspects of interest without long lags	Lags more an issue for real-time indicators.
Amplitude of response to change	Responds clearly to changes in the fundamental aspects of interest	Responsiveness important for comparing scenarios.
Perception of indicators:		
Ethical grounding	Is the indicator justifiable on ethical/moral grounds?	Likely to be important for at least some indicators.
Acceptance	Do stakeholders 'like' the indicator? To check in workshops.	Strong stakeholder focus in IMPRESSIONS.
Comprehensibility	Does the indicator simplify complex information in an easily understandable way? (different from aggregation via focus on simplicity/understanding rather than combining information on several features).	Aiming to analyse multiple paths across several scenarios.
Economic importance	May be relevant if using results to motivate adaptation expenditures	Some indicators may be, but this is not a criterion for excluding others.
Social characters/functions of the indicators:		
Ability to invest responsibly	Usefulness as a guide to adaptation decisions	Central to IMPRESSIONS.
Ability to monitor and manage low probability outcomes	Indicators should operate under and be sensitive to high-end / extreme conditions	Central to IMPRESSIONS.
Ductility in comparison with uncertainties and tipping-points	The indicator applies to all scenarios and does not 'break' if thresholds are reached	Central to IMPRESSIONS.
Familiarity of the indicator at the social level	For ready understanding without need for explanation/capacity building.	IMPRESSIONS is aimed at an expert audience and familiarity is not a key issue.
Sustainability in the relationship between several social variables.	The interpretation of the indicator is not strongly context-dependent / dependent on other variables.	Important for comparison across scenarios and with base case.

5.2. Selecting indicator methods in step with scenario, vision and model development

At the first stakeholder workshop in each IMPRESSIONS case study, the participants will develop socio-economic scenarios and combine these with climate scenarios. The outcome of this process will be a set of "input scenarios", with some quantification of variables subsequently required for modelling work on impacts and vulnerability.

At the second stakeholder workshop, the participants will first develop a vision of the world they would like to live in – or bequeath to future generations – in 2100. Stakeholders will then be presented with a selection of the modelled impacts of the input scenarios and the related vulnerabilities to changes in ecosystem services. This will demonstrate the gap between their vision and the possible future (scenario). For "utopic" scenarios (which are transformative) the gap will not be as large as for the more "dystopic" scenarios. For each scenario, the workshop participants will then develop pathways with adaptation and mitigation options, in an attempt to close the gap between the scenario (the path we could be on) and the vision (the end point we would like to reach).

Between the second and third workshops, a considerable amount of work will be carried out by the IMPRESSIONS project team. Some modelling activities could show whether the measures proposed by the stakeholders do indeed reduce vulnerabilities to changes in ecosystem services. Agent-based modelling could show in a qualitative manner the risks and opportunities of different kinds of pathways (e.g. strong mitigation, strong mitigation and strong adaptation, strong adaptation alone). Analysis will also be made of the synergies and trade-offs between the adaptation and mitigation measures proposed, continuing work started under the CLIMSAVE project (Berry et al., 2015).

Indicators and methods for assessing stakeholder-created strategies (and different climate change policies) will come from the scenarios and associated modelling, as well as from the visions and pathways. Candidate indicators will be evaluated against the criteria presented in Table 9, and integrated with the modelling work in order to make assessments of "costs and benefits" of different pathways. This initial assessment will provide input to the final stakeholder workshop. A related assessment, building on the conceptual framework being developed in IMPRESSIONS WP4, is to look at the adaptive capacity, the transformative capacity and the strategic capacity in the different pathways to identify barriers to adaptation, transformation and synergetic measures. One promising option is that indicators for assessing the impact of different policies could be tied closely to such capacity work (as noted above) considering changes in capacities.

In the final stakeholder workshop, participants will see the results of modelling of the pathways and initial assessments of the impact of different policies. They will also have the results of stress-testing of the pathways and will carry out a wildcard exercise to look at the robustness of their vision and proposed pathways. All of these results could lead to an adjustment of the pathways. All of this leads to a discussion of an action agenda for the case study area: who needs to do what by when in the face of HES.

6. Acknowledgements

We would like to thank the following people for helpful comments, ideas and review of this report: Agustin Arcilla, Magnus Benzie, Henrik Carlson, Adis Dzebo, Paula Harrison, John Haslett, Katharina Holscher, Franck Lecocq, Robert Lempert, Tiago Capela-Lourenço, Diana Mangalagiu and Varum Rao.

7. References

Aaheim, H.A. & Bretteville, C. (2001). Decision-making frameworks for climate policy under uncertainty. CICERO Working Paper, 2001:2, Norway.

Adelle, C. & Pallemaerts, M. (2009). Sustainable Development Indicators, An Overview of relevant Framework Programme funded research and identification of further needs in view of EU and international activities. European Communities. http://www.ieep.eu/assets/443/sdi_review.pdf

Alkire, S. (2003). A Conceptual Framework for Human Security. Centre for Research on Inequality, Human Security and Ethnicity (CRISE). University of Oxford, UK.

Anderson, P.W. (1972). More is different. Science, 177:4047, 393-396.

Arrow, K. J., Cropper, M., Gollier, C., Groom, B., Heal, G. M., Newell, R. G., Nordhaus W.D., Pindyck R.S., Pizer W.A., Portney P.R., Sterner T., Tol R.S.J. & Weitzman, M. (2012). How should benefits and costs be discounted in an intergenerational context? The views of an expert panel. Resources For the Future Discussion Paper 12-53.

Axtell, R. (1999). The emergence of firms in a population of agents: local increasing returns, unstable Nash equilibria, and power law size distributions. Center on Social and Economic Dynamics, Working Paper No. 3.

Balbi, S. & Giupponi, C. (2009). Reviewing agent-based modelling of socio-ecosystems: a methodology for the analysis of climate change adaptation and sustainability. University Ca'Foscari of Venice, Dept. of Economics Research Paper Series.

Ballot, G. & Weisbuch, G. (2000). Applications of Simulations to Social Sciences. Oxford: Hermes Science Publishing.

Ballot, G., Mandel, A. & Vignes, A., (2014). Agent-based modeling and economic theory: where do we stand ? Journal of Economic Interaction and Coordination, online first.

Barberis, N. & Thaler, R. (2003). A survey of behavioral finance. Handbook of the Economics of Finance, 1, 1053-1128.

Barker, T. (2008). The economics of avoiding dangerous climate change. An editorial essay on The Stern Review. Climatic Change, 89:3-4, 173-194.

Barthel, R., Janisch, S., Schwarz, N., Trifkovic, A., Nickel, D., Schulz, C., & Mauser, W. (2008). An integrated modelling framework for simulating regional-scale actor responses to global change in the water domain. Environmental Modelling & Software, 23:9, 1095-1121.

Battiston, S., Delli Gatti, D., Gallegati, M., Greenwald, B., & Stiglitz, J. E. (2007). Credit chains and bankruptcy propagation in production networks. Journal of Economic Dynamics and Control, 31:6, 2061-2084.

Battiston, S., Puliga, M., Kaushik, R., Tasca, P., & Caldarelli, G. (2012). Debtrank: Too central to fail? Financial networks, the FED and systemic risk. Scientific reports, 2:541, doi:10.1038/srep00541.

Beckenbach, F. & Briegel, R. (2011). Multi-agent modeling of economic innovation dynamics and its implications for analyzing emission impacts. International Economics of Resource Efficiency, pp. 289-315.

Benartzi, S. & Thaler, R. H. (1993). Myopic loss aversion and the equity premium puzzle (No. w4369). National Bureau of Economic Research.

Berman, M., Nicolson, C., Kofinas, G., Tetlichi, J., & Martin, S. (2004). Adaptation and sustainability in a small arctic community: Results of an agent-based simulation model. Arctic, 57:4, 401-414.

Berry, P.M., Brown, S., Chen, M., Kontogianni, A., Rowlands, O., Simpson, G. & Skourtos, M. (2015). Cross-sectoral interactions of adaptation and mitigation measures. Climatic Change, 128:3-4, 381-393.

Bharwani, S., Bithell, M., Downing, T. E., New, M., Washington, R., & Ziervogel, G. (2005). Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. Philosophical Transactions of the Royal Society B: Biological Sciences, 360:1463, 2183-2194.

Bognar, G. (2011). Can the Maximin Principle Serve as a Basis for Climate Change Policy? http://www.academia.edu/1823048/Can_the_Maximin_Principle_Serve_as_a_Basis_for_Climate_Change_Policy

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., & Tavoni, M. (2006). WiTCH a world induced technical change hybrid model. The Energy Journal, 13-37.

Bretteville Froyn, C. (1999). Decision criteria under uncertainty and the climate problem. CICERO Working Paper, 1999:10, Oslo, Norway.

Bretteville Froyn, C. (2005). Decision criteria, scientific uncertainty, and the global warming controversy. Mitigation and Adaptation Strategies for Global Change, 10: 183–211.

Brklacich, M., Chazan, M., & Bohle, H.G. (2010). Human security, vulnerability, and global environmental change. In: Global Environmental Change and Human Security [Matthew, R.A., Barnett, J., McDonald, B., and O'Brien, K. (eds)]. Cambridge, USA: MIT Press, pp. 35–51.

Broome J. (2012). Climate matters: ethics in a warming world. New York, USA.

Brown, D. G., Page, S., Riolo, R., Zellner, M., & Rand, W. (2005). Path dependence and the validation of agent-based spatial models of land use. International Journal of Geographical Information Science, 19:2, 153-174.

Camerer, C. F. (1992). Recent tests of generalizations of expected utility theory. In Utility theories: Measurements and applications, 207-251. Springer Netherlands.

Capela Lourenço, T., Carlsen, H., Dzebo, A., Haslett, J. & Harrison, P.A (2015). Draft Common Frame of Reference to support the understanding of adaptation decision-making under high-end scenarios. EU FP7 IMPRESSIONS Project Deliverable D1.1. January 2015.

Carter, T.R., Jones, R.N., Lu, X., Bhadwal, S., Conde, C., Mearns, L.O., O'Neill, B.C., Rounsevell, M.D.A. & Zurek, M.B. (2007). New Assessment Methods and the Characterisation of Future Conditions. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the

Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. & Hanson, C.E. (Eds.)]. Cambridge University Press, Cambridge, UK, 133-171. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch2.html

Cash, D. W., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L. & Young, O. (2006). Scale and cross-scale dynamics: governance and information in a multilevel world. Ecology and society, 11:2, 8.

Chambwera, M., Heal, G., Dubeux, C., Hallegatte, S., Leclerc, L., Markandya, A., McCarl, B.A., Mechler, R. & Neumann, J.E. (2014). Economics of adaptation. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. & White, L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.

Chang, M. H. & Harrington, J.E. (2006). Agent-based models of organizations. Handbook of computational economics, 2, 1273-1337.

Clark, D.A. (2005). The Capability Approach: Its Development, Critiques and Recent Advances. GPRG-WPS-032, Global Poverty Research Group.

Colander, D. (1996). Beyond Microfoundations: Post Walrasian Economics. Cambridge University Press.

Colander, D., Goldberg, M., Haas, A., Juselius, K., Kirman, A., Lux, T. & Sloth, B. (2009). The financial crisis and the systemic failure of the economics profession. Critical Review, 21:2-3, 249-267.

Costanza, R., Kubiszewski, I., Ervin, D., Bluffstone, R., Boyd, J., Brown, D., Chang, H., Dujon, V., Granek, E., Polasky, S., Shandas, V. & Yeakley, A. (2011). Valuing ecological systems and services. F1000 Biol. Rep., 3: 14.

Costanza, R., de Groot, R., Sutton P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S. & Turner, R.K. (2014). Changes in the global value of ecosystem services. Global Environmental Change 26:2014, 152–158.

Crowards, T.M. (1996). Addressing uncertainty in project evaluation: the costs and benefits of safe minimum standards. CSERGE Working Paper GEC 96-04. Centre for Social and Economic Research on the Global Environment (CSERGE), University of East Anglia and University College London.

Crowe, K.A. & Parker, W.H. (2007). Using portfolio theory to guide reforestation and restoration under climate change scenarios. Climatic Change, 89:3-4, 355-370, DOI 10.1007/s10584-007-9373-x.

D'Agostino, G. & Scala, A. (2014). Networks of Networks: The Last Frontier of Complexity. Understanding Complex Systems. Imprint: Springer.

Davies, G.R. (2013). Appraising Weak and Strong Sustainability: Searching for a Middle Ground. Consilience: The Journal of Sustainable Development, 10:1, 111 – 124.

Dawid, H. (2006). Agent-based models of innovation and technological change. Handbook of computational economics, 2, 1235-1272.

Dawid, H., Gemkow, S., Harting, P., Van der Hoog, S. & Neugart, M. (2014). Agent-based macroeconomic modeling and policy analysis: the Eurace@ Unibi model.

De Bruin, K. (2013). Ranking climate change adaptation options through multi-criteria analysis. NZCCRI Seminar Series, CICERO.

De Bruin, K., Dellink, R. B., Ruijs, A., Bolwidt, L., van Buuren, A., Graveland, J., de Groot, R.S., Kuikman, P.J., Reinhard, S., Roetter, R.P., Tassone, V.C., Verhagen, A. & van Ierland, E.C. (2009). Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climatic Change, 95:23–45.

De Groot, R., Van der Perk, J., Chiesura, A. & van Vliet, A. (2003). Importance and threat as determining factors for criticality of natural capital. Ecological Economics, 44:2-3, 187-204.

Dean, J. S., Gumerman, G. J., Epstein, J. M., Axtell, R. L., Swedlund, A. C., Parker, M. T. & McCarroll, S. (2000). Understanding Anasazi culture change through agent-based modeling. In: Dynamics in human and primate societies: Agent-based modeling of social and spatial processes [Kohler T.A., Gumerman G.J. (eds)], 179-205.

Delli Gatti, D., Guilmi, C. D., Gaffeo, E., Giulioni, G., Gallegati, M., & Palestrini, A. (2005). A new approach to business fluctuations: heterogeneous interacting agents, scaling laws and financial fragility. Journal of Economic behavior & organization, 56:4, 489-512.

Delli Gatti, D., Desiderio, S., Gaffeo, E., Cirillo, P., & Gallegati, M. (2011). Macroeconomics from the Bottom-up, 1, Springer.

Development Assistance Research Associates (DARA) (2012). Climate Vulnerability Monitor, A guide to the cold calculus of a hot planet 2nd ed.

Dietz, S. (2011). High impact, low probability? An empirical analysis of risk in the economics of climate change. Climatic Change, 103:3, 519-541.

Dietz, S. & Neumayer, E. (2007). Weak and strong sustainability in the SEEA: Concepts and measurement. Ecological Economics, 61:4, 617-626.

Dosi, G., Marsili, O., Orsenigo, L. & Salvatore, R. (1995). Learning, market selection and the evolution of industrial structures. Small Business Economics, 7:6, 411-436.

Dosi, G., Fagiolo, G. & Roventini, A. (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. Journal of Economic Dynamics and Control, 34:9, 1748-1767.

Dosi, G., Fagiolo, G., Napoletano, M. & Roventini, A. (2013). Income distribution, credit and fiscal policies in an agent-based Keynesian model. Journal of Economic Dynamics and Control, 37:8, 1598-1625.

Dunford, R., Harrison, P., Jäger, J., Rounsevell, M. & Tinch, R. (2015). Exploring climate change vulnerability across sectors and scenarios using indicators of impacts and coping capacity. Climatic Change, 128:3-4 339-354. DOI 10.1007/s10584-014-1162-8

Dunne, J. A., Williams, R. J., & Martinez, N. D. (2002). Network structure and biodiversity loss in food webs: robustness increases with connectance. Ecology letters, 5:4, 558-567.

Ekins, P., Folke, C. & De Groot, R. (2003). Identifying critical natural capital. Ecological economics, 44:2, 159-163.

Entwisle, B., Malanson, G., Rindfuss, R. R., & Walsh, S. J. (2008). An agent-based model of household dynamics and land use change. Journal of Land Use Science, 3:1, 73-93.

Eory, V., Topp, C.F.E. & Moran, D. (2013). Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environmental science and policy, 27:2013, 55-67.

Eory, V., Topp, C.F.E., Moran, D. & Butler, A. (2014). Assessing uncertainty in the cost-effectiveness of agricultural greenhouse gas mitigation. Contributed Paper prepared for presentation at the 88th Annual Conference of the Agricultural Economics Society, AgroParisTech. Paris, France.

European Commission (2007). Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Adapting to climate change in Europe – options for EU action. COM (2007) 354 final. Brussels, Belgium. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52007DC0354

European Commission (2009). Communication from the Commission to the Council and the European Parliament: GDP and beyond, Measuring progress in a changing world. COM (2009) 433 final. Brussels, Belgium. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52009DC0433

European Commission (2012). Consolidated version of the Treaty on the Functioning of the European Union. OJ C 326, 26.10.2012, p. 47–390. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:12012E/TXT

European Environment Agency (2013). Late lessons from early warnings: science, precaution, innovation. EEA Report No 1/2013.

Fagiolo, G., Valente, M., & Vriend, N. J. (2007). Segregation in networks. Journal of Economic Behavior & Organization, 64:3, 316-336.

Fagiolo, G., Reyes, J., & Schiavo, S. (2009). World-trade web: Topological properties, dynamics, and evolution. Physical Review E, 79:3, 036115.

Fagiolo, G., Roventini, A. (2012). On the scientific status of economic policy: a tale of alternative paradigms. The Knowledge Engineering Review, 27:02, 163-185.

Farber, S.C., Costanza, R. & Wilson, M.A. (2002). Economic and Ecological Concepts for Valuing Ecosystem Services. Ecological Economics, 41:3, 375–92.

Farley, J. (2008). Valuing Natural Capital: The Limits of Complex Valuation in Complex Systems. Conference paper, Economics and Conservation in the Tropics: A Strategic Dialogue, January 31 – February 1, 2008.

Felgenhauer, T. & Webster, M. (2013). Multiple adaptation types with mitigation: A framework for policy analysis. Global Environmental Change 23: 1556-1565.

Fiddaman, T. S. (2002). Exploring policy options with a behavioral climate–economy model. System Dynamics Review, 18:2, 243-267.

Filatova, T. V. (2009). Land markets from the bottom up: micro-macro links in economics and implications for coastal risk management. University of Twente.

Filatova, T., Voinov, A. & van der Veen, A. (2011). Land market mechanisms for preservation of space for coastal ecosystems: An agent-based analysis. Environmental Modelling & Software, 26:2, 179-190.

Friedman, M. (1953). The methodology of positive economics. Essays in positive economics, 3:3.

Gaffard, J. L. & Napoletano, M. (2012). Improving the toolbox. Revue de l'OFCE, 5, 7-13.

Geden, O. (2012). The end of climate policy as we knew it. In: Expect the unexpected [Pethes, V., Lippert B. (Eds.)], 19–22. Berlin: Stiftung Wissenschaft und Politik (SWP) (German Institute for International and Security Affairs).

Gerst, M. D., Wang, P., Roventini, A., Fagiolo, G., Dosi, G., Howarth, R. B. & Borsuk, M. E. (2013). Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework. Environmental Modelling & Software, 44, 62-75.

Gilboa, I. & Schmeidler, D. (1989). Maximin expected utility with non-unique prior. Journal of Mathematical Economics, 18:141–153, 1989.

Global footprint network (2010). The Ecological Wealth of Nations, Earth's biocapacity as a new framework for international cooperation.

Grasso, M. (2010). Justice in funding adaptation under the international climate change regime. Dordrecht: Springer.

Grasso, M. & Redclift, M.R. (2013). Handbook on Climate Change and Human Security. Chapter 10, Cheltenham-Northampton.

Haldane, A. G. & May, R. M. (2011). Systemic risk in banking ecosystems. Nature, 469:7330, 351-355.

Hallegatte, S., Lecocq, F. & de Perthuis, C. (2011a). Designing Climate Change Adaptation Policies - An Economic Framework. Policy Research Working Paper 5568, The World Bank.

Hallegatte, S., Przyluski, V. & Vogt-Schilb, A. (2011b). Building world narratives for climate change impact, adaptation and vulnerability analyses. Nature Climate Change, 1:3, 151-155.

Hare, M. & Deadman, P. (2004). Further towards a taxonomy of agent-based simulation models in environmental management. Mathematics and computers in simulation, 64:1, 25-40.

Hasselmann, K. (2008). Simulating human behaviour in macroeconomic models applied to climate change. In: Proceedings of the Heraeus seminar on Energy and Climate, 25. Bad Hoeneff, Germany, May 26.

Hasselmann, K. & Kovalevsky, D. V. (2013). Simulating animal spirits in actor-based environmental models. Environmental Modelling & Software, 44: 10-24.

Heal, G.M. & Millner, A. (2014). Agreeing to disagree on climate policy. PNAS 2014, 111:10, 3695-3698; published ahead of print February 24, 2014, doi:10.1073/pnas.1315987111.

Heink, U. & Kowarik, I. (2010). What criteria should be used to select biodiversity indicators? Biodiversity and Conservation, 19:13, 3769-3797. DOI:10.1007/s10531-010-9926-6.

Heltberg, R., Siegel, P.B. & Jorgensen, S.L. (2009). Addressing Human Vulnerability to Climate Change: Toward a 'No Regrets' Approach. Global Environmental Change, 19:1, 89-99.

Hidalgo, C. A. & Hausmann, R. (2009). The building blocks of economic complexity. PNAS, 106:26, 10570-10575.

Hommes, C. (2013). Behavioral rationality and heterogeneous expectations in complex economic systems. Cambridge University Press.

Hurwicz, L. (1951). Optimality Criteria for Decision Making Under Ignorance. Cowles Commission Discussion Paper, Statistics 370.

IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104pp.

IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014a). Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, & L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPCC (2014b). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, & L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC (2014c). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, & L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 688.

Jaeger, C.C., Paroussos, L., Mangalagiu, D., Kupers, R., Mandel, A. & Tàbara, J.D. (2011). A new growth path for Europe. Generating Prosperity and Jobs in the Low-Carbon Economy. Synthesis Report PIK, University of Oxford, ICCS, Université Paris, 1.

Jaeger, C., Paroussos, L., Mangalagiu, D., Kupers, R., Mandel, A. & Tàbara, J.D. (2012). Assessing Green Growth: The case of Europe. In: Jaeger, C. C., Hasselmann, K., Leipold, G., Mangalagiu, D., and Tàbara, J. D. Reframing the Problem of Climate Change: From Zero Sum Game to Win-Win Solutions. Oxon, UK, New York, USA & Canada: Earthscan and Taylor and Francis.

Janssen, M., & de Vries, B. (1998). The battle of perspectives: a multi-agent model with adaptive responses to climate change. Ecological economics, 26:1, 43-65.

Janssen, M. A., & Jager, W. (2002). Stimulating diffusion of green products. Journal of Evolutionary Economics, 12:3, 283-306.

Jordan, A., Rayner, T., Schroeder, H., Adger, N., Anderson, K., Bows, A., Le Quéré, C., Joshi, M., Mander, S., Vaughan, N. & Whitmarsh, L. (2013) Going beyond two degrees? The risks and opportunities of alternative options. Climate Policy, 13:6, 751-769, DOI: 10.1080/14693062.2013.835705

Julius, S.H. & Scheraga, J.D. (2000). The TEAM Model for Evaluating Alternative Adaptation Strategies. In: Research and Practice in Multiple Criteria Decision Making: Proceedings of the XIVth International Conference on Multiple Criteria Decision Making (MCDM) Charlottesville, Virginia, USA, June 8–12, 1998 [Haimes Y.Y. & Steuer R.E. (eds)]. Lecture Notes in Economics and Mathematical Systems, 487:319-330

Kahneman, D. & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. Econometrica: Journal of the Econometric Society, 263-291.

Kates, R. W. (1997). Impacts, adaptations and mitigation – Climate Change 1995. Environment, 39:9, 29-33.

Kelly, R.A., Jakeman, A. J., Barreteau, O., Borsuk, M. E., Elsawah, S., Hamilton, S. H., Henriksen, H. J. & Voinov, A. A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. Environmental Modelling & Software, 47: 159-181.

King, G. & Murray, C.J.L. (2002). Rethinking human security. Political Science Quarterly, 116:4, 585–610.

Kirby, K.N. (1997). Bidding on the future: evidence against normative discounting of delayed rewards. Journal of Experimental Psychology: General, 1261, 54-70.

Klibanoff, P., Marinacci, M. & Mukerji, S. (2005). A smooth model of decision making under ambiguity. Econometrica, 73: 1849–1892.

Knight, F. H. (1921). Risk, Uncertainty, and Profit. Boston, MA: Hart, Schaffner & Marx; Houghton Mifflin Company.

Kubal C., Haase D., Meyer V. & Scheuer S. (2009). Integrated urban flood risk assessment – adapting a multicriteria approach to a city. Natural Hazards and Earth System Sciences, 9: 1881–1895.

Kunreuther, H., Heal, G., Allen, M., Edenhofer, O., Field, C.B. & Yohe, G. (2012). Risk management and climate change. Nat. Clim. Change, 3: 447–450, Working paper # 2012-16.

Lane, D. A. (1993). Artificial worlds and economics, part II. Journal of evolutionary economics, 3:2, 89-107.

Leary, N., Kulkarni, J. & Seipt, C. (2007). Assessment of Impacts and Adaptation to Climate Change, Final Report of the AIACC Project. A Global Environment Facility Enabling Activity in the Climate Change Focal Area, Project No. GFL-2328-2724-4330. http://start.org/download/publications/AIACCfullreport.pdf

Lempert, R.J. & Collins, M.T. (2007). Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches. Risk Analysis, 27:4.

Lengnick, M. (2013). Agent-based macroeconomics: A baseline model. Journal of Economic Behavior & Organization, 86: 102-120.

Lichtenstein, S. & Slovic, P. (1971). Reversals of preference between bids and choices in gambling decisions. Journal of experimental psychology, 89:1, 46.

Lorenz, J. (2007). Continuous opinion dynamics under bounded confidence: A survey. International Journal of Modern Physics C, 18:12, 1819-1838.

Lourenço, T.C., Rovisco, A., Groot, A., van Bree, L., Street, R., Garrett, P. & Duarte Santo, F. (2013). Making adaptation decisions: the far end of the uncertainty cascade. Impacts World 2013, International Conference on Climate Change Effect, Postdam, Germany

Mabey, N., Gulledge, J., Finel, B. & Silverthorne, K. (2011). Degrees of risk: Defining a risk management framework for climate security. Brussels: E3G

Malerba, F., Nelson, R., Orsenigo, L. & Winter, S. (1999). 'History-friendly' models of industry evolution: the computer industry. Industrial and Corporate Change, 8:1, 3-40.

Mandel, A., Fürst, S., Lass, W., Meissner, F. & Jaeger, C. (2009). Lagom generiC: an agent-based model of growing economies. In European Climate Forum, Working Paper volume 1.

Mandel, A., Landini, S., Gallegati, M. & Gintis, H. (forthcoming). Price dynamics, financial fragility and aggregate volatility, Journal of Economic Dynamics and Control.

Marengo, L., & Dosi, G. (2005). Division of labor, organizational coordination and market mechanisms in collective problem-solving. Journal of Economic Behavior & Organization, 58:2, 303-326.

Massetti, E. & Merola, M. (2009). Indicatori di qualità della vita e di sviluppo umano sostenibile. In: Qualità della vita e sviluppo umano sostenibile [Chiappero-Martinetti, E., & Pareglio, S., (Eds)]. Carocci, Roma.

Matrosov, E. S., Padula, S. & Harou, J. J. (2013). Selecting portfolios of water supply and demand management strategies under uncertainty—contrasting economic optimisation and 'robust decision making' approaches. Water resources management, 27:4, 1123-1148.

Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G., & Gotts, N. M. (2007). Agent-based land-use models: a review of applications. Landscape Ecology, 22:10, 1447-1459.

Meadows, D. (1998). Indicators and information systems for sustainable development – A report to the Balaton Group. The Sustainability Institute, Hartland, VT.

Means III, E., Laugier, M., Daw, J., Kaatz, L. & Waage, M. (2010). Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning. USA.

Millennium Ecosystem Assessment (2005). Ecosystems and Human Well Being: General Synthesis. Washington, DC: Island Press.

Millner, A., Dietz, S. & Heal, G. (2010). Ambiguity and climate policy. National Bureau of Economic research, Working paper 16050, USA.

Montanari, A. & Saberi, A. (2010). The spread of innovations in social networks. PNAS, 107:47, 20196–20201.

Moss, S. (2002). Agent based modeling for integrated assessment. Integrated Assessment, 3:1, 63-77.

Moss, S., Pahl-Wostl, C. & Downing, T. (2001). Agent-based integrate assessment modeling: the example of climate change. Integrated Assessment, 2: 17-30.

Moxnes, E. (2014). Discounting, climate and sustainability. Ecological Economics, 102: 158-166.

Nasra Haque, A., Grafakos, S. & Huijsman, M. (2012). Participatory integrated assessment of flood protection measures for climate adaptation in Dhaka. Environment and Urbanization 2012, 24: 197.

Nelson, R. R. & Winter, S. G. (1982). An evolutionary theory of economic change. Harvard University Press.

New, M., Liverman, D. & Anderson, K. (2009). Mind the Gap. Nature Reports Climate Change. doi:10.1038/climate.2009.126.

Newbold, S.C. & Daigneault, A. (2009). Climate response uncertainty and the benefits of greenhouse gas emissions reductions. Environmental and Resource Economics, 44:351–377.

Nolt, J. (2014). Casualties as a Moral Measure of Climate Change. Climatic Change, 1-12.

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. Science, 258: 1315-1315.

Nordhaus, W. D. (1994). Managing the global commons: the economics of climate change. Vol. 31. Cambridge, MA: MIT press.

Nordhaus, W. D. (2001). Global warming economics. Science, 294:5545, 1283-1284.

Nordhaus, W.D. (2007). A review of the Stern Review on the economics of climate change. Journal of Economic Literature, 45:3, 686–702.

Nordhaus, W. D. (2008). A question of balance: Weighing the options on global warming policies. Yale University Press.

Nordhaus, W. D. (2011). The economics of tail events with an application to climate change. Review of Environmental Economics and Policy, 5:2, 240-257.

Nordhaus, W. D. & Boyer, J. G. (1999). Requiem for Kyoto: an economic analysis of the Kyoto Protocol. The Energy Journal, 93-130.

Norris, F. H., Stevens, S.P., Pfefferbaum, B., Wyche, K.F. & Rose, L. P. (2008). Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness. In: American Journal of Community Psychology, 41:1-2, 127-150.

OECD (2011). How's Life?: Measuring well-being, OECD Publishing. http://dx.doi.org/10.1787/9789264121164-en

Ostrom, E. (2000). Collective action and the evolution of social norms. The Journal of Economic Perspectives, 14:3, 137-158.

Pastor-Satorras, R. & Vespignani, A. (2001). Epidemic spreading in scale-free networks. Physical review letters, 86:14, 3200.

Patt, A. & Siebenhüner, B. (2005). Agent-based modeling and adaptation to climate change. Vierteljahrshefte zur Wirtschaftsforschung, 74:2, 310-20.

Pindyck, R. S. (2011). Fat tails, thin tails, and climate change policy. Review of Environmental Economics and Policy, 5:2, 258-274.

Pindyck, R. S. (2013). Climate Change Policy: What Do the Models Tell Us? Journal of Economic Literature, 51:3, 860-872.

Polishchuk, Y. & Rauschmayer, F. (2011). Ecosystem effects on well-being: more than just benefits? Looking at ecosystem services through the capability approach, UFZ Discussion Papers 6/2011 - GeNECA 2, Germany.

Porritt, J. (2006). Capitalism as if the World matters. Earthscan, London, UK.

Raberto, M., Cincotti, S. & Teglio, A. (2014). Fiscal consolidation and sovereign debt risk in balance-sheet recessions: an agent-based approach. Economic Policy and the Financial Crisis, Routledge.

Rauschmayer, F., Omann, I., & Frühmann, J. (2012). Sustainable development: capabilities, needs, and well-being. Routledge.

Riccetti, L., Russo, A., & Gallegati, M. (2013). Leveraged network-based financial accelerator. Journal of Economic Dynamics and Control, 37:8, 1626-1640.

Robinson, D. T., Brown, D. G., Parker, D. C., Schreinemachers, P., Janssen, M. A., Huigen, M., Wittmer, H., Gotts, N., Promburom, P., Irwin, E., Berger, T., Gatzweiler, F. & Barnaud, C. (2007). Comparison of empirical methods for building agent-based models in land use science. Journal of Land Use Science, 2:1, 31-55.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T.M., Scheffer, M., Folke C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Roghe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Lieverman, D., Richardson, K., Crutzen, P. & Foley, J. A. (2009). A safe operating space for humanity. Nature, 461:7263, 472-475.

Safarzyńska, K., Brouwer, R., & Hofkes, M. (2013). Evolutionary modelling of the macro-economic impacts of catastrophic flood events. Ecological Economics, 88: 108-118.

Salle, I., Yıldızoğlu, M., & Sénégas, M. A. (2013). Inflation targeting in a learning economy: An ABM perspective. Economic Modelling, 34: 114-128.

Schwartz, P. (1991). The Art of the Long View: Planning for the Future in an Uncertain World. New York, Doubleday.

Scrieciu, S.S. (2007). The inherent dangers of using computable general equilibrium models as a single integrated modelling framework for sustainability impact assessment. A critical note on Böhringer and Löschel (2006). Ecological Economics, 60:4, 678-684.

Sen, A. (1992), Inequality Re-examined. Oxford: Clarendon Press.

Smajgl, A., Brown, D. G., Valbuena, D. & Huigen, M. G. (2011). Empirical characterisation of agent behaviours in socio-ecological systems. Environmental Modelling & Software, 26:7, 837-844.

Smith, S., Horrocks, L., Harvey, A. & Hamilton, C. (2011). Rethinking adaptation for a 4◦C world. Philosophical Transactions of the Royal Society A, 369: 196–216.

Stern, N. (2006). Executive Summary. In: Stern review: The Economics of Climate Change.

Stern, N. (2007). The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge.

Stiglitz, J.E, Sen, A. & Fitoussi, J.P. (2009). Report by the Commission on the Measurement of Economic Performance and Social Progress. France. Available here: http://www.stiglitz-sen-fitoussi.fr/documents/rapport_anglais.pdf

Tàbara, J. D., Mangalagiu, D., Kupers, R., Jaeger, C. C., Mandel, A. & Paroussos, L. (2013). Transformative targets in sustainability policy making: the case of the 30% EU mitigation goal. Journal of Environmental Planning and Management, 56:8, 1180-1191.

Taleb, N.N., Read, R., Douady, R., Norman, J. & Bar-Yam, Y. (2014). The Precautionary Principle (with Application to the Genetic Modification of Organisms), Extreme Risk Initiative — NYU School Of Engineering Working Paper Series.

Tesfatsion, L. (2006). Agent-based computational economics: A constructive approach to economic theory. Handbook of computational economics, 2: 831-880.

Tesfatsion, L. & Judd, K. (2006). Handbook of Computational Economics, Vol. 2: Agent-Based Computational Economics. Handbooks in Economics Series, Elsevier/North-Holland, Amsterdam, the Netherlands.

Tinch, R., Jäger, J., Omann, I., Harrison, P.A., Wesely, J. & Dunford, R. (2015). Applying a capitals framework to measuring coping and adaptive capacity in integrated assessment models. Climatic Change 128:3-4 323-337. DOI: 10.1007/s10584-014-1299-5.

Tol, R.S. (2003). Is the uncertainty about climate change too large for expected cost-benefit analysis? Climatic Change, 56:3, 265-289.

Tol, R.S.J., Van der Burg, T., Jansen, H. M. A. & Verbruggen, H. (1995). The climate fund. Some notions on the socio-economic impacts of greenhouse gas emissions and emission reductions in an international context. Institute for Environmental Studies. Amsterdam, Netherlands.

Toman, M.A. (1992). The Difficulty in Defining Sustainability. Resources 106 (Winter): 3-6.

UNECE (2009). Measuring sustainable development: Prepared in cooperation with the Organisation for Economic Co-operation and Development and the Statistical Office of the European Communities (Eurostat). New York and Geneva: United Nations. http://www.cbs.nl/NR/rdonlyres/0E68A254-32DB-450C-BA47-3E16A4A658F8/0/UN_Measuring_sustainable_development2009.pdf

UNFCCC (2002). Annotated guidelines for the preparation of national adaptation programmes of action, Least Developed Countries Expert Group.

UNFCCC (2011). Assessing the Costs and Benefits of Adaptation Options – An Overview of Approaches. The Nairobi Work Programme on Impacts, Vulnerability and Adaptation to Climate Change. Bonn, Germany.

United Nations (2007). Indicators of Sustainable Development: Guidelines and Methodologies, Third edition. Economic and Social Affairs, New York, USA. http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf

UNU (United Nations University) (2007). Measuring Human Well-Being: Key Findings and Policy Lessons. UNU WIDER Policy Brief 3. Helsinki, Finland: UNU WIDER.

van den Bergh, J. C. (2013). Economic-financial crisis and sustainability transition. Environmental Innovation and Societal Transitions, 6: 1-8.

Viguie, V. & Hallegatte, S. (2012). Trade-offs and synergies in urban climate policies. Nature Climate Change 2, 334-337, doi:10.1038/NCLIMATE1434.

von Neumann, J. & Morgenstern, O. (1944). Theory of games and economic behavior. Priceton University Press.

Walker, W.E., Harremoes, P., Rotmans, J., Van der Sluijs, J.P., Van Asselt, M.B.A., Janssen, P. & Krayer von Krauss, M.P.K. (2003). Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. Integrated Assessment, 4:1, 5–17.

Watkiss, P., Hunt, A., Bharwani, S., van Ierland, E. & Werners, S. (2012). Framework for costs, cost-effectiveness, and other methods (including taking into account uncertainties) for socio-economic assessment. Deliverable 3.4, Mediation.

Watkiss, P., Hunt, A., Blyth, W. & Dyszynski, J. (2014). The use of new economic decision support tools for adaptation assessment: A review of methods and applications, towards guidance on applicability. Climatic Change. DOI 10.1007/s10584-014-1250-9.

Weaver, P.M., Haxeltine, A., van de Kerkhof, M. & Tabara, J.D. (2006). Mainstreaming action on climate change through participatory appraisal, International Journal of Innovation and Sustainable Development, 1:3.

Weber, M., Barth, V. & Hasselmann, K. (2005). A multi-actor dynamic integrated assessment model (MADIAM) of induced technological change and sustainable economic growth. Ecological Economics, 54:2, 306-327.

Wegner, G. & Pascual, U. (2011). Cost-benefit analysis in the context of ecosystem services for human well-being: a multidisciplinary critique. Global Environmental Change, 21:2, 492-504.

Weitzman, M.L. (2007). A review of the Stern Review on the economics of climate change. Journal of Economic Literature, 45:3, 703–724.

Weitzman, M.L. (2009). On Modeling and Interpreting the Economics of Catastrophic Climate Change. The Review of Economics and Statistics, XCI:1. Harvard University, USA. Available at this address: http://scholar.harvard.edu/files/weitzman/files/modelinginterpretingeconomics.pdf

Werner, B. T. & McNamara, D. E. (2007). Dynamics of coupled human-landscape systems. Geomorphology, 91:3, 393-407.

Wilhite, A. (2001). Bilateral trade and ‘small-world’ networks. Computational Economics, 18:1, 49-64.

Wolf, S., Bouchaud, J.-P., Cecconi, F., Cincotti, S., Dawid, H., Gintis, H., van der Hoog, S., Jaeger, C. C., Kovalevsky, D. V., Mandel, A., and Paroussos, L. (2013a). Describing economic agent-based models – Dahlem ABM documentation guidelines. Complexity Economics, 2, pp. 63-74.

Wolf, S., Fürst, S., Mandel, A., Lass, W., Lincke, D., Pablo-Martí, F., & Jaeger, C. (2013b). A multi-agent model of several economic regions. Environmental Modelling and Software, 44: 25-43.

World Bank (2005). Where is the Wealth of Nations? Measuring Capital for the 21st Century. Washington, DC. https://openknowledge.worldbank.org/handle/10986/7505

World Bank (2011). The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium. https://openknowledge.worldbank.org/handle/10986/2252

Yohe, G.W. (2010). Addressing Climate Change through a Risk Management Lens. In: Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond [Gulledge, J., Richardson, L.J., Adkins, L. & Seidel, S. (eds.)]. Proceedings of workshop on assessing the benefits of avoided climate change, March 16-17, 2009. Pew Center on Global Climate Change: Arlington, VA. P. 201-231.

Zuber, S. & Asheim, G.B. (2012). Justifying social discounting: the rank-discounted utilitarian approach. J. Econ. Theory, 147:4, 1572-1601.