# Scenario techniques for energy and environmental research: An overview of recent developments to broaden the capacity to deal with complexity and uncertainty

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# Scenario techniques for Energy and Environmental Research : an overview of recent developments to broaden the capacity to deal with complexity and uncertainty

Editorial of the Thematic Issue "Innovative Techniques for Quantitative Scenarios in Energy and Environmental Research"

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## Abstract

Scenario techniques are a teeming field in energy and environmental research and decision making. This Thematic Issue (TI) highlights quantitative (computational) methods that improve the development and use of scenarios for dealing with the dual challenge of complexity and (deep) uncertainty. The TI gathers 13 articles that describe methodological innovations or extensions and refinements of existing methods, as well as applications that demonstrate the potential of these methodological developments. The TI proposes two methodological foci for dealing with the challenges of (deep) uncertainty and complexity: diversity and vulnerability approaches help tackle uncertainty; multiple-objective and multiple-scale approaches help address complexity; whereas some combinations of those foci can also be applied. This overview article to the TI presents the contributions gathered in the TI, and shows how they individually and collectively bring new capacity to scenarios techniques to deal with complexity and (deep) uncertainty.

**Keywords:** scenarios, uncertainty, complexity, diversity, vulnerability, multiple-objective, multiple-scale.

## 1. Introduction

Scenario thinking forms the core of future analysis in energy, climate and other environmental research and decision making. While no universal definition exists, *scenarios* have been described as plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces. The conjunction of (deep) uncertainty and complexity, inherent in energy, climate and other environmental systems, is, and was from the beginning of the development of scenario approach, the raison d'être of scenarios. *Complexity* arises because the questions at stake imply interconnected systems, with feedbacks and non-linearities, strategies or policies with multiple objectives and/or cross-scales linkages. *Deep uncertainty* is a situation in which analysts do not know or decision makers cannot agree on (i) models that relate key forces that shape the future, (ii) probability distributions of key variables and parameters in these models, and/or (iii) the value of alternative outcomes (Lempert, 2003).

Scenario approach initially aimed to aid decision making under deep societal and political uncertainty. First developments date back to about 60 years ago. To think about strategic policy choices under uncertainties in post-World Word II period, Herman Kahn introduced a technique of describing the future in stories as if written by people in the future. He adopted the term "scenarios" to describe these stories (Kahn and Wiener, 1967). In parallel to Kahn developing scenario planning at RAND, Gaston Berger was developing similar methods at the Centre d'Etudes Prospectives in France. His method, named 'La Prospective' (Berger, 1964), was to develop normative scenarios of the future which were to be used as a guide in formulating public policy. In the 1960s, several large companies also began to embrace scenario planning, in particular Dutch Royal Shell, well known for its scenarios challenging Shell's corporate strategy by imagining discontinuities and surprises (Wack, 1985).

For natural systems, since mid-18th century, forecasting techniques were used, such as weather forecasting. Due to the progressing understanding of complexities and uncertainties in natural systems and the role of humankind in shaping these systems (Crutzen, 2002), at the end of the 20th century forecasting has been joined by scenario approaches in long-term analysis of natural systems too. Growing computational power enabled use of increasingly elaborated quantitative models to construct scenarios, such as system dynamics for the Limits to Growth report to the Club of Rome (Meadows et al., 1972), linear programming for energy system analysis (Schrattenholzer, 1981) or projections, based on historical trends and scenario axes of several key uncertainties (EIA, 1979).

Sustainability research is a domain where both complexity and (deep) uncertainty are particularly salient (Swart et al., 2004). Indeed, it involves studying and understanding the evolution, over the long term, of human-natural coupled systems, in which subsystems have multiple interactions and feedbacks in "Nexuses" such as the climate-development "Nexus" (Davidson et al., 2003), energy-water-food "Nexus" (Bazilian et al., 2011), or climate, land-use, energy and water (CLEW) "Nexus" (Howells et al., 2013). In this realm, policies or decisions have to account for synergies or trade-offs between multiple objectives, such as poverty reduction, food security, energy security, climate change mitigation and other sustainable development goals (United Nations, 2016). Non-linearities, potential irreversible changes or tipping points in the evolution of systems, and cross-scales linkages from local to global scales add to the complexity dimension. Deep uncertainty arise from the complexity itself, but also from the long timescales involved, competing theories or models to represent human choice, the potential for surprises and potential disagreement about the values of different outcomes.

In the last two decades, the development of scenarios for sustainability research has been a teeming field. Emerging environmental concerns worldwide and better understanding of interdependencies between the natural, built and social systems gave rise to integrative scenario approaches that bridge quantitative modeling and socio-economic considerations. The story-and-simulation approach (Alcamo, 2008) has been widely used for creating storylines of future developments, which are then used to parameterize the models in order to quantify the storylines (see Box 1 for references to prominent applications). Cross-impact balance analysis (Weimer-Jehle, 2006) has been increasingly used for developing internally consistent storylines. Global sensitivity analyses have been applied to address parametric uncertainty in models (Branger et al., 2015, Pye et al., 2015, Marangoni et al., 2017). The urge to solve environmental problems has put more emphasis on using scenarios to inform decisions and to induce learning. Approaches enabling this link include normative scenarios and backcasting (Robinson et al., 2011), robust decision making (Lempert et al., 2006), links across multiple geographical and time scales (Zurek and Henrichs, 2007), and stakeholder and public engagement in co-development of scenarios (Shaw et al., 2009).

The scope of this Thematic Issue (TI) is to broaden the capacity of scenarios techniques to deal with complexity and (deep) uncertainty. It gathers 13 articles that describe some of the latest developments to push the frontier of scenarios techniques capabilities. It has therefore a methodological focus, and the key theme is the use of computational/quantitative methods to enhance the scenario practice. The articles present methodological innovations or extensions and refinements of existing methods mentioned above (see also Box 1 and Table 1), as well as applications that demonstrate the potential of these methodological developments. The TI has no ambition to provide a comprehensive overview of the vast literature on scenarios approaches to deal with complexity and (deep) uncertainty, nor can it be representative of the diversity of approaches. Rather, it proposes two methodological foci for addressing each core challenge (or "axis" in this paper): diversity and robustness for the uncertainty axis, multiple-objective and multiple-scale for the complexity axis; and some combinations of those foci (Figure 1). In the context of uncertainty, one approach is indeed to ensure that the scenarios built adequately spans the range of uncertainties, i.e. that they represent the diversity of plausible futures. An alternative approach is to focus on the vulnerability (or lack of vulnerability, i.e. robustness) of a chosen strategy to uncertainties at play; scenarios then serve to highlight the vulnerability of strategy to uncertainties, or on the contrary its robustness. The complexity challenge often arises from the fact that the system under study involves multiple scales, or from the fact that strategies aim at multiple objectives. Therefore, scenarios techniques need to be able to handle such cases of multiple scales systems and/or multiple objectives strategies.

The 13 articles in the TI can be located in the uncertainty/complexity space, in a plane defined by two axes: the diversity – robustness/vulnerability axis which is linked to the (deep) uncertain challenge, and the multi-objectives – multi-scales axis which are two elements at the root of the complexity challenge. The precise location of the TI articles results from a choice from the authors of this overview article, to highlight some of the specificities and strengths of the methodologies, as will be discussed in Section 2.

For a broader perspective on the topic of uncertainty, the interested reader may refer to Maier et al. (2016) for an integrated view of concepts for dealing with a highly uncertain future in modelling, and to Trutnevyte et al. (2016) for a discussion of focal points for reinvigorating the scenario technique to help scenarios developers and users expand uncertainty consideration. For complementary contributions on the axis on complexity, two TIs of Environmental Modelling & Software can be mentioned: the TI on "Innovative Approaches to Global Change Modelling" (Giupponi et al., 2013), and the TI on the "Future of Integrated Modeling Science and Technology" (Laniak et al., 2013). For a broader range of scenario techniques, beyond quantitative methods, and for discussions on the role of scenarios in decision processes in organizations and the interplay of actor motivations and behaviours, one may refer to the Technological Forecasting and Social Change Special Issue on "Scenario methodology: New developments in theory and practice" (Wright et al., 2013).

The rest of this overview article to the TI summarizes the methodological developments gathered in the TI, and shows how they individually and collectively bring new capacity to scenarios techniques to deal with complexity and (deep) uncertainty.

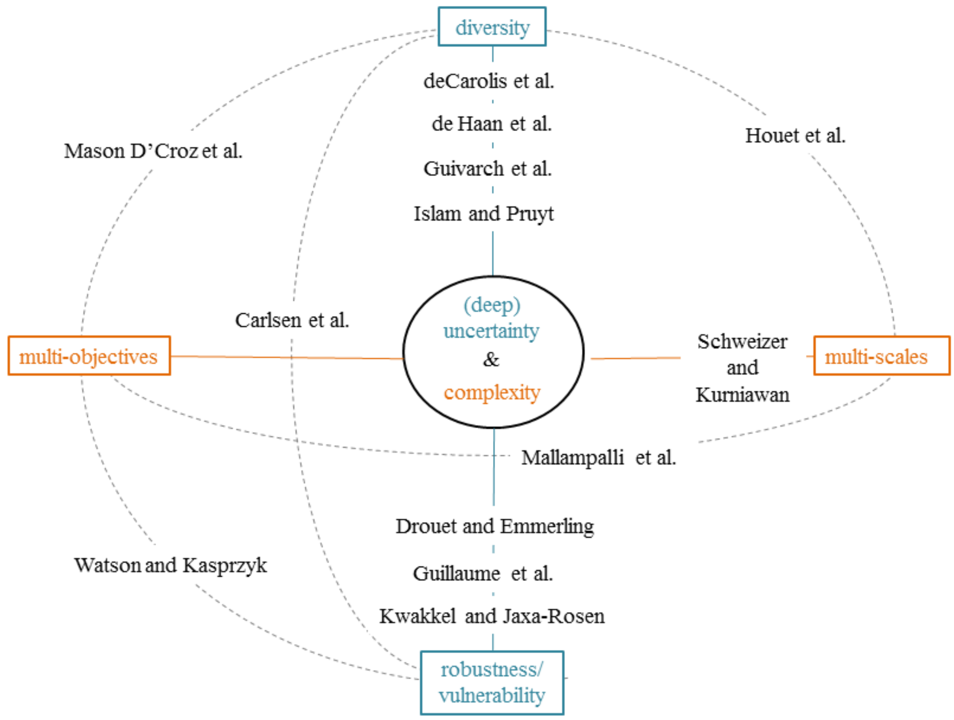


Figure 1: Articles in the Thematic Issue located in the uncertainty/complexity space. The vertical (blue) axis presents the uncertainty dimension; the horizontal (orange) axis presents the complexity dimension.

## 2. Overview of methodological developments gathered in the Thematic Issue

Table 1 summarizes the methods developed or extended, and the applications presented, in the 13 articles of this TI. Box 1 gives a brief overview, and associated references, of the key methodologies to which articles in this TI bring new development. It also categorizes the contributions of this TI into four ways that quantitative methods can enhance scenario approaches:

1) building and analyzing large numbers of scenarios, to explore a broad range of possible futures,

2) choosing small sets of scenarios, for further analysis, use or communication. Depending on the intended use, the criteria and method to select a small number scenarios may vary, for exemple focusing either on diversity or on consistency,

3) linking methods, to combine their respective strengths,

4) methods to improve the use of scenarios for decisions support.

TI applications cover various elements of the “Nexuses” concerned in environmental research: water, energy, climate change, food, resources, land-uses, and growth. Applications range from the global scale to the local (from continental to urban) scale, with case studies on five continents. In addition, two articles are specifically focused on the issue of multi-scales scenarios (Schweizer and Kurniawan, 2016 and Houet et al., 2016).

| | Methods | Applications | | Type of contribution | | | |
|---|---|---|---|---|---|---|---|
| | | Topics | Geographical scales and area of application | Building and analyzing large numbers of scenarios | Choosing small sets of scenarios | Linking Methods | Using Scenarios in Decisions |
| Carlsen et al. (2016) | Scenario diversity and scenario discovery | Climate resilient infrastructures for river basins | River basins scale - 3 basins in Africa (Volta, Orange, Zambezi) | | X | X | |
| DeCarolis et al. (2016) | Modelling to Generate Alternatives | Energy system optimization (electric sector and light duty transport) | National scale- USA | X | | | X |
| de Haan et al. (2016) | Multi-Pattern Approach | Technological sustainability transitions | City scale - Metropolitan Melbourne (case study on green water management assets for stormwater quality control, 1960-2010) | X | | X | |
| Drouet and Emmerling (2016) | Optimal policy and cost measures under baseline uncertainty | Climate change mitigation | Global | X | | | X |
| Guillaume et al. (2016) | Crossover point scenarios | (1) Cost-benefit analysis of managed aquifer recharge, (2) water footprint impact of changing diet | (1) Local scale: Hypothetical farm in the lower Namoi district, Murray-Darling Basin, Australia, (2) National scale: Finland | | | | X |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Guivarch et al. (2016) | Scenario discovery | Climate change mitigation | Global | X | X | | |
| Houet et al. (2016) | Story-and-Simulation | Urban growth and climate adaptation | City scale and multi-scale - City of Toulouse (France), multi-scale from global to urban block | | | X | |
| Islam and Pruyt (2016) | Adaptive output-oriented sampling | Resource scarcity | No specific geographical scale considered, approach potentially applicable for different geographical scales | X | | | |
| Kwakkel and Jaxa-Rosen (2016) | Scenario discovery | No specific application developed in the article | | | X | | |
| Mason D'Croz et al. (2016) | Story-and-Simulation | Food and climate | Regional and national scale - Southeast Asia, Cambodia, Laos and Vietnam | | X | X | |
| Mallampalli et al. (2016) | Evaluation of methods for translating narrative scenarios into quantitative assessments | Land use | No specific geographical scale considered, approach potentially applicable for different geographical scales | | | X | |
| Schweizer and Kurniawan (2016) | Linked Cross-Impact-Balances | Climate change mitigation and adaptation | Multi-scales (global to regional) | | X | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Watson and Kasprzyk (2017) | Multiple Objectives Robust Decision Making | Water planning portfolio | River basin scale - Lower Rio Grande Valley of Texas, USA | | | | X |

Table 1: Methods developed or extended, applications presented, and type of contribution to enhance scenario methods in the 13 articles of the Thematic Issue.

**Box 1 – Key techniques to which articles in this TI bring new developments**

**1. Story-and-Simulation (SAS)**

Story-and-Simulation (Alcamo, 2001, 2008) is an "open" process in that stakeholders are involved in the development of the scenarios. It starts with the development of qualitative "storylines" by a group of stakeholders and experts. Then models are used to translate the storylines and produce quantitative scenarios. An iterative process harmonizes the qualitative and quantitative storylines. The SAS approach has been extensively used in sustainability research. Prominent examples include the Millenium Ecosystem Assessment scenarios (MEA, 2005), the IPCC-SRES scenarios (Nakicenovic et al., 2000), the Global Environmental Outlook-4 scenarios (Rothman et al., 2007) and the new socioeconomic scenarios for climate change research, the so-called Shared Socioeconomic Pathways (SSPs) (Riahi et al., 2017) at the global scales, and hundreds of scenarios developed for national, regional or local studies.

In this TI, Houet et al. (2016) and Mason D'Croz et al. (2016) describe two full implementations of an SAS process, with a specific focus on creating and maintaining diversity of scenarios throughout the process, and some developments to focus on multi-scales (Houet et al., 2016) and multi-objectives (Mason D'Croz et al., 2016).

***Translation of narrative scenarios for quantitative modelling***

One crucial step in the SAS is the translating of storylines into quantitative scenarios. In this TI, Mallampalli et al. (2016) evaluate the current state of the art of translation methods and outlines their relative advantages and disadvantages.

**2. Consistency and diversity approaches**

***Cross-Impact-Balance (CIB) analysis***

Cross-Impact-Balance analysis (Weimer-Jehle, 2006) is a tool to validate the internal consistency of storylines (or qualitative scenarios) and to identify most internally consistent storylines. To do so, it uses numerical judgments from experts or stakeholders for state-dependent influences between drivers to construct cross-impact matrixes and identify internally consistent scenarios.

In this TI, Schweizer and Kruniawan (2016) demonstrate a modification to CIB (which they call "linked-CIB") that partitions a single cross-impact matrix into multiple smaller matrices to allow the analysis of large CIB matrices and identify internally consistent linked of scenario elements across spatial scales and sectors.

### *Modelling to Generate Alternatives (MGA)*

Modelling to Generate Alternatives (DeCarolis, 2011, Trutnevyte, 2016) is an optimization technique that generates a sequence of near optimal solutions that are very different in the decision space. It can be used to explore alternative solutions under conditions of deep uncertainty.

In this TI, DeCarolis et al. (2016) incorporates MGA into an open source energy system optimization model with a user interface that constitutes a tool of exploration allowing users to interrogate the model.

### *Multi-Pattern Approach (MPA)*

The Multi-Pattern Approach (de Haan, 2010; de Haan and Rotmans, 2011) is a theoretical framework from sustainability transitions studies that conceptualizes transition pathways as concatenations of elementary change patterns, of which there are only a few. The MPA specifies the conditions under which those patterns may emerge, but acknowledges that those conditions do not uniquely determine what pattern will eventuate, meaning that there are multiple possible futures at any moment in time.

In this TI, de Haan et al. (2016) use the MPA to generate a very large number of sustainability transition pathways, and cluster pathways into a small number of ideal types that share qualitative similarities.

## 3. Vulnerability and robust decision making approaches

### *Robust Decision Making (RDM)*

Robust Decision Making (Lempert et al., 2006) is a combination of scenario planning with powerful computing to support decision makers by helping to identify potential strategies that are robust to future unknowns, characterize the vulnerabilities of such strategies, and evaluate tradeoffs among alternatives. In this context, the vulnerabilities of a strategy are the combinations of uncertainties under which it performs poorly. Characterizing vulnerabilities allows for the iterative improvement of the strategy. In the RDM process, scenario discovery is used to uncover the combinations of uncertainties to which the strategy under study is vulnerable.

### *Scenario discovery*

"Scenario discovery" cluster analysis (Bryant and Lempert, 2010) provides a computer-assisted method of scenario development that applies statistical algorithm to databases of simulation model results to characterize the combinations of uncertain input parameters values most predictive of specified classes of results. Often used as a key step in RDM analyses, scenario discovery provides a systematic manner to find which combinations of the model input parameters lead to specific "outcomes of interest", i.e. cases where output variables are located in specified areas of the results space.

In this TI, Kwakkel and Jaxa-Rosen (2016) improve the scenario discovery algorithm for handling heterogeneous uncertainties and multinomial classified outcomes, and Guivarch et al. (2016) for increasing the diversity of combinations of model paramaters uncovered by the algorithm.

***Many Objectives Robust Decision Making (MORDM)***

Many Objective Robust Decision Making is a decision making framework that enhances RDM with Multiobjective Evolutionary Algorithms (MOEAs) to help identify robust strategies that can achieve multiple objectives (Kasprzyk et al., 2013; Herman et al., 2014). MOEA uses a detailed simulation model of a system to characterize performance of solution alternatives, by generating tradeoff sets that show compromises among the objectives sought.

In this TI, Watson and Kasprzyk (2017) proposes an approach for including deeply uncertain factors into the MORDM framework.

***Crossover point***

Crossover points are used to compare (environmental) management alternatives in situations of uncertainty. Crossover point scenarios are combinations of values of variables where the preferred alternative will change, i.e. where several alternatives are of equal values in cost-benefit or other trade-off analysis frameworks.

In this TI, Guillaume et al. (2016) propose a method to reduce the complexity of dealing with many variables by identifying single crossover points of greatest concern.

Subsequent sections 2.1 and 2.2 describe the contributions of individual TI articles in depth, and discusses how these contributions help address the uncertainty/complexity challenge in scenario approaches. The sections are organized along the uncertainty and complexity axes from Figure 1.

## 2.1 Along the (deep) uncertainty axis

### 2.1.1 Developments of the Story-And-Simulation approach to enhance its capability to explore the uncertainty space

The SAS approach, as described in Box 1, is the standard approach to scenario development in the sustainability research field. It relies on the development of qualitative storylines by a group of stakeholders and/or experts to explore the uncertainty space. By "exploring uncertainty" we mean addressing the challenge of coming up with a small number of scenarios that can effectively be used in decision support and that span the space of plausible futures. To explore the uncertainty, SAS uses the judgment of the group of experts and stakeholders who develop the stories to identify the main "driving forces" of future evolution of the system under study, i.e. the developments that are both uncertain (and thus can unfold in different directions) and could have a decisive impact for the system of interest. The identified driving forces and the alternative directions in which they could unfold are then combined to sketch out the storylines. Often, two main driving forces are selected and plotted along two axes, thus defining four scenario quadrants in which storylines are developed to represent alternative perspectives on how the future main unfold. This method is called the "scenario-axes technique" (van't Klooster and van Asselt, 2006).

Mason D'Croz et al. (2016) and Houet et al. (2016), in this TI, describe two implementations of the SAS approach with a specific emphasis on developing and maintaining a diversity of scenarios (a "large possibility space" in the language from Mason D'Croz et al., 2016) throughout the process. The diversity focus stems from the concern to explore the uncertainty space, the space of plausible futures, as effectively as possible.

Mason D'Croz et al. (2016) combine this emphasis on diversity with a focus on multiple objectives. The authors present a participatory scenario process, based on the SAS approach, to build and maintain a large possibility space (a diversity of futures explored). They go beyond the scenario-axes technique, by identifying more than two driving forces (which they call factors of change), clustering them into a small set of primary factors of change (4 in their case study), using several sub-groups of participants to identify plausible alternative future states of the primary factors of change and considering all possible combinations before selecting a small subset of the possible combinations to form the final set of scenarios. This selection is done with both (i) systematic methods to exclude implausible combinations, to maximize diversity of a subset of scenarios (OLDFAR, Lord et al., 2016), and (ii) voting of participants to build legitimacy and ownership of the scenario selection. Furthermore, they use multiple models in the quantification step of the storylines, to ensure diversity at this step as well. The emphasis on diversity is justified by the purpose of the scenarios envisaged in the case study: the scenarios are intended to be applied to diverse policy processes in Southeast Asia to develop robust policies with multiple objectives (improving food security, livelihoods and resilience to climate change).

Houet et al. (2016) combine narratives and modeling approaches, in a process based on the SAS approach, to simulate fine scale and long-term urban growth scenarios for climate adaptation. The challenge of their case study for the SAS approach lies primarily in the multi-sectors (transport, buildings, energy etc.) and multi-scales (from the urban block scale necessary to study heat waves impacts for instance, to global trends that influence technology availability and energy prices for instance) to consider. To tackle this challenge and at the same time span the largest possible world of futures for the city under study (the French city of Toulouse), their methodology first identifies driving forces for the sectors and scales relevant to the study (28 in their case study), then groups them into three sets: "local trends", "land use planning" and "technology trends". For each set a participative workshop is used to create a small number of storylines. The storylines for each three sets are then combined to create multi-sectoral multi-scales scenarios.

### 2.1.2. Alternative methods to generate scenarios exploring uncertainty

The SAS approach is very broadly used and is successful along the criteria of relevance, legitimacy, credibility and creativity (Alcamo, 2008). However, the exploration of uncertainty in the SAS method is subject to human cognition biases and social effects at play in the group of stakeholders and experts developing the storylines, which may hinder its capacity to effectively span the full range of uncertainties (Morgan and Keith, 2008). For exemple, scenarios often are built on the assumption that there are experts in the relevant domains who can provide informed insight, which is not always true. In addition, people who are thought to have expertise are frequently subject to overconfidence or lack of imagination (Morgan, 2014). Moreover, the SAS method is non-reproducible[1] because the storylines are developed through a group process in which the assumptions and mental models of the storyline writers remain unstated. Therefore, alternative methods to generate scenarios exploring the uncertainty space may be needed for some cases. Below, we group the articles from the TI that contribute to this effort, by developing methods to either ensure diversity of scenarios generated (DeCarolis et al., 2016; de Haan et al., 2016; Guivarch et al., 2016; Islam and Pruyt, 2016) or focus on identifying the

[1] The non-reproducibility is one of the two main drawbacks of the SAS approach identified by Alcamo (2008), the second being the conversion (from qualitative storylines to quantitative model simulations, and back). One article in the TI (Mallampalli et al., 2016) addresses this second drawback.

robustness/vulnerability of strategies to the uncertainty (Emmerling and Drouet, 2016; Guillaume et a., 2016; Kwakkel and Jaxa-Rosen, 2016), or by combining both (Carlsen et al., 2016).

Focus on diversity

In a situation of uncertainty, scenarios users may want to span a broad range of possible futures. The challenge is to do so with a small set of scenarios (Tietje, 2005); Berntsen and Trutnevyte (2017) provide an overview of some of the methods to facilitate the choice of this small set of scenarios. A scenarios set can fail to be diverse in two ways: (1) by being too conservative, with all scenarios close together, or (2) by being unbalanced, in the sense that the set contains some extreme scenarios in one direction and conservative in others (Carlsen et al., 2016).

The traditional method to systematically generate model-based scenarios than cover the uncertainty space is to use sampling approaches for the model inputs (e.g. Monte Carlo sampling or Latin Hypercube sampling). However, in a context of deep uncertainty and complexity, there is no guarantee that such input-oriented sampling approaches reveal the full spectrum of outputs that could be generated. To address this issue, Islam and Pruyt (2016) develop an adaptive output-oriented sampling approach for exploring the full behavioral spectrum that could be generated by computational models in view of generating interesting, even previously undiscovered, scenarios. They use a resource scarcity model to illustrate the approach, show the difference with other sampling approaches, and demonstrate the usefulness for scenario discovery. They show that this approach can be used for revealing the behavioral spectrum of models, identifying regions of the input space that generate particular behaviors, and selecting (sets of) scenarios that are representative in terms of output and input spaces.

Another approach to generate scenarios that are diverse in terms of output is Modelling to Generate Alternatives (see Box 1). In many scenarios that depend upon models, too little attention is given to the implications of plausible alternative model functional forms. Hence, for example, modelling efforts are directed to produce cost optimal results, without exploring whether plausible alternative models might lead to very different future optima. Modelling to Generate Alternatives is a method that addresses this limitation of common uses of optimization models. Rather than generating different scenarios based on different model input assumption, the MGA algorithm changes the underlying structure of the mathematical model to search the near-optimal region of the output space for alternative outputs that are very different in the decision space. DeCarolis et al. (2016), in this TI, represent the MGA application to an open-source energy system optimization model called Temoa (Tools for Energy Model Optimization and Analysis). Temoa is used to explore alternative energy futures in a simplified single region energy system that represents the U.S. electric sector and a portion of the light duty transport sector. The MGA-based analysis is used to produce scenarios of technology deployments under a cost constraint, i.e. the near-optimal region of scenarios with an overall cost close to the minimal cost. The results indicate that many technologies beyond those deployed in the base and $CO_2$ cap scenarios could play a significant role in a future energy system. A novel and critical element of the Temoa framework is also its interactive nature that allows the users to interrogate the model and iteratively generate a sequence of near-optimal scenarios to extend their own cognitive abilities by generating model results on demand.

Yet another approach may be not to focus on the diversity of outputs per se, but rather on the diversity of inputs or pathways that lead to a given type of output, in the manner of "many roads lead to Rome". For example, such an approach might be useful to explore the conditions that can lead to a desirable (or undesirable) future. In the TI, two articles develop such approaches: deHaan et al. (2016) and Guivarch et al. (2016). Both use a model, a multi-pattern approach model in the former and a global integrated assessment model in the latter, to generate a large ensemble of scenarios. deHaan et al. (2016) then uses clustering techniques to identify a small number of ideal types of pathways. They show that the input scenario influences how often a type of pathway emerges, but not what type emerges.

Guivarch et al. (2016) adapt a "scenario discovery" cluster analysis (see Box 1) to uncover the diversity of input combinations leading to a given outcome of interest, and apply it to the large ensemble of scenarios they constructed. Their application concerns the new scenario framework developed by the climate change research community. This framework rests on the fundamental logic that a diversity of socio-economic pathways can lead to the same radiative forcing, and therefore that a given level of radiative forcing can have very different socio-economic impacts. The adapted "scenario discovery" cluster analysis is used to systematically identify diverse groups of scenarios that share common outcomes among a database of socio-economic scenarios. In two examples demonstrating the methodology, the authors find that high emissions scenarios can be associated with either high or low per capita GDP growth, and that high productivity growth and catch-up are not necessarily associated with high per capita GDP and high emissions.

Focus on robustness/vulnerability

In a situation of (deep) uncertainty, when a decision has to be taken, the purpose of scenarios may be different from "merely" exploring the uncertainty space. Indeed, when a decision is at stake, what may matter most is to use scenarios to identify if a candidate decision (strategy or policy) is robust to the uncertainty, and if not, identify the cases when it is vulnerable (i.e. it does not meet its objective) and use this information to build more robust strategies.

Robust Decision Making (see Box 1) is a method aimed at supporting the design of robust strategies/policies under deep uncertainty. One of the key elements in the RDM process is aforementioned "scenario discovery" cluster analysis which allows to systematically illuminate the vulnerabilities of a given strategy. In this TI, Kwakkel and Jaxa-Rosen (2016) improve the ability of one of the most scenario discovery algorithms, the Patient Rule Induction Method (PRIM), for handling heterogeneous uncertainties and multinomial classified outcomes. Heterogeneous uncertainties refer to the case when uncertain input factors are of more than one type: continuous, integer or categorical. The authors develop a more lenient objective function in PRIM algorithm to allow handling heterogeneous uncertainties. Also, the original PRIM algorithm can only be used for binary classification of the output. To extend the capacity of PRIM to be used directly in situations where the output data is classified using more than two classes, the authors develop an alternative objective function using Gini impurity.

Another approach to identify the vulnerabilities of a strategy is to generate crossover points (see Box 1). Guillaume et al. (2016) extend previous work on the crossover points approach by introducing principles, design and implementation of a new method to analyze crossover points. It reduces the complexity of dealing with many variables by identifying single crossover points of greatest concern. They present three implementations using R, Excel and a web interface, and develop two examples involving cost-benefit analysis of managed aquifer recharge and the water footprint impact of changing diets.

Emmerling and Drouet (2016) focus on robust climate policy selection under socio-economic scenario uncertainty. They study the role of uncertainty about the two main baseline drivers of the economy, namely population and GDP, for the determination of the optimal climate policy and the evaluation of policy costs. They estimate the cost of baseline uncertainty from a decision maker's perspective using different metrics. Then, they discuss how measures of the costs of climate change induced impacts and climate policy costs can be compared under different and uncertain baseline assumptions. They show that the cost from baseline uncertainty leads to a moderate increase of the welfare losses from climate change.

Combining both foci

Finally, Carlsen et al. (2016) develop a method to join the two foci with an optimization-based method for choosing a small number of relevant scenarios that combine both vulnerability and diversity approaches. The authors apply the method to a case of climate resilient infrastructure for three African river basins (Volta, Orange and Zambezi). Introducing selection criteria in a stepwise manner helps examine how different criteria influence the choice of scenarios. The results suggest that combining vulnerability- and diversity-based criteria can provide a systematic and transparent method for scenario selection.

### 2.2. Along the complexity axis (multiple scales and multiple objectives)

The multi-scale nature of the systems under study and/or the multi-objective strategies envisaged are two elements that specifically generate complexity for scenarios approaches.

To tackle the complexity challenge, the widely-used SAS approach (see Box 1) uses the articulation of qualitative storylines and quantitative simulations. The qualitative storylines provide a vehicle for communicating the messages of the scenarios and can express the more complex dimensions and inter-connectedness of sustainability issues. While, the quantitative scenarios provide a consistency check to the different assumptions of the qualitative scenarios, and the numerical data often needed in sustainability research and for sustainability decisions. However, the articulation between the qualitative and quantitative elements of the SAS approach, while critical, is also one of the difficult part of the approach and one of its two major drawbacks, the "conversion problem", as identified by Alcamo (2008) because these conversions are based on "expert judgment" to translate the text in a storyline to quantitative model inputs, which tends to be neither reproducible nor transparent.

In this TI, Mallampalli et al. (2016) focus on this step of translating storylines into quantitative scenarios. They survey and evaluate the current state of the art in scenario translation methods and outline their relative advantages and drawbacks, as well as the respective roles of stakeholders and experts in the different methods. They develop a tool for scenario developers to choose the best method suited to the purpose of their scenario study: a decision matrix summarizing performances of the methods along evaluation criteria (scenario purpose, extensibility, type of participation and compatibility with model types). They use examples from the land use and land cover literature, whereas their analysis can be used in other domains of sustainability research.

Another difficulty in the articulation between stories and simulations lies in the mutual validation presumed in the approach: a plausible story acts as a guide for assumptions that would be interesting to model, while a finished simulation is considered a demonstration of the internal consistency of a story. However, recent research has called into question this assumed relationship (Schweizer and Kriegler, 2012, Trutnevyte et al., 2014). Because quantitative models may be simplifications of stories (and vice versa), stories may also benefit from internal validation before they are handed off to modelling teams. Failing to do this can result in scenarios that overlook policy relevant risks (Schweizer and Kriegler, 2012). A tool that can validate the internal consistency of stories is Cross-Impact Balance analysis (CIB) (see Box 1). However, validating the internal consistency of a highly detailed story, such as one that is multi-scales, would be intractable with traditional CIB. To address this problem, Schweizer and Kurniawan (2016) introduce the concept of 'linked CIB', which takes the structure of judgements for how scenario elements interact to partition a single cross-impact matrix into multiple smaller matrices. This method enables analysis of large CIB matrices and ensures internally consistent linking of scenario elements across scales so that localized versions of scenarios can be produced that are demonstrably internally consistent with the global version. The authors demonstrate their method with an example in the context of the new Shared Socioeconomic Pathways framework for climate change research (O'Neill et al., 2014).

On the challenge posed by strategies or policies with multiple objectives, in the TI Watson and Kasprzyk (2016) extend the capacity of the Multiobjective Evolutionary Algorithm with Robust Decision Making (MORDM) framework (see Box 1). They propose an approach for including deeply uncertain factors directly into a multi-objective search procedure, to aid in incorporating divergent quantitative scenarios within the model-based decision support process. Traditional MORDM first optimized a problem under a baseline scenario, then evaluated candidate solutions under an ensemble of uncertain conditions, and finally discovered scenarios under which solutions are vulnerable. One potential limitation of this approach is that the set of decision variables comprising each solution are only "trained" to the historical data and may not be adaptable if the data fundamentally changes. Therefore, Watson and Kasprzyk (2016) modify MORDM to incorporate multiple combinations of uncertain factors into the MOEA search process itself. The goal is to develop more diverse sets of decision variables that are potentially more adaptable under extreme conditions. The authors demonstrate how the solutions perform under other scenarios that were not included in the original optimization run. They demonstrate the approach through a water planning portfolio example in the Lower Rio Grande Valley of Texas.

## 3. Conclusion

Scenarios are key tools in energy, climate and environmental research and decision making. This TI gathers recent methodological innovations in quantitative techniques to push the frontiers of scenarios capabilities and demonstrates how they can contribute to address the dual challenge posed by the context of (deep) uncertainty and complexity. One of the virtues of quantitative scenarios is indeed that they may help address cultural cognition issues (Kahan and Braman, 2006; Kahan, 2012) and make the process more systematic and repeatable.

Obviously, scenarios approaches will always have limitations, either because there is a tendency to ignore unpleasant or politically unpopular futures, or because scenarios developers would be subject to overconfidence or lack of imagination, or else because the underlying model structures used convey their own limitations and biases. However, many of the scenarios techniques discussed in this special issue are designed to help address these challenges. For instance, scenario discovery and diversity approaches aim to expand the range of scenarios considered while conveying potentially inconvenient scenarios in a manner that can prove more difficult to ignore.

The methods gathered here, together with methods referenced in other recent reviews and Thematic/Special Issues cited above, add into the "toolbox" for scenarios developers and users. Depending on the context of their study or decision at stake, they could choose methods adapted to the purpose of scenarios (e.g. knowledge creation, exploration, or decision support) and to the specificities of the system or decision under study (including the cases of multiple scales and multiole objectives).

To fully allow a useful "toolbox" to emerge, three directions for future work have to be addressed. First, these and other methods should be tested in a variety of cases to better understand the breadth of methodological opportunities and challenges. Second, methods should be compared and/or combined. For example, one should explore how different techniques focusing on diversity compare to each other or could be combined together to build on each strengths. Similarly, approaches using crossover points should be compared to RDM. Also, combining techniques with different foci can be relevant. In this TI, one article (Carlsen et al., 2016) proposes a way to combine a diversity focus and a vulnerability/robustness focus. Other combinations are worth exploring. For instance, quantitative techniques can inform or interact with the story part of SAS. Cross-Impact-Balance-And-Simulation (Weimer-Jehle et al., 2016) is an example of such interaction. Further work could explore others. Third, to inform the choice of techniques best suited to given contexts and scenario users, there is a need for more research evaluating the tools and processes.

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