Coping with deep uncertainties in sustainability transitions using exploratory modelling

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Abstract

Sustainability transitions, as an emerging field, aims to enhance the understanding of long-term transformational changes, such as transitions in energy, transport, and water systems. This understanding, however, is challenged by the presence of many complexities in the sense that nonlinear and time-delayed interactions among agents and system components result in emergent patterns and pathways. Transitions analysis also faces 'deep uncertainties'—a situation where there is a diversity of stakeholder views and the future of transitions and their surrounding environment is unknown or cannot be agreed upon. Deep uncertainty can lead to ambiguity in the framing and conceptualisation of transitions and can also create disagreement among stakeholders about the desirability and normative direction of transition pathways. Previous transitions modelling research has discussed ways of dealing with complexities, based on formal modelling techniques, such as agent-based modelling and system dynamics approaches. However, the treatment of deep uncertainties in transition pathways, while a significant topic, has remained underdeveloped in transitions modelling as well as in the broader area of sustainability transitions. This article focuses on the application of exploratory modelling—as a model-based approach for coping with deep uncertainties—to transitions. Exploratory modelling of transitions will be an approach based on the computational exploration of many possible transition pathways under different assumptions regarding (a) the conceptualisation of the transition process, (b) the structure of the transitions model, and (c) the model parameters' value. Exploratory modelling of transitions does not

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necessarily need *new* models, but that it is an approach one can use with existing models. An important aspect of this approach is therefore that it can be used to get potentially more out of the established models, such as the treatment of deep uncertainties in the use of the MATISSE model in sustainable mobility or the use of energy transitions models in energy sectors. The article uses the application of exploratory modelling in the long-term planning of electricity transitions to show how this approach informs transitions modelling under the highly versatile circumstances of the future. With reference to this example, the article discusses four potential benefits that exploratory modelling can offer to transitions modellers and sustainability transitions researchers in general. First, it enables us to deal with various uncertainties in understanding and steering transitions such as many alternative model structures and different values for model input parameters. Second, it enhances the robustness of decision and policy insights in the face of many future possibilities based on the analysis of a portfolio of what *could* happen as opposed to what *will* happen in the future. Third, it allows the development of proactive and adaptive policy interventions in which transition pathways are shaped by some near-term choices in a context following up by some subsequent actions in the future in response to potential variation. This facilitates a forward-thinking approach in sustainability transitions by answering questions such as ‘under what favourable conditions could future targets be met?’ and ‘under what circumstances, regardless of their likelihood, could policy interventions fail?’. Fourth, it provides a platform for resolving disagreements among stakeholders by considering the implications of various ways of framing transitions.

Keywords: Exploratory modelling, Transitions modelling, Sustainability transitions, Robustness, Adaptation, Uncertainty.

1 Introduction

Transitions modelling is an emerging area of research, within the broader area of sustainability transitions. Transitions modelling uses a variety of mathematical and computational modelling techniques to formalise and to understand transition dynamics using computer simulation (Halbe et al., 2015; Holtz, 2011; Holtz et al., 2015; Köhler et al., 2018; Moallemi et al., 2017a). Transition dynamics are complex, exhibiting non-linear system behaviour, path dependency, and diversity and heterogeneity of factors and actors (Köhler et al., 2018). Transition dynamics also feature a variety of techno-economic, social, and political contingencies and unpredictable events, called ‘deep uncertainties’, which by their very nature cannot be predicted or estimated with a probability distribution. Deep uncertainties express a condition where the future state of systems, interactions among systems' components, and the driving forces of the environment are unknown. No agreement can be formed about the future of these uncertainties because of the multiplicity of views about them which are held by many different stakeholders (Lempert et al., 2003). Deep uncertainty can significantly influence our understanding of transition dynamics and unfolding transition pathways and therefore can challenge the effectiveness of transition policies in long-term future.

While previous transitions modelling researches have proved to be successful in addressing the complexity of transition dynamics, the incorporation of deep uncertainties in transitions models has not been discussed extensively so far (Köhler et al., 2018). Deep uncertainty challenges transitions models by causing ambiguity in the qualitative conceptualisation of transition dynamics which underpins a transitions model, by creating a variety of equally-valid model structures that can be constructed, by resulting in unknown model input data needed for model simulation and by leading to disagreement about the desirability of outcome and normative direction of transitions. Responding to this lack of knowledge by diminishing these deep uncertainties to an overly narrow definition as 'manageable risks' and a single 'definitive interpretation' of transitions could lead to misleading understanding and failures in our (supposedly science-based) policy advice (Stirling, 2010). A new way of thinking about transitions is therefore needed to consider various areas of uncertainty, regardless of their chance of occurrence and how different stakeholders characterise the likelihood of various alternatives in different future scenarios.

Exploratory modelling is the name of a group of model-based approaches used for the treatment of deep uncertainty in different areas such as decision making, planning, the design of a new system, model calibration, and uncertainty estimation. Approaches in exploratory modelling can serve different purposes. As two examples, Many Objective Robust Decision Making (MORDM) (Kasprzyk et al., 2013) is an approach for making robust decisions maximising the fulfilment of multiple objectives and Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot et al., 2013) is an approach for proposing dynamic adaptive plans based on designing sequences of actions over time. Exploratory modelling approaches can also be used to enhance transitions modelling under uncertainty by exploring how a transition would unfold under a range of assumptions regarding the model and its parameters using computational experimentation (Bankes, 1993; Bankes et al., 2001). This is opposite to a traditional consolidating perspective in modelling where all known data are integrated into a single (or few multiple) model(s), and an accurate prediction of a single (or few multiple) future(s) based on a fixed set of initial assumptions is sought. Exploratory modelling can also help to understand the most promising transition pathways as well as the conditions for unlikely pathways to become viable.

This article focuses on the application of exploratory modelling for the treatment of deep uncertainties in sustainability transitions. The article uses an example of long-term planning in electricity transitions to show how exploratory modelling can deal with deep uncertainties of transition pathways. The example shows how various uncertainties in electricity transitions, such as uncertainty in the price of fossil fuel and uncertainty in investment, result in divergent transition pathways and different futures for the electricity sector. The example also shows how the awareness of the multiplicity of future possibilities helps to design robust and adaptive policies for promoting electricity transitions. The article then discusses the potential benefits which the use of exploratory modelling can deliver to the study of transitions.

The rest of the article is structured as follows. Section 2 introduces the idea of using exploratory modelling for dealing with uncertainties of transitions. Section 3 briefly introduces an application of the exploratory modelling of transitions within the electricity sector. Section 4 discusses the results and potential benefits of using exploratory modelling in general and with reference to the specific example of the previous section. Section 5 concludes the article with some directions for future research.

2 Exploratory modelling of transitions

2.1 Background

Exploratory modelling includes a group of computer-assisted approaches which enable models to systematically explore the impacts of various uncertainties using computational experimentation and to draw robust conclusions about model behaviour by applying statistical and data-mining techniques over a large number of generated computational experiments (Bankes, 1993; Lempert et al., 2003; Walker et al., 2013). The application of exploratory modelling to transitions complements the primarily qualitative area of sustainability transitions to enhance robust understanding and policymaking under deep uncertainty. On the one hand, exploratory modelling uses concepts from the sustainability transitions literature to better represent the long-term, multi-dimensional, path-dependent, and polycentric processes of societal system changes. It can also use a participatory approach to incorporate the diverse perspectives of stakeholders and to shape common understanding and consensus about transition process. On the other hand, systematic computational experimentation is used to assess the implication of many assumptions regarding the future instead of using a single best-guess estimate of the future or few discrete predictive scenarios (Maier et al., 2016).

2.2 Review of the literature

Moallemi and Malekpour (2018) investigated this emerging application of exploratory modelling of transitions from a methodological point of view. They proposed a step-wise framework for long-term planning and policy analysis of transitions by integrating sustainability transitions concepts and participatory exploratory modelling methods. Apart from this methodological work, few previous studies exist in which exploratory modelling has been used within the context of sustainability transitions. One group of them have used the application of exploratory modelling of transitions for designing case-specific policy advice (or *case-based models* as called in Boero and Squazzoni (2005)) in a context where the aim is to propose robust policy solutions and decision support systems for specific problem of a complex real-world system. Among them are (Eker and van Daalen, 2015; Hamarat et al., 2013; Hamarat et al., 2014; Kwakkel and Pruyt, 2013; Kwakkel and Yücel, 2014; Moallemi et al., 2017b; Pye et al., 2015). Most of exploratory modelling examples, in terms of their application, are applied to case-specific insight development. Another group of previous studies has used exploratory modelling for generic insight development (or *typifications* Boero and Squazzoni (2005)) to provide an explanation for a potential phenomenon of interest and to test or refine a set of hypothesis and assumptions in transitions studies. This use of exploratory modelling of transitions adopts a high-level of abstraction and is used for theory development, when the results of exploratory modelling under a certain theoretical assumptions falsify the theory or fail to reject theory and ask for refinement. One example of this group (with a transitions model) is (de Haan et al., 2016).

2.3 Processes for exploratory analysis

Steps to be taken in the exploratory modelling of transitions can be different depending on whether it is for designing case-specific policy advice or for *generating* generic insight development. Here, we only briefly describe this process for the purpose of long-term policy analysis i.e. case-specific policy advice, based on (Lempert et al., 2013). We have also made these steps more generic to be more consistent with the broader literature of sustainability transitions based on (Moallemi and Malekpour, 2018). This includes four steps:

1. **Problem formulation**, where key uncertainties and their ranges of variation (i.e. uncertainty) are specified, the transitions model is developed (i.e. relationships within the socio-technical system), various policy options whose impacts on transitions are of interest are determined (i.e. policy levers) and outcomes of interest and the desired behaviour in transitions are defined (i.e. performance measures),
2. **Experiment generation**, where various transitions pathways, based on the selected outcomes of interest, are generated with the model by running many simulations based on quasi-random samples from the defined uncertainty space. Simulation runs create an ensemble of experiments, each experiment corresponding to a single possible transition pathway with an equal likelihood of occurrence to other pathways.
3. **Computational exploration & discovery**, where generated transition pathways are analysed using a variety of statistical techniques e.g. envelope plotting and Kernel

Density Estimate (KDE) (Rosenblatt, 1956)), data-mining (e.g. scenario discovery (Bryant and Lempert, 2010; Groves and Lempert, 2007)), or optimisation (Maier et al., 2014).

4. **Trade-off analysis, adaptation & deliberation**, where the results of analysis in the previous step are used to answer the research questions. The objectives can be to obtain a robust understanding of transitions dynamics, how transitions unfold in the future and the conditions under which presently less likely pathways can become viable. The objective can also be to influence transitions, which then includes comparison of the impact of various policy interventions on transitions pathways, identifying potential vulnerabilities of various policy interventions, and developing proactive and adaptive measures to enhance the robustness of policy interventions and to realise the desired transition pathway across numerous possible futures.

3 Application to the example of electricity transition

3.1 Background

We used the long-term policy analysis of India's electricity transition under deep uncertainty in Moallemi et al. (2017b) as an example of exploratory modelling of transitions. This study investigates the transition of the electricity sector, between 1990 and 2030, from an existing coal-dominated fossil fuel sector towards a solar and wind-dominated renewable sector. This transition unfolds in a deeply uncertain context in which numerous possible surprises and shocks around techno-economic factors (such as investment costs of energy technologies) and socio-political factors (such as investors' preferences and policy support) can significantly alter the direction of transition pathways. The question of this study, from an exploratory modelling point of view, is 'how might future electricity transition pathways unfold, given the presence of various uncertainties?' Understanding future transition pathways can inform the design of effective policy interventions for the realisation of a renewable-dominated electricity sector in the future.

3.2 Methods

The study explored future transition pathways under different deliberate choices of future spaces where transition could emerge, defined as normative contexts. Six normative contexts were defined based on the combination of the two variations of the structure of the electricity sector in the future (whether it is dominated by market forces or government control) and three variations in the priority of societal needs which the electricity transition could realise (whether it prioritises energy equity, energy security or energy sustainability). See **Table 1**.

Table 1. The normative contexts of the future transition pathways

	Equity-driven	Security-driven	Sustainability-driven
Government-led	**Normative Context 1**	**Normative Context 2**	**Normative Context 3**
Market-led	**Normative Context 4**	**Normative Context 5**	**Normative Context 6**

This study used a Python package called the Exploratory Modelling Workbench (Kwakkel, 2017) for the implementation of exploratory modelling methods. The study also used a system dynamics energy transitions model (Moallemi et al., 2017a), developed based on concepts from the sustainability transitions area (Moallemi et al., 2017c), as the simulation of engine in the exploratory modelling process. Six different model parameterisations, each corresponding to one normative context, were set up, and they were used to perform 15000 simulation runs (i.e. computational experiments).

4 Results and benefits of exploratory modelling of transitions

The results from the application of exploratory modelling to this example showed that several divergent transition pathways could unfold in the future, among which are solar-dominated and coal-dominated futures, under different normative contexts. It was observed that a transition pathway towards a renewable—mainly solar—dominated electricity sector is more likely to be realised under a normative context with:

- A government-led structure, where transition is coordinated by active interventions rather than by relying only on market forces, and also with
- A sustainability and security driven transition, where the priority is on the clean and less fuel import-dependent generation of electricity rather than only the stable and abundant generation of electricity to meet growing demand.

Further details of these final results will be presented in the next subsection in which benefits of exploratory modelling for transitions modelling is discussed.

4.1 Treatment of deep uncertainties

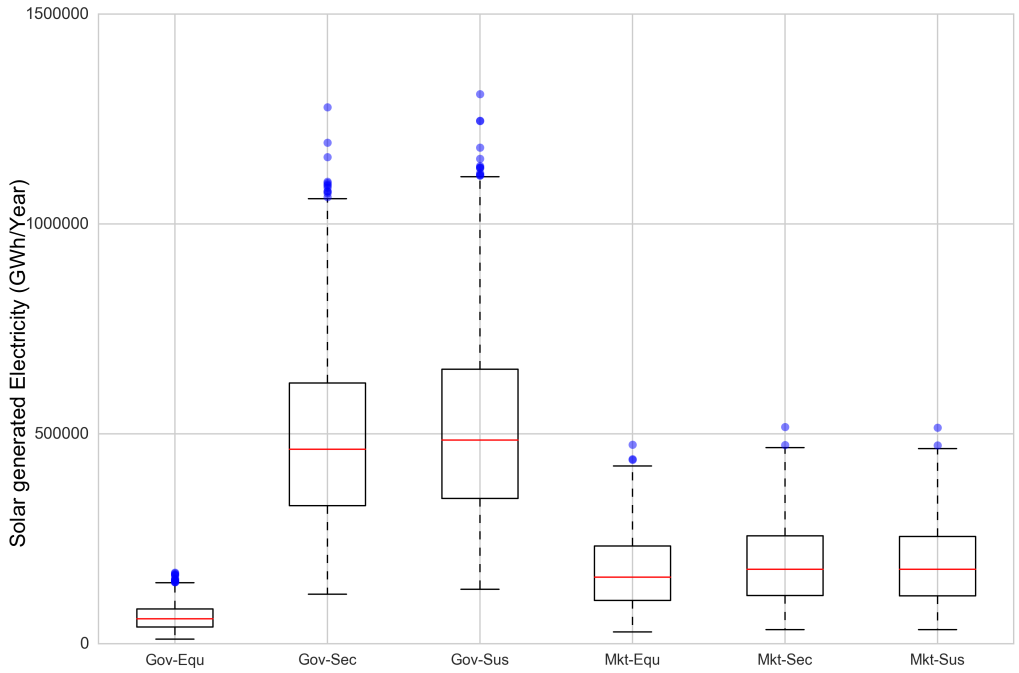
The first benefit of exploratory modelling for transition studies is in the better treatment of deep uncertainties. The management of deep uncertainties in exploratory modelling of transitions enables the use of many alternative simple models. This makes it unnecessary to develop complicated transitions models, which take long time to run, only for better simulating the reality. This also reduces the pressure on validating transitions model structure because final *robust* insights are independent of variations in model structure. The treatment of deep uncertainties in this approach also enables the use various values for model input parameters. This can simplify the time consuming search for finding accurate and valid data by considering possible variations of data in a wide uncertainty space. This also could create a consensus among stakeholders as it can integrate many potentially divergent perspectives of stakeholders (regarding conceptual framing, model, and data) about futures in a participatory environment.

In our example of electricity transitions, exploratory modelling enabled the energy transitions model to explore systematically the impacts of various parametric uncertainties (such as learning curve of energy technologies) and non-parametric uncertainties (such as different model settings in normative contexts) by preforming thousands of computational experiments with equal likelihood of occurrence; each experiment corresponding to a single possible of future realisation of the electricity sector. The study considered several uncertainties including the potential installed capacity of renewable sources, the changeable capacity factor of fossil fuel power plants, the learning curve of renewable generation technologies, the grid loss of electricity, and the rate of policy mechanisms, such as feed-in tariffs. The study assumed an estimated value of these uncertain parameters as base value and then consider a variation of +/- 50% of the estimated value as uncertainty ranges. Computational experiments were performed based on quasi-random value sets sampled from these uncertainty ranges. Generated experiments represent not only most-likely transition pathways but also those less-likely pathways but with highly significant impact, which could be considered most important in analysing long-term transitions of high-value systems (e.g. infrastructure investment) in a highly volatile environment (e.g. fast changing fossil fuel market). This created a portfolio of what *could* happen, as opposed to what *will* happen (Maier et al., 2016).

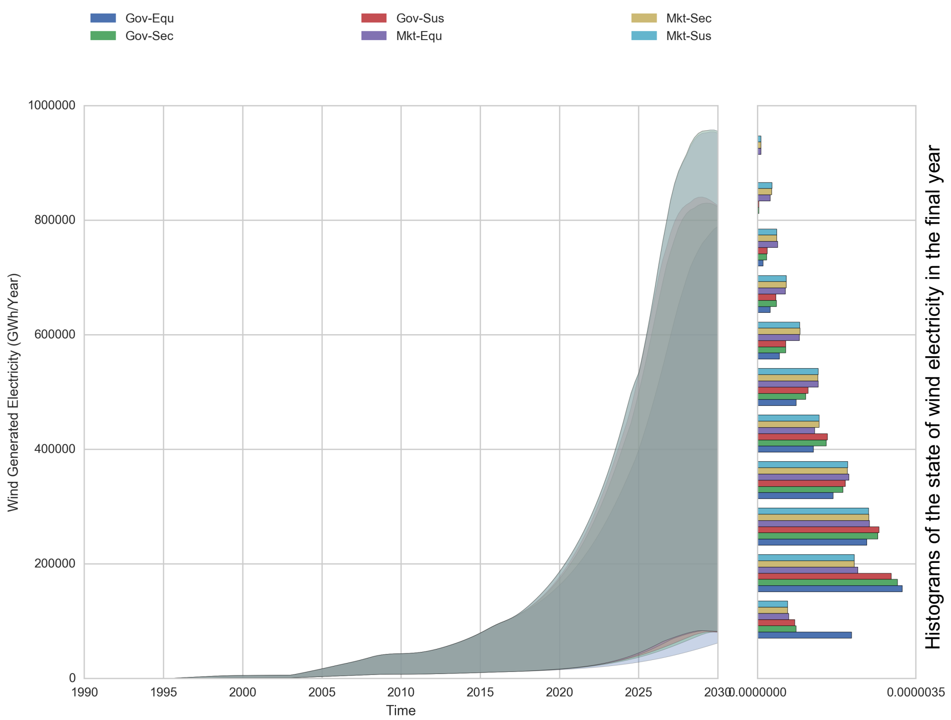
4.2 Obtaining a robust understanding of transition dynamics and impact of policies

Under deep uncertainty, a best-guess understanding(s) of transition dynamics obtained in a most-likely future (or a handful of limited future scenarios) may not hold in all future scenarios. An optimised design of transition policies that only consider known constraints under these conditions may turn out to be highly vulnerable and fail in the face of unexpected events. Exploratory modelling of transitions offers an alternative approach based on a robust understanding of transition dynamics and impact of policies; an understanding which remains insensitive to potential future changes, to misspecifications of models and to model input forecast errors. Exploratory modelling can also help to understand the most promising transition pathways as well as the conditions for unlikely pathways to become viable. The (in)sensitivity of the model response to potential changes in the input parameters is used to quantify robustness (Maier et al., 2016). Herman et al. (2015) have extensively discussed the concept of robustness and how it should be defined.

In our example of electricity transitions, an understanding of future transition pathways was obtained based on a collective measure of robustness, e.g. to what extent a function of multiple model outcomes, such as installed capacity of renewable sources, generated electricity, and GHG emissions, remains stable in response to deep uncertainties over time. To facilitate a robust understanding, the variation in the state of model outcomes was represented with boxplots, KDEs, and histograms. According to Figure 1 (a), government-led transitions lead to a higher mean of solar generated electricity compared to a market-led transitions because of subsidies, proactive localisation, and mission-oriented initiatives in government-led transitions which cause faster reduction of technology price and higher installation of new solar capacities. Equity-driven transitions also seem to be less favourable for solar generated electricity compared to security and sustainability driven-transitions. Conventional sources in an equity-driven transition can outcompete solar (and other renewables) by more stable generation of electricity and better fulfilment of growing electricity demand. According to Figure 1 (b), in another view, the envelop plot shows the bandwidth of future trend of wind generated electricity and the histogram shows the density of their end state in 2030. Future trends are influenced similarly across different normative contexts and substantially in response to assumed deep uncertainties. The highest density of the final estimate of future wind generated electricity in 2030 is likely to be distributed around 200,000 GWh per year.



(a)



(b)

Figure 1. The state of (a) solar generated electricity in boxplots and (b) wind generated electricity in envelope plots with the histogram of their end states

A minimum performance threshold expected from a system is another collective measure to assess robustness. In our example of electricity transitions, this threshold can be represented as those future scenarios which only lead to total government expenditure percent of GDP lower than a certain limit (0.006). A parallel coordinate plot in Figure 2 (a) was used to show the state of three outcomes: government expenditure percent of GDP, net total generated electricity, and GHG emissions, in response to different normative contexts. The fulfilment of this threshold with respect to normative contexts was analysed by reducing the number of generated future scenarios (called *brushing (Chang, 2017)*) to those lower than the threshold limit. The breakdown of feasible scenarios (see Figure 2 (b)) showed that a government-led equity-driven transition is more likely to meet this threshold while market-led with security or sustainability-driven transitions have the least likelihood.

4.3 Designing adaptive and proactive policy interventions

The long-term policy analysis of transition pathways cannot rely on static policy interventions designed solely based on a current understanding of transition dynamics as these policies may fail to deliver their effectiveness in some future conditions. Robust policy packages need to be developed by considering a variety of future circumstances. Robust policy packages should include adaptive policy interventions to be modified over time as new conditions emerge and proactive measures (or coping strategies) to address the future vulnerabilities (failures) of policies and keep them viable. Exploratory modelling of transitions facilitates a forward-thinking approach by answering questions such as 'under what favourable conditions could future targets be met?' and 'under what circumstances, regardless of their likelihood, could policy interventions fail?'. Exploratory modelling can benefit from a variety of methods for the design of adaptive and proactive policies. Among them is a machine learning method called scenario discovery (Bryant and Lempert, 2010; Groves and Lempert, 2007; Lempert, 2013). This method has been used in the exploratory modelling literature to identify extreme circumstances under which less-likely but highly desired transition pathways could become viable and also to specify potential vulnerabilities of current policy interventions in long-term futures. The results of scenario discovery enhance the robustness of our policy packages by choosing policies from those extreme circumstances which could lead to favourable transition pathways and by designing proactive measures which can ameliorate identified vulnerabilities. The results of scenario discovery can also facilitate adaptability in the face of changing circumstances.

Scenario discovery identifies the subsets of the input space which could result in similar classes of model performance. It processes the generated computational experiments, identifies similar classes of model behaviour, and specifies alternative subsets (known as scenarios or boxes) from the input space which can be responsible for the generation of the classes of model behaviour. Scenario discovery uses different measures of quality (coverage, density, and interpretability) and a p-value for selecting the most appropriate subset of the input space responsible for the generation of a particular class of model behaviour (see (Bryant and Lempert, 2010) for explanation of the measures). Scenario discovery has been implemented using Classification and Regression Tree (CART) (Breiman et al., 1984) and Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999).

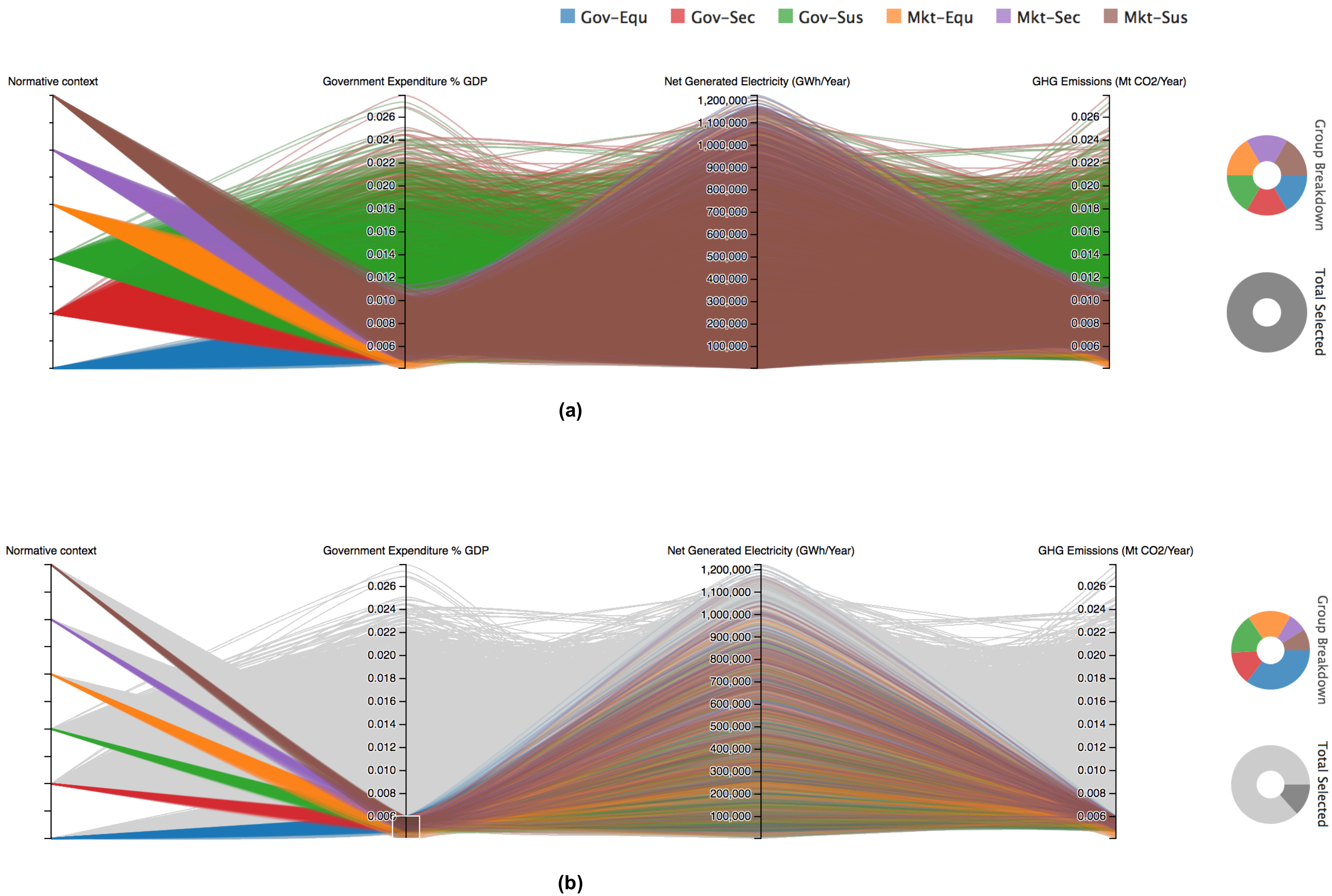
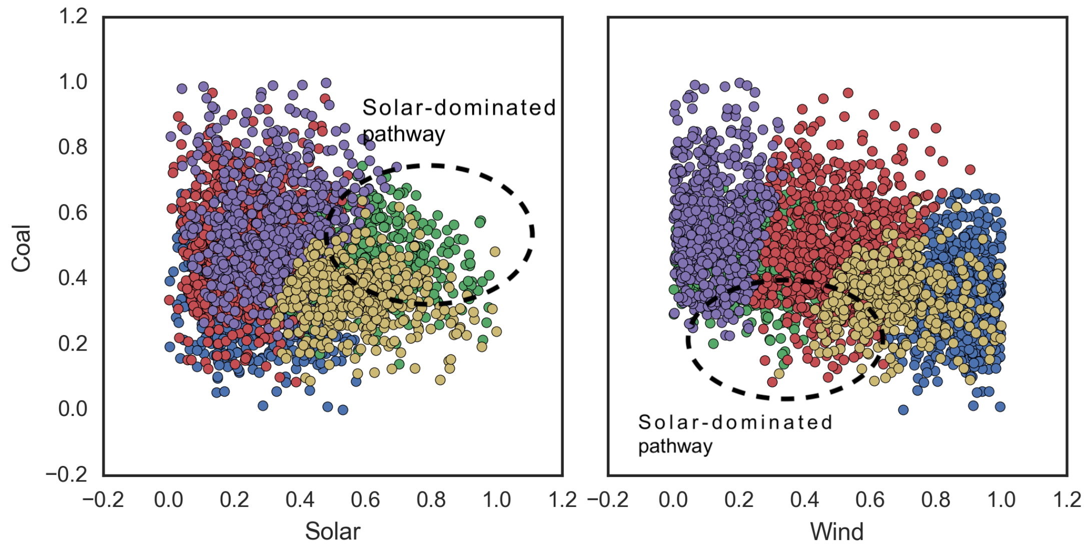


Figure 2. The parallel coordinate plots representing the state of the model outcomes (a) in all generated scenarios and (b) in those scenarios where government expenditure percent of GDP is lower than 0.006.

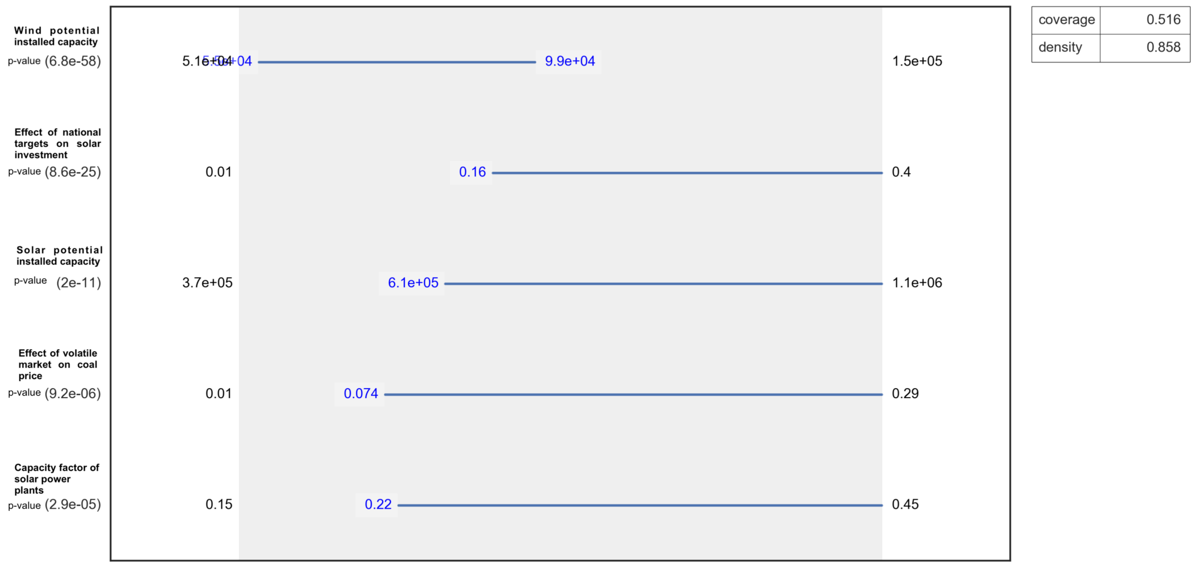
In our example of electricity transitions, the study suggests that it is highly unlikely that the governmental objective of 100 GW solar installed capacity before 2028 will be achieved as solar only accounts for 3% of total installed capacity (MNRE, 2016). However, the study used scenario discovery to identify those extreme favourable conditions which could make the less-likely transition pathway to a solar-dominated sector in 2030 viable. The study initially clustered generated computational experiments based on their state of coal, solar and wind installed capacity in 2030 using a multi-dimensional clustering technique (Gerst et al., 2013) (see Figure 3 (a)). The result showed that a scenario where solar dominated the electricity sector is possible in one cluster. The study then used multi-dimensional scenario discovery (with PRIM) to identify the extreme favourable conditions (i.e. the subspace of the input space) which could lead to this solar-dominated pathway (see Figure 3 (b)). The result of scenario discovery was interpreted as solar could gain power when three conditions are met if: (1) the government sets ambitious targets for the transition process and increases the rate of governmental investments to realise these targets, (2) investment in wind becomes less attractive compared to investment in solar based on the limited potential for wind capacity, and (3) investment in coal becomes less profitable to solar by not controlling the volatility of fossil fuels' prices through government subsidies.

4.4 Resolving the disagreements among stakeholders

Transitions emerge in a multi-stakeholder context with many (sometimes opposing) views and perspectives regarding how transition dynamic will unfold as well as how to steer and govern transition. Disregarding this diversity of perspective would result disagreement among stakeholders, a biased understanding towards dominant views, and therefore a failure in the design and implementation of effective policy interventions. The adoption of a participatory approach can therefore enhance sustainability transitions research (Köhler et al., 2018; Halbe et al. 2015), to which exploratory modelling can contribute. Exploratory modelling can assist sustainability transitions to open up discussion among various stakeholders in a systematic process and uncovers their implicit assumptions in different modelling steps, in early steps to identify critical uncertainties and in late steps to interpret and validate the analysis of results (Eker et al., 2017; Malekpour et al., 2016).



(a)



(b)

Figure 3. The clusters of future transition pathways (multi-dimensional clustering in (a)) and the conditions leading to a solar-dominated scenario (scenario discovery results in (b))

Exploratory modelling can bridge various perspectives and areas of expertise to create a room for dialogue and a common understanding among different stakeholders—a common understanding around the impact of policy outcomes and the normative direction of transition. The results of exploratory modelling can create an experimentation space for testing and observing the future impacts of various policy interventions and their potential vulnerabilities. It also creates a platform for group thinking about proactive measure to address these vulnerabilities. This leads to negation, reflexivity, and learning among stakeholders (Malekpour et al., 2017) based on evidences from transition pathways in many possible futures. Second, the results of exploratory modelling can facilitate the formation of a shared idea and consensus about the normative direction of transitions, i.e. the visions through which transitions are negotiated and navigated. In the example of electricity transitions, many possible future pathways were generated and then clustered based on the similarity of their behaviour (see Figure 3). The generated clusters showed potential transitions pathways, including a solar-dominated pathway, that can be expected as a normative direction for electricity transition.

5 Conclusions and future research directions

This research showed the potential benefits of using exploratory modelling in the treatment of deep uncertainties in the sustainability transitions research. As it was discussed before, only few previous transitions studies have taken advantage of the computational capabilities of exploratory modelling for understanding and policy analysis of transition pathways. This article reviewed the potential benefits of this application as follows using an existing example from the literature:

- First, it enables better treatment of deep uncertainties in understanding and steering transitions, where there are many alternative model structures and different values for model input parameters;
- Second, it enhances the robustness of decision and policy insights in the face of many future possibilities based on the analysis of a portfolio of what *could* happen as opposed to what *will* happen in the future. Exploratory modelling can help to understand the most promising transition pathways as well as the conditions for unlikely pathways to become viable;
- Third, it allows the development of proactive and adaptive policy interventions in which transition pathways are shaped by some near-term choices in a context following up by some subsequent actions in the future in response to potential variation. This facilitates a forward-thinking approach in sustainability transitions by answering questions such as ‘under what favourable conditions could future targets be met?’ and ‘under what circumstances, regardless of their likelihood, could policy interventions fail?’
- Fourth, it provides a platform for representing different views and resolving disagreements among stakeholders by considering the implications of various ways of framing transitions.

One direction of future research is to use new transitions models from wider sectoral contexts for new case-specific policy insights over a very large variety of plausible transient scenarios. This direction of future research can also be about testing well-known transitions theories, such as typology of transition pathways (Geels and Schot, 2007), which were only proposed using qualitative arguments, with exploratory modelling approaches.

Further research could investigate the application of different exploratory modelling approaches, such as MORDM and DAPP, in the context of sustainability transitions to construct dynamic adaptive transition pathways. The application of these exploratory modelling approaches can bring new quantitative capabilities to the sustainability transitions research. They can address the combinatorial problem which arises from the multiplicity of ways in which episodes of pathways (or patterns as it is called in (de Haan and Rotmans, 2011)) can be sequenced over time. The application of these approaches can also address the need to identify governing rules (or adaptation tipping points (Kwadijk et al., 2010)) which tell us when new episodes should be triggered for constructing adaptive pathways.

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