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Narrative-informed exploratory analysis of energy transition pathways: A case study of India's electricity sector

Enayat A. Moallemi[a,b,*], Fjalar de Haan[a,c], Jan Kwakkel[b], Lu Aye[a]

[a] Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia
[b] Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands
[c] Melbourne School of Design & Melbourne Sustainable Society Institute, The University of Melbourne, Victoria 3010, Australia

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ABSTRACT

Energy transitions unfold under the influence of socio-technical, political and economic uncertainties. This paper introduces a narrative-informed exploratory approach for analysing future energy transition pathways under these uncertainty conditions. In this approach, exploratory modelling is used to explore the impact of various uncertainties, such as potential installed capacity and supporting policies for different energy options, on the unfolding of transition pathways. The approach produces several sets of scenarios. We complement this quantitative exploration of the future with narratives (storylines) generated based on the concepts in the sustainability transitions field. Narratives are used (i) as a supporting framework for model structure; (ii) to guide the exploration of the future; and (iii) to interpret the ensemble of quantitative scenarios. We describe how synergies between narratives and exploratory modelling inform both the framed and open-ended exploration of future transition pathways. The approach is demonstrated with a case study of the transition in India's electricity sector. We show that the realisation of the 100 GW solar electricity target by 2022 is unlikely, and that the development of solar electricity is highly dependent on the active role of government.

1. Introduction

1.1. Background

Societal transitions, such as those in energy sectors, are defined in the sustainability transitions field as long-term and multi-dimensional transformation of societal systems (e.g. energy systems) aiming to satisfy societal needs (e.g. energy security and sustainability) (de Haan and Rotmans, 2011; de Haan et al., 2014; Rotmans et al., 2001). Transitions unfold over time under the influence of many highly-uncertain technical, political, and economic driving forces. These driving forces are considered deeply uncertain in the sense that they cannot be ranked in order of importance or even described with a probability distribution (Bankes, 1993; Lempert et al., 2003).

In the case of energy transitions, deep uncertainty around fossil fuels and renewable energies in the future, changes the traditional paradigm of decision making and challenges the effectiveness of the government energy policies and the realisation of targets. Under deep uncertainty, the 'best-guess' paradigm of decision making and 'traditional scenarios planning' with a few limited scenarios for the future face unexpected surprises and shocks and do not lead to robust decisions (Bryant and Lempert, 2010; Maier et al., 2016; Malekpour et al., 2016; Pye et al., 2015). Potential shifts in the US policies around climate change and fossil fuels' exploitation, after the 2016 US presidential election, is an example of these unexpected shocks. This situation has been referred to as the 'wickedness of public policy problems' (Kwakkel et al., 2016; Rittel and Webber, 1973). Policy interventions can also result in unintended consequences due to the complexity and nonlinearity of energy transitions. The government interventions in the European electricity market and their damaging impacts on falling wholesale prices, reducing generation investments in conventional sources and rising final consumer prices, known as the 'scissors effect', is an example of these unintended consequences (Robinson, 2015).

Divergent transition pathways can be explored, and robust decisions can be designed, using exploratory modelling (Auping et al., 2016; Bankes, 1993; Bankes et al., 2001; de Haan et al., 2016; Eker and van Daalen, 2015; Kwakkel, 2010; Lempert, 2002; Lempert et al., 2003; Walker et al., 2013). Exploratory modelling is the systematic exploration of the impacts of various parametric, structural, and methodological uncertainties, using computational experimentation (Kwakkel and Pruyt, 2013). With exploratory modelling, one can generate prospective

* Corresponding author at: Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia.
E-mail address: e.moallemi@unsw.edu.au (E.A. Moallemi).

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transition pathways for different assumptions about how various deeply uncertain factors might be pan out. Exploratory modelling can also be used to identify the favourable conditions under which future targets can be met.

We argue that the model-based exploratory understanding of future energy transition pathways using exploratory modelling can be complemented by qualitative narratives. In this context, a narrative is a coherent storyline describing how a transition unfolds through the initial state of systems, the internal and external mechanisms of change and the new state of systems. Such a narrative can be developed using the concepts from the sustainability transitions field, for example. A narrative-informed exploratory modelling approach can provide a richer and more interpretable picture of how future transition pathways could unfold (Foxon, 2013; Maier et al., 2016). This paper aims to investigate the methodological synergies between a narrative and an exploratory modelling approach for the analysis of transition pathways.

1.2. Narratives-modelling interactions

Our proposed approach exploits the two-way interactions between narratives and models. On the one hand, exploratory modelling uncovers how the chain of causes and consequences in future energy transitions can unfold. The impact of these causal relations in long-term cannot be understood with qualitative narrative scenarios alone. This is because of the complexities and deep uncertainties which demand analytical power beyond the human mental model-based narratives (Holtz et al., 2015). On the other hand, qualitative narratives inform the model development process of an energy transition through the demarcation of the systems' boundary, the explanation of internal dynamics, and the identification of external forces and contingencies (Moallemi et al., 2017a). Narratives guide the process of exploring the impacts of various deep uncertainties and possible normative directions on the emergence of specific energy transition pathways. Narratives are also used to interpret the ensemble of generated scenarios with models, as well as to better convey model-based policy implications to different actors (Greeven et al., 2016).

The idea of enabling quantitative approaches with qualitative techniques and vice versa has been advocated in recent studies. Maier et al. (2016) discussed how qualitative conceptual models give a holistic picture of the system and how they can be used as underlying supporting framework for quantitative models. Geels et al. (2016) argued the necessity of bridging between quantitative systems modelling and qualitative socio-technical analysis to inform governance decisions. de Haan et al. (2016) explored the emergence of various transition pathways based on a limited number of underlying qualitative change patterns. Robertson (2015) applied the qualitative socio-technical transition frameworks to interpret the future quantitative scenarios in the analysis of low carbon transition pathways. Trutnevyte et al. (2014) translated a qualitative storyline as input assumptions into multiple quantitative models of the UK power system transitions, and also enriched the qualitative storyline with model outputs.

1.3. The case of transition in India's electricity sector

This paper demonstrates the various ways in which narratives and exploratory modelling can be combined to inform policy interventions in energy transitions, using a case study. The case study is the transition of India's electricity generation sector from fossil fuels (mainly coal) towards renewable resources (mainly on-grid solar photovoltaics (PV) and wind). This is an important case to study as the country is now the third in the world in terms of emissions from fossil fuels, and will be the second in terms of increase in the global energy demand by 2035 (World Bank, 2015). The development of renewable electricity in India is also a matter of interest because of the different (and new) roles that government targets, policies and strategies can play in developing countries (Bagheri Moghaddam et al., 2012). The targets set by the Central Government of India are to have 100 GW on-grid solar and 60 GW wind installed capacity by 2022. The government steers and stimulates this transition with market-based policy instruments (e.g. feed-in tariff), command-and-control actions (e.g. imperative targets, renewable purchase obligations), and direct interventions (e.g. government funds) (Moallemi et al., 2017b). The question from an exploratory modelling point of view is 'what the future transition pathways would look like under current policies, given the presence of various uncertainty factors?' The answer to this question will bring policy insights on how to address concerns regarding energy poverty, energy security, and sustainability.

1.4. The energy transitions model

We used an energy transitions model as a scenario generator in the exploratory modelling process. There is a broad literature on energy modelling approaches for simulating energy transitions. Among them are the models developed with dynamic modelling techniques, such as the System Dynamics approach and Agent-Based Modelling (Chappin, 2011; Ghorbani, 2013; Vogstad, 2004; Yücel, 2010) where the primary focus is on understanding systemic non-linearities, multi-causalities, and agent interactions. There are also formal energy techno-economic models and optimisation models, such as MARKEL (Loulou et al., 2004) and TIMES (Loulou et al., 2005), among other examples (Li et al., 2015), where the primary focus is on modelling economic characteristics, technical feasibilities, and natural resource limitations. The simulation model of the current study is a system dynamics 'energy transitions model' (Moallemi et al., 2017a), from a new group of energy models called 'socio-technical energy transition (SEIT) models' (Li et al., 2015) and the broader category of transitions models (Holtz et al. 2015). It is a model of long-term transformational changes developed based on theoretical concepts from the sustainability transitions field and informed by the narrative of the historical transitions of India's electricity sector from 1970s till 2015. The theoretical concepts and qualitative narrative enabled the model to conceptualise the specific features of electricity sector transitions, i.e. being a long-term multi-generational process, having multiple social, technical, economic and political dimensions, and having path-dependency to the established conventional electricity generation systems. They also informed the normative direction of transition in the model, i.e. improving access to electricity (demand-supply balance), reducing fossil fuels dependency (energy security) and decreasing greenhouse gas (GHG) emissions (energy sustainability).

1.5. Structure of the paper

The rest of this paper is structured as follows. Section 2 presents the key interactions between narratives and exploratory modelling. Section 3 presents an overview of the energy transitions model. Section 4 shows how narratives can guide the exploration of future transition pathways. Section 5 shows how the results of exploratory modelling can be interpreted and communicated using narratives. Section 6 concludes the paper.

2. Interactions between narratives and models in exploratory modelling

Concepts and theories from the sustainability transitions field can conceptualise the raw data from a case study of historical transitions. Several previous studies used this approach to produce historical narratives, such as de Haan (2010), Geels and Schot (2007), Hekkert and Negro (2009), Moallemi et al. (2014, 2015), Suurs (2009). We argue that these concepts and theories can also be used to interpret, frame and put into perspective quantitative future scenarios resulted from exploratory modelling. In this study, we used a theoretical framework for state-influenced empowerment of renewable niches (Moallemi et al., 2017c) to conceptualise historical and future transitions. This framework incorporated concepts from existing transition frameworks, such as the Multi-Pattern Approach (de Haan and Rotmans, 2011), the Multi-Level Perspective (Geels, 2002), the Actor-Option Framework (Yücel, 2010), and the theoretical framework developed by Frantzeskaki (2011). The application of this framework in the exploratory modelling process results in stylised narratives, i.e. structured storylines. Stylised narratives can describe energy transitions in terms of the initial systems' state, the required conditions for change, the endogenous and exogenous mechanisms of change, and the new systems' state. These narratives can complement the modelling process and enrich the exploratory analysis in three ways:

2.1. Historical narratives and model structure

Exploratory modelling uses a simulation model as a scenario generator. Narratives of historical transitions can serve as an underlying conceptual framework for this simulation model. Narratives inform the development of the model structure through the demarcation of systems in transition and the explanation of the internal dynamics of systems (see Section 3). They also identify the exogenous forces and contingencies that fall outside the boundary of the system but affect the final outcomes significantly. Modelling techniques are generally unable to incorporate these external forces as explicit choices have to be made about the system boundaries. A model structure informed by historical narratives reflects a more inclusive picture of reality (with less simplification) in the simulation model. The resulted simulation model can also generate the intrinsic characteristics of societal transitions, such as being long-term, multi-dimensional, revolutionary, and path-dependent.

2.2. Historical narratives and framed exploratory modelling

Narratives can inform the exploration of future transition pathways. Narratives frame the exploratory modelling process and guide the analysis of extensive simulation results (see Section 4). For example, narratives can be used to describe prospective normative contexts, i.e. the deliberate choices of public and governments and the spaces of the future in which transitions could unfold. Normative contexts for future transitions are extracted from historical narratives. They are identified based on the driving forces that not only shaped transitions in the past, but also will remain in force and effective in the future (Fouquet, 2010; Rühl et al., 2012; Zhao et al., 2016).

2.3. Open-ended exploratory modelling and future narratives

Exploratory modelling can be conducted in an open-ended way if there is no agreement on the prefixed set of normative contexts. In this case, a vast number of transition pathways, in response to various uncertainties and different normative contexts, are generated. The resulting ensemble of transition pathways is then clustered based on the similarity of their behaviour. Clusters with similar behaviour are interpreted as distinct future scenarios (de Haan et al., 2016). These scenarios can be described in narratives, drawing on concepts and mechanisms of change from sustainability transitions. These narratives can better communicate the results from exploratory modelling to different actors (see Section 5).

Each of these interactions is explained in our case study in the three following sections.

3. Overview of the energy transitions model

We used a system dynamic (SD) energy transitions model developed by (Moallemi et al., 2017a). The overall model structure for the transition in India's electricity sector is presented in Fig. 1. We used a historical narrative of electricity sector transitions in India to inform the model development process. A summary of the historical narrative is presented in Appendix A. The narrative informed model development in several different ways:

First, the narrative helped us to develop a model customised for the multi-dimensional and multi-scale nature of transitions. This historical narrative divided the broader transition of India's electricity sector into (1) changes in the government interventions approach (from a centrally coordinated to partially liberalised) and (2) changes in the sources of generation (from conventional to renewables and mostly to wind and solar). The historical narrative, then, described these changes in multiple development phases over time with the concepts borrowed from the sustainability transitions field. Accordingly, the transition process was conceptualised as a sequence of the *destabilisation* of old fossil systems and the *formation* of new renewable systems under the influence of *internal and external driving forces* such as government interventions and technological advances. The electricity sector was conceptualised as a *societal system*, composed of several generation options as competing *constellations* and functioning normatively to satisfy demand-supply balance (or generation), energy security (or fuel imports dependency), and emissions reductions (sustainability) as *societal needs* (de Haan and Rotmans, 2011; de Haan et al., 2014). We represented this multi-dimensional conceptualisation of transitions in the overall model structure with the following components:

- **Pricing** component for specifying tariffs, costs, and benefits in the trade of electricity between generators, distributors, and end-users;
- **Investment** component for determining the investments in renewable vs. conventional sources;
- **Capacity** component for simulating the growth in installed capacity and also the learning curves of generation technologies;
- **Generation** component for determining the generation of electricity from each individual source;
- **Demand-Supply Balance**, **Energy Security**, **Emissions Reduction, and Satisfaction of Societal Needs** components for measuring the satisfaction of three societal needs and aggregating their fulfilment in a single index;
- **Policy** component for determining the rate of policies, e.g. feed-in tariff and accelerated depreciation; and
- **Financial Burden** component for assessing the total government expenditures.

The historical narrative, by emphasising the dynamics of transition processes, also helped us to specify the scope and boundary of the model and to make a trade-off between the depth and breadth of modelling in each component. We characterised the depth and breadth of the model by dividing between endogenous, exogenous, and omitted variables in the modelling process (see Fig. B.1. in Appendix B).

Second, the historical narrative qualitatively explained how the transition unfolded and what the interactions between different identified components were. We used these historical interactions to explain the chain of causes and consequences between the components of our model, i.e. how the interactions between Pricing, Investment, Capacity and Generation, impacts the Demand-Supply Balance, Energy Security, Emissions Reduction, and Satisfaction of Societal Needs, how the state of societal needs signals for corrective policies in Policy, and how these policies influence the dynamics of the system in return and increase the Financial Burden of the government (see Fig. 1).

Third, the historical narrative informed us how to capture the underlying social processes (the roles of actors) and the impact of contingencies and external forces on different model components. The historical narrative assumed that what enables the system and its components to work and to satisfy societal needs are *system actors* and *actor decisions*. They were seen as the underlying mechanisms of transitions (Yücel, 2010). We used this actor conceptualisation to model the decision process (e.g. preferences, priorities, perception delays) of government, investors, generators, providers, distributors, and end-

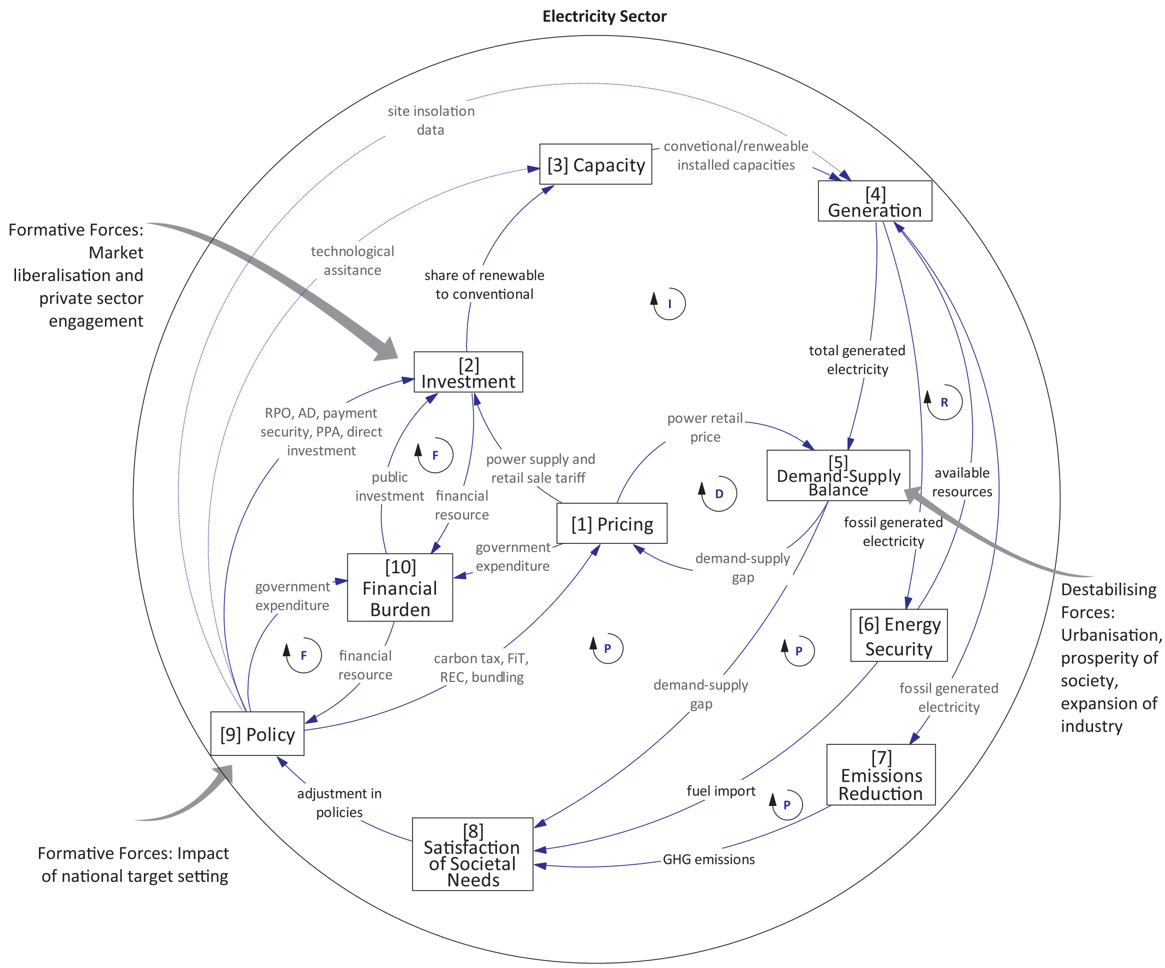

Fig. 1. Causal loop diagram representing the interactions between different societal components in India's electricity sector based on the conceptualisation of transitions in the historical narrative (Moallemi et al., 2017a).

users. The historical narrative also showed how internal system interactions and actor decisions are influenced by contingencies (external formative or destabilising forces). We used these identified contingencies as complementary assumptions to the model structure. One example of these contingencies was the external impact of market liberalisation and private sector engagement (promoted in the Electricity Act 2003) on the sudden increase of investment rate on renewable sources in the Investment component. Two other identified external forces are also shown in Fig. 1 as examples.

The model was implemented in Vensim DSS and was set up to investigate the interactions among coal, gas, wind, and on-grid solar PV. Other energy sources, including large hydro, nuclear, and small hydro, were not modelled in detail and were handled as exogenous inputs because of the less significant growth of these sources in the past years and also to avoid further complication of the model. Each component was modelled with stock and flow variables, and the relations between them were defined by the relevant equations. Simulations were run for the period from 1990 to 2030. The values of model parameters and initial states of stock variables were extracted from historical (1990–2015) data (CEA, 2015; GoI, 2006, 2015; MNRE, 2010; MoP, 2003, 2015) and from the forecasted (2015–2030) trends in the International Futures (IFs) model database (UDenver, 2015). Appendix B presents the details of the model (stock and flow) structures with their mathematical equations. We also refer interested readers to (Moallemi et al., 2017a) for an in-depth explanation of the model used in this paper.

4. Framed exploration of transition pathways

4.1. Procedure and implementation

Normative contexts, i.e. deliberate choices by the government and by general public which impact how future transition pathways unfold, can frame the exploration of transition pathways in the future. In this section, the impact of deep uncertainty on the unfolding of transition pathways is assessed within the qualitative framework of these normative contexts. The following four steps are taken in performing the framed exploration of future transitions:

- The first step is to extract normative contexts from the historical narrative. They characterise different normative futures within which a transition can unfold. They are distinguished from each other based on different assumptions regarding the priority of societal needs (e.g. energy equity, security, and sustainability) and the influence of government or market forces. The result is several alternative settings, referred to as normative contexts.
- The second step is to identify critical uncertainties and their range of variation. These uncertainties are related to the intrinsic characteristics of the system (such as uncertainty in technological efficiencies).
- In the third step, one explores over both the set of alternative normative contexts, and the various sources of uncertainty. For this, we use the Exploratory Modelling Workbench (Kwakkel, 2017), which is a Python package for implementing exploratory modelling techniques. The exploration relies on systematic computational

experimentation, resulting in a large database of transitions pathways.

- The fourth step is to analyse the results of computational experiments. The analytical approach used here is scenario discovery (Bryant and Lempert, 2010; Kwakkel and Jaxa-Rozen, 2016). In the context of this paper, we use scenario discovery to identify the combination of uncertainties under which particular classes of interesting model behaviour occur (Kwakkel et al., 2013). Scenario discovery uses statistical and data-mining algorithms that aim at finding combinations of values for the uncertain input variables that result in similar classes of outcomes. We used PRIM (Patient Rule Induction Method) for conducting scenario discovery (Friedman and Fisher, 1999). PRIM seeks a set of subspaces of the uncertainty space within which the value of a single dependent variable is considerably different from its average value over the entire domain. PRIM describes these subspaces in the form of hyper rectangular boxes of the uncertainty space. PRIM produces a collection of alternative boxes. The analyst can subsequently choose the most appropriate box based on a trade-off between two quality criteria: coverage and density. Coverage measures how completely the behaviour of interest can be explained with the selected ranges of uncertainties (the universality of the boxes). Density measures the number of experiments with the irrelevant behaviours within the selected ranges of uncertainties (the purity of the boxes).

4.2. Identification of normative contexts

Transitions pathways are "intrinsically normative" (Rotmans, 2005). We used this concept of normative pathways to guide the exploration of transition pathways. We only relied on the narrative of historical transitions and literature review for the development of normative contexts. However, the engagement of experts and incorporating different stakeholders' perspectives, e.g. in a workshopping process, can enrich the identification of these contexts too. We defined six normative contexts based on variations in the structure of electricity sector and the priority of societal needs:

- First, the future transition pathways of India's electricity sector are dependent on the structure of the sector, which is a normative direction with respect to the role of government. The electricity sector can be dominated by the market as a result of the liberalisation of the economy started in India in the early 1990s. However, the sector can remain, by and large, government-owned with an interventionist approach. This market vs. government structure of the sector is similar to the governance logics which were developed for the future of the UK energy transition (Foxon, 2013; Trutnevyte et al., 2014). We made some assumption for each setting. In a *market-led* future, we assumed that the free market competition coordinates the interaction amongst actors. The government and regulatory frameworks are still in place and incentivise these interactions. However, government uses market-based policy instruments to reach the market equilibrium (rather than to enforce for the fulfilment of governmental targets). A preferred policy within this setting is Feed-in Tariff (FIT), which can maximise the economic efficiency while does not impose mandates on any involving stakeholders. Also, in a market-led future, actors' investment decisions are sensitive to profit and financial return, and therefore the incumbent regime tends to remain dominant because of its intrinsic economic advantages. In short, a market-led sector forms an economically efficient pathway for transition. In contrast, in a *government-led* future, we assumed that the government actively shapes transitions by setting targets, coordinating actions, removing barriers (e.g. transmission capacity and required skills), etc. Renewable Purchase Obligation (RPO) and Accelerated Depreciation (AD) are the preferred policies as they can better secure the achievement of targets through command and control mechanisms. Technological progress can be faster because the government initiates technology-push and mission-oriented programs to support specific types of technologies. The government funds and directly invests in new installed capacity. It also influences the attractiveness of different sources for investment through the enforcement of national targets and priorities. In short, a government-led sector can better satisfy top-down targets but at the expense of financial burden on the government.
- Second, future transition pathways are dependent on the priority of societal needs which an electricity sector aims to meet. This indicates the normative direction of transitions with respect to general public values. The priority of societal needs may change over time, deliberately (e.g. by government campaigns for access to energy for all) or under the influence of external forces (e.g. extreme weather conditions). Over the past 25 years in India, energy transitions have been used to achieve energy equity, energy security, and energy sustainability (Moallemi et al., 2017c). This is similar to what has been referred to as the 'energy policy trilemma' in the experience of the UK's energy transition (Trutnevyte et al., 2015). In an *equity-driven* transition, we assumed that the generation of abundant electricity for meeting growing demand is the first priority. Conventional sources become more competitive in this situation as they can generate more stable energy compared to renewables. In a *security-driven* transition, reducing dependency on fuel imports is the primary direction. In a *sustainability-driven* transition, reducing GHG emissions becomes important and outweighs all other societal needs. In both security-driven and sustainability-driven transitions, renewables are more competitive. Policies such as carbon pricing and environmental premiums for the purchase of renewables fit these directions.

Six normative contexts emerge by combining the sectoral structures with the prioritising of societal needs (see Table 1). We chose different values for the model parameters in each normative context in harmony with the qualitative assumptions of sectoral structure and priority of societal needs (see Table C.1 and C.2 in Appendix C). For example, we chose 0.4 (-) for the model parameter related to the external effect of national targets on solar investment in Normative Context 3 (Government-led, Sustainability-driven) compared to 0.01 (-) for the same parameter in Normative Context 6 (Market-led, Sustainability-driven). This quantification was based on the assumption that national targets and government priorities are more influential in a government-led structure and more in favour of renewable sources in a sustainability-driven transition compared to a market-led structure where the market competition has the main role. We quantified the rest of the model parameters related to normative contexts in the same manner. This quantification resulted in the six sets of model setups (Table C.2 in Appendix C). We used the model setups to run simulations and to explore transition pathways in each normative context in Section 4.4.

4.3. Identification of uncertainties

Table 2 (and Table D.1 in Appendix D) shows critical uncertainties with their ranges of variation, considered in exploratory modelling. The criticality of uncertainties was assessed based on lack of knowledge/unavailability of data about their future values as well as the impact of

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*

Table 2
Uncertainties of parameters and their ranges.

Parameter	Source	Abbreviation	Range of uncertainty (< ± 50%)
Potential installed capacity (MW)	Coal	pic	500000 – 1200000
	Gas	pic 0	50000 – 150000
	Wind	pic 1	51394 – 154182
	Solar	pic 2	374000 – 1122000
Exogenous learning (growth rate between 2015 and 2030) due to global technological progress (-)	Coal	elr	0.0004 – 0.0006
	Gas	elr 0	0.0004 – 0.0006
	Wind	elr 1	0.00025 – 0.00075
	Solar	elr 2	0.00025 – 0.001
Endogenous learning rate due to the scale of installed capacity (-)	Coal	lix	0.0 – 0.01
	Gas	lix 0	0.0 – 0.01
	Wind	lix 1	0.0 – 0.1
	Solar	lix 2	0.0 – 0.1
Capacity factor coefficient of power plants of different sources (-)	Coal	cfc	1.04972 – 3.14916
	Gas	cfc 0	0.731435 – 2.194305
	Wind	cfc 1	0.2 – 0.6
	Solar	cfc 2	0.15 – 0.45
Future rate of change in FIT (-)	Wind	fit 1	−4000 – 4000
	Solar	fit 2	−4000 – 4000
Future rate of change in RPO (-)	Wind	rpo 1	−0.1 – 0.1
	Solar	rpo 2	−0.075 – 0.075
Future rate of change in AD (-)	Wind	ad 1	−0.8 – 0.8
	Solar	ad 2	0.0 – 0.8
Population growth (million persons)	N/A	population growth	10.181 – 18.797
Grid losses in transmission and distribution networks (-)	N/A	Grid losses gl	0.115 – 0.345

their uncertainty (i.e. the variation of their values) on model outcomes. Potential uncertainties and their estimated (base) values were identified initially based on the review of documents. The documented data for the base value of these uncertainty were compiled from MoP (2015), GoI (2015), CEA (2015), GoI (2006), MNRE (2010), MoP (2003). The missing/unavailable data for the base value of some uncertainties (such as capacity factor coefficients) were estimated based on the calibration of model parameters. A range of minus–plus 50% of the estimated (base) value was assumed as the uncertainty range for each parameter. Then, we used the built-in standard sensitivity analysis function in Vensim DSS to assess the criticality of identified uncertainties within the specified ranges and their significance in the exploratory modelling process. This resulted in five categories of critical uncertainties as follows.

4.3.1. Uncertainty in the potential installed capacity of different energy sources

This specifies the availability of renewable resources for generation. As an energy generation source approaches its maximum capacity, interest for further investments in it declines. The higher the potential installed capacity, the higher the maximum ceiling for investment. The source of this uncertainty is mainly associated with different estimates presented by various private and governmental bodies. The estimates for the potential installed capacity also change over time in response to advances in generation technologies and with new accurate measurements.

4.3.2. Uncertainty in the learning curve of generation technologies

With technological progress, investment cost for energy generation technologies declines, and they become more attractive options for further investment. The reduction in the investment cost is explained by endogenous and exogenous factors (Vogstad, 2004). The exogenous factor is the fractional reduction in cost per year due to global technological achievements. The endogenous factor is the reduction of investment costs due to the experience and learning from the accumulation of installed capacity. They are both subject to high uncertainty (divergent estimates and expectations exist about their future trends). In general, conventional sources, such as coal and gas, are less sensitive to these uncertainties as they have already reached technological maturity. However, the future state of renewables, such as wind and solar, is impacted more as their technological efficiencies are still improving. In calculating the impact of exogenous learning on investment cost, we assumed that the uncertainty around the exogenous learning rate is dynamic between 1990 and 2030. This considered the exponential improvement in some of renewable technologies (e.g. solar PV) in the recent years and their expected further improvement in the future. We assumed a fixed value for the exogenous learning rate between 1990 and 2015 (coal: 0.004, gas: 0.004, wind: 0.03, solar: 0.07), and an uncertain growth rate (added to this initial value) between 2015 and 2030. The parameters related to the exogenous learning rates in Table 2 (elr, elr 0, elr 1, and elr 2) only show the range of uncertainty for this growth rate.

4.3.3. Uncertainty regarding grid losses

Grid losses arise due to loss of electricity in transmission and distribution networks as well as due to electricity theft. Grid losses will directly impact the total generation of electricity, and subsequently influence the supply and demand balance. Given doubts about the expansion programs for the transmission and distribution networks and the government actions for reducing electricity theft, grid losses are considered an important source of uncertainty.

4.3.4. Uncertainty in the capacity factor of power plants for different sources

The capacity factor describes the ratio between the actual output in a given period (a year) and the potential output if it is possible to operate at full capacity all the time. The capacity factor is a function of efficiency and generation cost (when there is a spot market condition). However, it was not modelled deeply because technical details were not the focus of this study. The capacity factor was modelled as a function of resource efficiency, availability of fuels (for convectional), and a capacity factor coefficient. Because of the unavailability of documented data for capacity factor coefficients, a range of uncertainty around their value was included in exploratory modelling.

4.3.5. Uncertainty in the rate (intensity) of policy instruments

The uncertainty around the future state of the policies, including feed-in tariff, renewable purchase obligation and accelerated depreciation, impacts the attractiveness of renewables compared to conventional sources, and therefore influences their investments and installed

Table 3
The outputs of interest whose behaviour are explored over the time.

Output	Unit
Demand per sector (agriculture, commercial, industrial, domestic, misc)	GW h a^{-1}
Demand and supply balance	GW h a^{-1}
Installed capacity per source (coal, gas, wind, solar)	MW
Investment cost per source (coal, gas, wind, solar)	INR MW^{-1}
Public Investment	INR a^{-1}
Private Investment	INR a^{-1}
Generated electricity per source coal, gas, wind, solar	GW h a^{-1}
Total generated electricity	GW h a^{-1}
Total GHG emissions from electricity generation	Mt CO_2-e a^{-1}
Total fossil fuels import for electricity generation	t a^{-1}
State of Feed-in Tariff (wind, solar)	INR MW h^{-1}
Government expenditure per GDP	–

capacity.

4.4. Results and discussion

An ensemble of six models was created. Each of these models reflects one particular realisation of normative contexts. Fifteen thousand computational experiments (2500 experiments per each normative context) were run in total for the specified ranges of uncertainties and from 1990 to 2030 with the time step of quarter of year. The analysis of the results is presented in the following sections.

4.4.1. Comparison of transition pathways across normative contexts

Energy transition pathways were explored in terms of the behaviour of the outcomes of interest, presented in Table 3.

Fig. 2 shows boxplots of the impact of different normative contexts on six outcomes of interest for the range of uncertainties specified in Table 2. The outcomes are coal-, wind-, and solar-generated electricity, net total generated electricity, government expenditure per unit of GDP, and GHG emissions. They were chosen based on their significance for the policy analysis in our case study.

Based on the results shown in Fig. 2, the following conclusions can be made regarding the impact of normative contexts on future transition pathways:

- From Fig. 2(a), the destabilisation of coal systems, in a sense that generation from coal does not significantly grow, is more likely to happen in a market-led sectoral structure in the future. In a market-led future for the electricity sector, the direct support of the government for fossil fuels (i.e. fuel subsidies and government investments) is no longer legitimised, and renewable and fossil fuel resources can compete on a level playing field. However, market-led futures (driven by security or sustainability) come at an expense of having less net total generation capacity (Fig. 2(b)) as a result of the destabilisation (phase out) of fossil fuel energy generation that currently composes 70% of the total installed capacity.
- From Fig. 2(c) and (d), the highest wind generated electricity and lowest total GHG emissions can be achieved in market-led futures. This makes sense considering the long-term preference of actors towards wind over coal in a market-led electricity sector because of the impact of market-based policy instruments, such as renewable feed-in tariff and fossil fuel carbon pricing mechanism. The cost competitiveness of wind turbine technology can also add to this long-term inclination towards wind. The total GHG emissions is then lowered by having more generated electricity from wind and less from coal. Market-led futures also result in lower government expenditure (see Fig. 2(f)) in comparison to government-led futures. This is because of less government funding and investments in the electricity sector.
- Unlike wind generated electricity, market-led futures do not lead to the highest solar electricity, and the maximum solar electricity would be more likely to be achieved in government-led futures and with a normative direction towards energy security or sustainability (see Fig. 2(e)). *First*, this conclusion implies that an equity-driven transition is not favourable for solar electricity because of the primary aim of equity-driven transitions, which is to fulfil the growing electricity demand with a stable source of electricity generation. Conventional sources can outcompete solar (and renewables in general) in this respect by a stable generation of electricity and with a high capacity factor from their installed capacity. *Second*, Fig. 2(e) implies that liberalised market interactions would not be sufficient for achieving the maximum possible increase of solar electricity, and an active participation of the government would be required. This behaviour can be explained by referring to the assumptions we made in the definition of normative contexts in Section 4.2. One assumption was that the domestic technological progress and therefore cost reduction and competitiveness of solar technologies are improved faster in a government-led future supported by proactive localisation and mission-oriented initiates compared to a market-led future in which the government interest is only to regulate competition in the electricity market. Faster technological progress and lower technology cost can increase solar installed capacity significantly. Another assumption was that in a market-led future, feed-in tariff is the main policy incentive for investment in solar electricity, and the private sector is the primary source of investment. This can increase solar generated electricity, but to an extent limited by the availability of private investments and in competition with other sources. However, in a government-led future, meeting national targets set for each specific source is of high priority, and command and control mechanisms, such as Renewable Purchase Obligation (RPO) and Accelerated Depreciation (AD), are sought to secure the realisation of these targets. Also, the development of solar electricity in a government-led future is not only reliant on private investments, and the government is committed to fund and directly invest in new installed capacity. This can further boost the expansion of solar electricity.
- While the presence of direct interventions in government-led futures could boost solar electricity, it would come at some costs. One is the increase in government expenditure and public financial burden (Fig. 2(f)). Another is the increase in coal electricity generation and consequently increased GHG emissions compared to market-led futures (especially in equity-driven transitions). The government has interest to co-invest in coal if they lead energy transitions. This is because of the low investment cost, the huge amount of sunk investment and the high capacity factor in coal power plants.

The impact of deep uncertainties on the wind and solar generated electricity can be discussed from another perspective. Fig. 3 presents the envelope plot of wind and solar generated electricity over time and Gaussian Kernel Density Estimates (KDE) of their end state in 2030. From Fig. 3(a), it is apparent that for every normative context, wind-generated electricity is quite sensitive to the various uncertainties. The impact of deep uncertainty on the final wind electricity generation, in terms of the bandwidth of the future trends (envelope plots) and the density of the final state (KDE curves), is also comparable across the various normative contexts. In other words, uncertainty impacts each of the normative contexts similarly and substantially. The highest density of the final state (i.e. generated electricity in 2030) reaches about 200,000 GWh per annum (see KDE curve). For solar energy, this is different. The impact of uncertainty on the state of solar electricity differs across normative contexts. Government-sustainability and government-security are the contexts which result in the widest bandwidth and a flattened density for the final state in 2030 (see Fig. 3(b)). This implies that if these two normative contexts are followed, there would be a significant uncertainty around the final state for solar electricity.

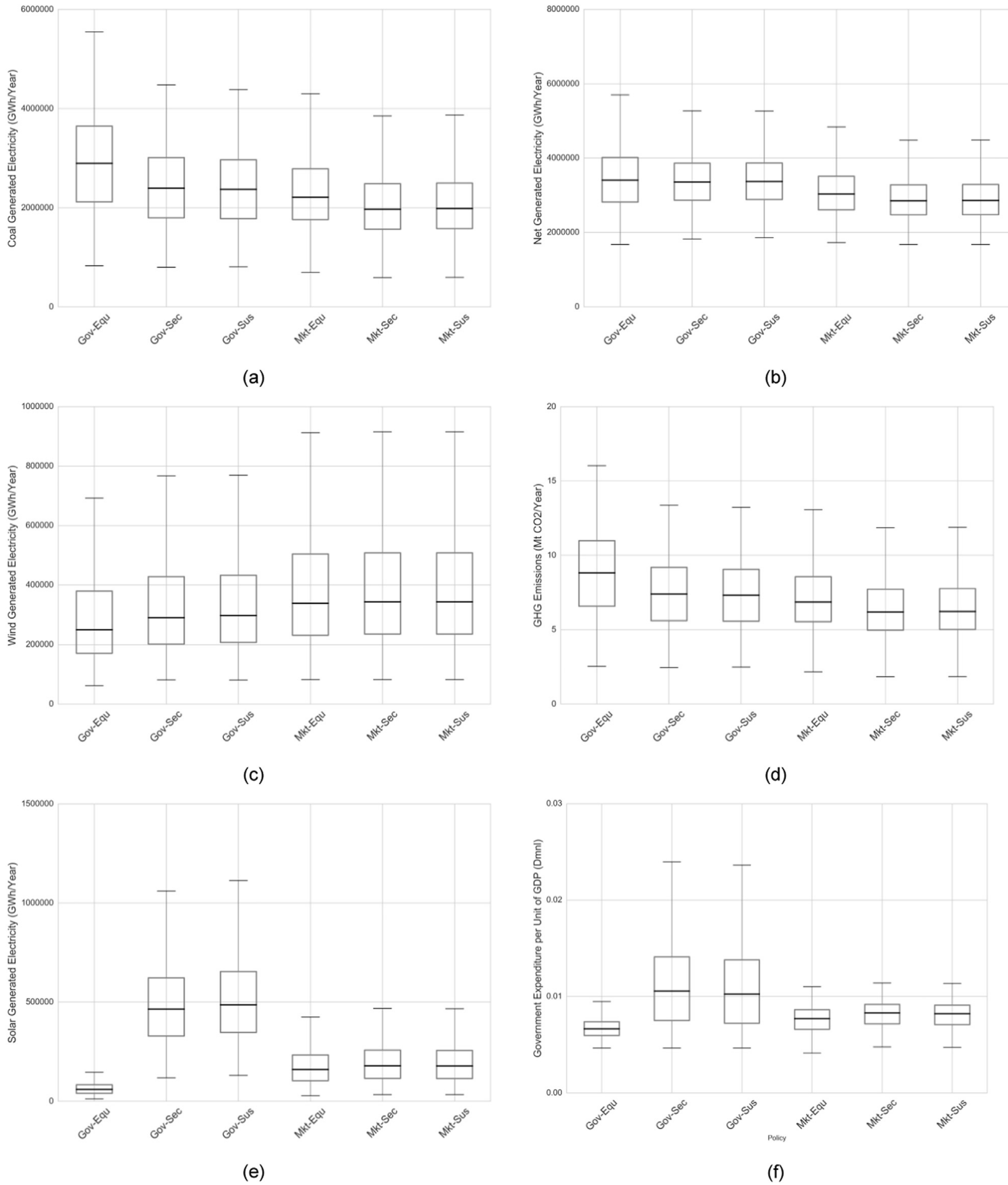

Fig. 2. The state of outputs of interest in different normative contexts in 2030 under deep uncertainty. Gov-Equ: government-equity, Gov-Sec: government-security, Gov-Sus: government-sustainability, Mkt-Equ: Market-equity, Mkt-Sec: Market-security, Mkt-Sus: Market-sustainability.

4.4.2. Required conditions for the realisation of transition targets

Another analysis on the computational experiments was performed by asking:

- Are the targets of the 100 GW solar and the 60 GW wind achievable by 2022?
- If the targets are unachievable, what is the earliest possible time (after 2022) for meeting the targets? and
- Under what conditions (i.e. ranges of uncertainties) are the targets more likely to be realised?

To answer the first and second question, we evaluated how many experiments could meet the target at each time step from 2022 onward.

The results are presented with boxplots, KDEs, and cumulative success curves:

- According to Fig. 4(a) and (e), the earliest possible point in time at which the solar target can be achieved is after 2023. This implies that even under the best conditions, the solar target is unlikely to be

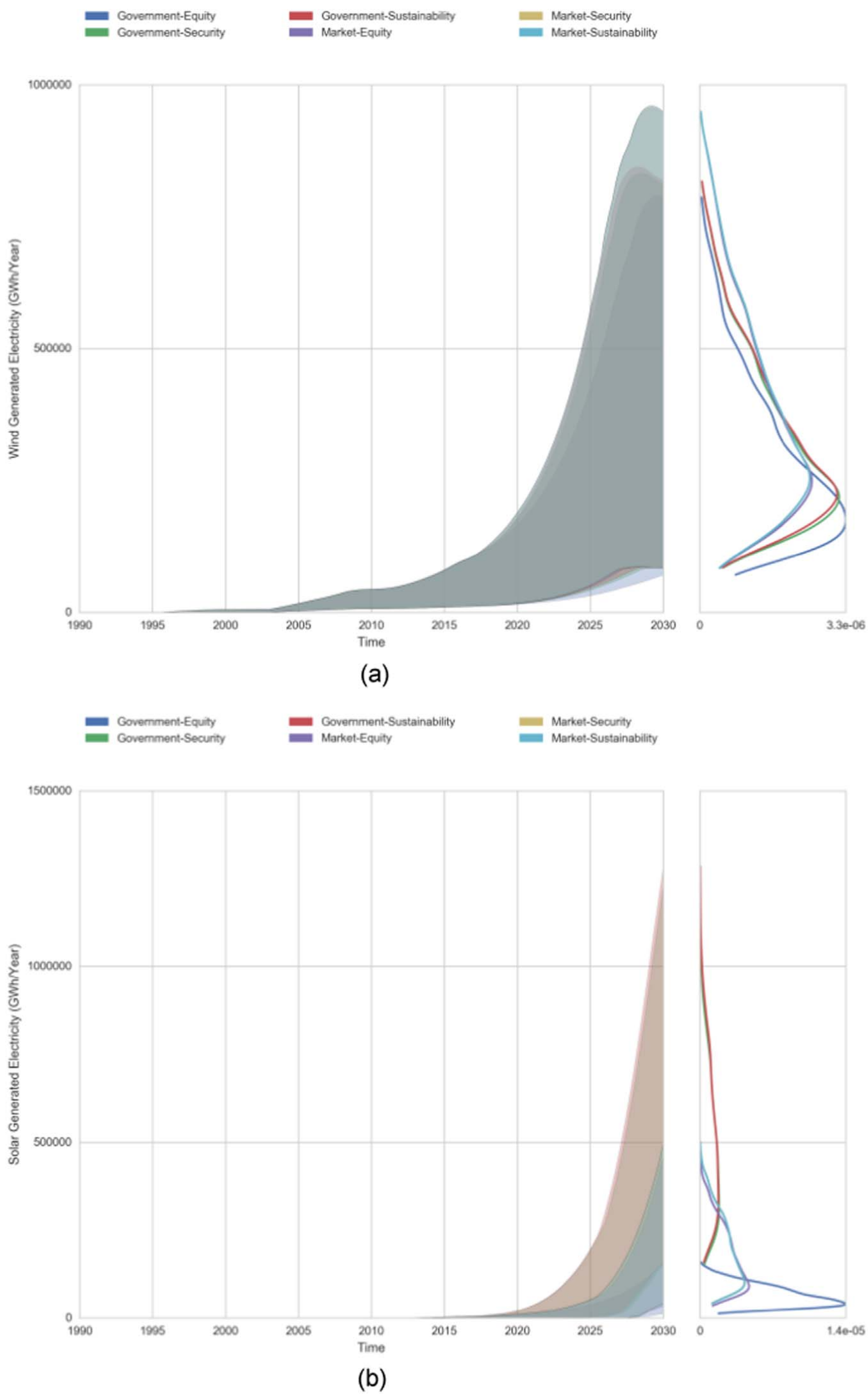

Fig. 3. The impact of uncertainty on (a) wind and (b) solar generated electricity over time and across six normative contexts. The left-hand side plots are the envelope plots of (a) wind and (b) solar generated electricity over time. The right-hand side plots show the Gaussian Kernel Density Estimates (KDE) of the end state of generated electricity from (a) wind and (b) solar in 2030.

realised by 2022 as planned by the government. This, however, becomes increasingly likely to be met from 2023 afterwards. It is also observed from Fig. 4(a) that the median of successful experiments is around 2028. The wind target is more realistic since successful experiments in the cumulative curve take off before 2022 and they peak around 2024, much earlier than the solar target (see Fig. 4(b) and (d)).

- Looking into the peaks in the KDE curve in Fig. 4(c), it is apparent that there is a local maximum for the number of successful experiments in solar around 2025 (which was not visible in Fig. 4(a)) and the global maximum around 2029 (which was already identified in Fig. 4(b)).
- The cumulative curves (Fig. 4(e) and (f)) for solar and wind are peaking at 0.8 and 0.9 respectively, and they do not reach 1 in 2030. This means that there are some experiments where the solar and wind targets are not met even by 2030. Fig. 4(d) shows that the KDE curve for wind slides towards zero by 2030. It implies that there are very few experiments where the target is realised on 2030. In other words, it is very unlikely to have the target met in 2030 if it has not happened before.

To answer the question of ‘under what conditions’, we conducted a PRIM analysis for the solar target for each year between 2025 and 2030. We used PRIM to identify the combination of uncertainties under which the solar target of 100 GW installed capacity is achieved. This gives insights on how the uncertainties that contribute positively to the achievement of the target change over time. It is assumed that the target is not going to be realised by 2022 (see Fig. 4), but it should be

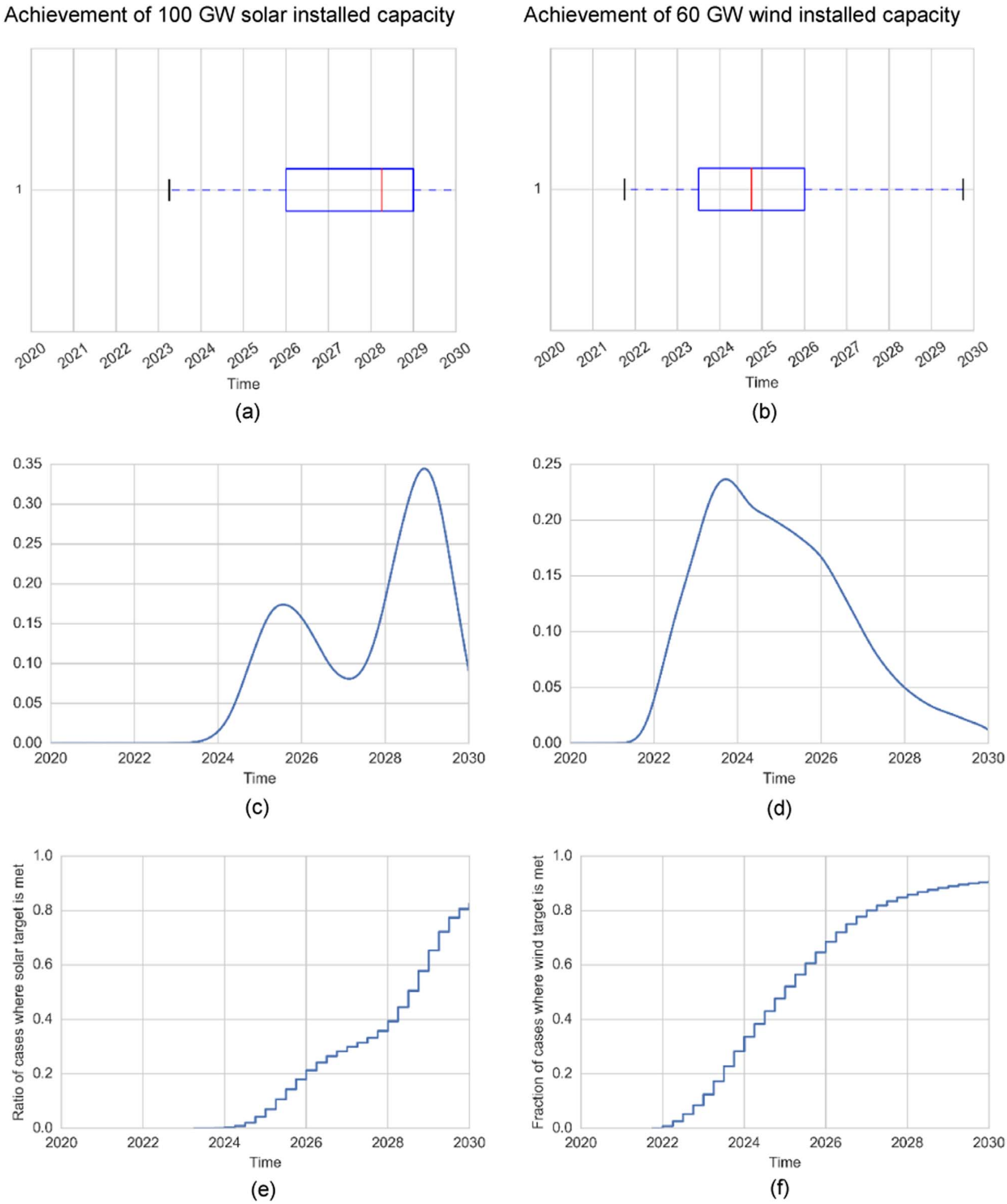

Fig. 4. The distribution of the earliest time that the solar and wind targets are met across 15,000 experiments in six normative contexts. (a) and (b) are the boxplots representing the skewness with min, max, 1st and 3rd quarters and the median; (c) and (d) are the KDE curves representing the number of success cases at each time step, (e) and (f) are the cumulative curves representing the cumulative number of success cases at each time step.

realised at the earliest possible time after 2022. We have left 2023 and 2024 out of the analysis because the number of experiments that meet the target in these years is too low for PRIM to produce meaningful results.

Based on the PRIM-generated boxes (see Fig. 5), sustainability and security always characterise the desired priority of societal needs in a successful transition, i.e. where the solar target is met. The favourable sectoral structure in a successful transitions is government-led. However, this desired sectoral structure changes over time. As we approach 2030, a market-led structure also becomes capable of fulfilling the solar target. Apart from the conditions related to normative conditions, the realisation of the solar target is also dependent on having the wind and

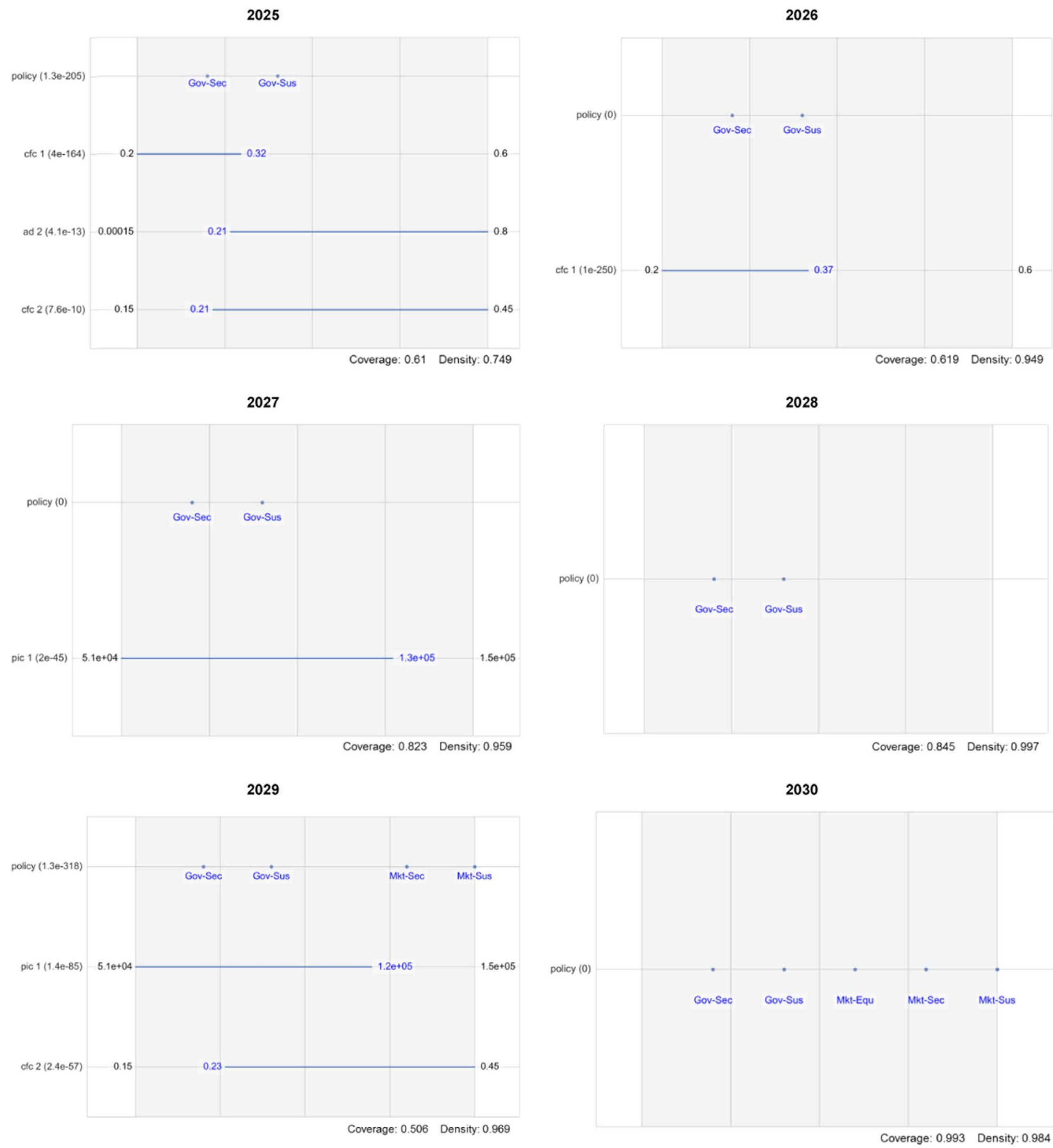

Fig. 5. PRIM results – the dynamics (between 2025 and 2030) of uncertainties required for the realisation of the 100 GW solar. In each plot: the coverage and density of the selected PRIM box are on the top right corner; the acronyms of uncertain parameters (see Table 2) in the selected PRIM box are on the left side of the plot; the statistical significance (p-value) of each identified range of parameter is presented in front of the acronyms and in parenthesis; the full possible range of uncertainty for each parameter is marked with numbers in black colour on the left and right of the grey square; and the accepted range of uncertainty in each parameter for meeting the solar target is identified with lines/dots and numbers/texts.

solar sectors' characteristics (i.e. potential installed capacity and capacity factor) bounded in specific ranges; the ranges which make solar more attractive than wind for investment and electricity generation. The dynamics of the desired conditions can be explained in the two following periods:

- 2025–2028: the solar target in this period is always realised under the government-security and government-sustainability normative contexts. Other desired conditions change in each year. In 2025, the wind and solar capacity factor coefficients (i.e. cfc 1 and cfc 2) should be less than 0.32 and more than 0.21 respectively. This increases the amount of electricity generation from solar and makes it a more attractive option for new investment compared to wind. The presence of the accelerated depreciation policy for solar (i.e. ad 2) over 0.21 is also required. The higher rate of AD for solar reduces the tax cost and makes solar investment more profitable. In 2026, solar generated electricity is highly dependent on the state of wind as its most serious competitor. Wind attractiveness can impede further investment in solar. The realisation of the target in this year demands for a wind capacity factor coefficient (i.e. cfc 1) no more

than 0.37. In 2027, the solar electricity target is still dependent on the state of wind. At this time, the wind potential installed capacity (i.e. pic 1) should not be more than a certain limit (130 GW). And in 2028, no further condition is required and the achievement of the solar target is only dependent on having a government-led security or sustainability-driven normative contexts.
- 2029–2030: In this period, the necessary condition is to have a security or sustainability driven normative direction, no matter whether the sector is coordinated by the government or by the market. In 2029, the wind potential installed capacity (i.e. pic 1) should be less than 120 GW in order to redirect investments from wind towards solar. Moreover, the solar capacity factor coefficient (i.e. cfc 2) should be more than 0.23. A high value for this parameter makes the generation from solar more profitable. All these extra conditions will no longer be required in 2030 except for having the normative direction towards energy security or energy sustainability.

It was observed that PRIM results did not identify a specific range for uncertainty in the learning indices of generation technologies (and therefore technology costs) as the required conditions for the fulfilment of the solar target. Two explanations can be proposed for this behaviour. First, this can be because the ranges of uncertainty, which we set for learning rate parameters (see Table 2), were not chosen wide enough to which model outcomes show high sensitivity. Therefore, those uncertain learning rates were not identified in PRIM results. This could be changed if we would broaden the ranges of uncertainty for the learning rates and would generate our experiments again with the new ranges. Second, this behaviour can be because of the way that the simulation model was structured. The model was developed around the satisfaction of societal needs—demand-supply balance, energy security and sustainability (see Section 3). Learning rates influenced the satisfaction of societal needs in the model structure only indirectly and through sequential impacts on levelised cost of electricity, generation profit, installed capacity, and the amount of generated electricity (see Appendix B). This indirect chain of causal relations in the model structure decreases the correlation of the behaviour of model outcomes to the range of uncertainty in learning rates in our generated experiments. This could be changed if we would perform our computational experiments again with several alternative model structures, including the one that specifically emphasises the role of learning curves.

5. Open-ended exploration of transition pathways

5.1. Procedure and implementation

While the qualitative narratives of normative contexts can guide the exploration process, they can be also constraining in the incorporation of deep uncertainty around future pathways by proposing definitive and limited frames for future behaviour and by preventing us from proposing other alternative pathways. To address this limitation, this section takes a bottom-up approach in generating future scenarios. It explores open-ended futures for the extensive list of normative contexts, where a sectoral structure between government and market and simultaneous priority of multiple societal needs are possible. We defined continuous ranges (unlike the six sets of discrete values that we had in Section 4.2) for the model parameters characterising normative contexts in Table 4. In the case of open-ended exploration, narratives do not limit the exploratory process. Instead, the conceptual framework that they provide is used afterwards for interpreting the results. The open-ended exploration is recommended when there is no agreement (i.e. uncertainty) on future normative contexts. It results in a broader picture of futures, more inclusive of possible shocks and surprises, and more robust decisions about future actions. However, it is challenged by the presence (and interpretation) of huge amount of data generated by the vast number of uncertainties.

The analytical technique used is multi-dimensional clustering of computational experiments analogous to Gerst et al. (2013). The clustering is useful when scenarios depend on the behaviour of multiple outcomes of interest and when there is no clear threshold for the desired outcomes' behaviour to distinguish between experiments. The use of clustering can be contrasted to the imposition of *a priori* rules for clustering as used by Guivarch et al. (2016), Rozenberg et al. (2013).

The following steps were taken to investigate the open-ended future scenarios:

- A set of outcomes of interest, meaningful for future scenarios, is selected. Outcomes should not be necessarily correlated with each other although uncorrelated outcomes make the clustering harder.
- We sample over both the uncertainties associated to normative contexts and the previous list of the uncertainties (see Table 2) jointly, in order to generate a large ensemble of plausible futures.
- We identify clusters of similar futures using a Gaussian Mixture Model (GMM), i.e. a probabilistic model that explains the state of outcomes with a mixture of Gaussian distributions (clusters) with unknown parameters (McLachlan and Peel, 2004). To select an appropriate number of clusters, we use two information criteria, namely Bayesian Information Criterion (BIC) and Aikake's Information Criterion (AIC).
- For each cluster, we perform a PRIM analysis (multi-dimensional scenario discovery) to identify the combination of uncertainties that is responsible for generating the results in the cluster.
- The results of the combined clustering and PRIM analysis are interpreted in narratives through the lens of theoretical concepts presented in Section 3. Narratives use the values of outcomes to describe the state of electricity systems and the satisfaction of societal needs in the electricity sector. They also use PRIM analysis results to interpret internal and external driving forces of transition.

5.2. Identification of uncertainties

In addition to the uncertainties discussed in Table 2, those related to normative contexts are included too (see Table 4). The minimum and maximum values of these uncertainties are set based on a sensitivity analysis and in a range that ensures that the model outcomes remain in a meaningful range.

5.3. Results and discussion

Three thousand computational experiments were run for the ranges of uncertainties in Tables 2 and 4. These uncertainties impact the state of model outcomes in the future. The impact of deep uncertainty on generation per capita, installed capacity, and reduction in investment costs is different for different sources in the future (see Appendix E). To identify future scenarios and to understand the conditions contributing to these scenarios, we clustered the results using a GMM. The outcomes of interest, on which the future scenarios are based, are the installed capacity in coal, wind, and solar sectors. The appropriate number of clusters, corresponding to the lowest BIC, is five. Each cluster implies a certain future behaviour of energy system. Fig. 6 shows the distribution of the simulated experiments in the three outcomes of interest and the clusters formed based on their proximity. The combination of uncertainties that explains the behaviour of each cluster was identified using multi-dimensional scenario discovery. With these generated clusters, five different scenario narratives were explored (see Figs. 6 and 7). Each scenario narrative describes the state of different sources of electricity generation, the fulfilment of the societal needs, and the conditions (internal and external driving forces) required to realise each scenario in the time horizon of 2030.

5.3.1. Solar-dominated pathway

Cluster 1 is a 'solar-dominated pathway'. Solar electricity becomes the dominant system followed by coal, and wind. Coal does not grow

Table 4
Ranges of uncertainty corresponding to the normative contexts.

Parameter	Name	Range of uncertainty
Sensitivity of satisfaction of societal needs to demand-supply balance	future ec	0.001 – 0.08 (–)
Sensitivity of satisfaction of societal needs to GHG emissions	future er	0.01 – 0.07 (–)
Sensitivity of satisfaction of societal needs to fuel import	future ps	0.01 – 0.09 (–)
External effect of national vision and targets on government funding and investment in:		
coal,	fvt;	0.03 – 0.09 (–)
gas,	fvt 0;	0.024 – 0.037 (–)
wind,	fvt 1;	0.053 – 0.093 (–)
solar	fvt 2	0.01 – 0.4 (–)
External impact of fossil fuel price's shocks on:		
Coal,	fps;	0.01 – 0.29 (–)
Gas	fps 0	0.02 – 0.22 (–)
External effect of market liberalisation on public and private investments	future mli	0.01 – 0.8 (–)
External effect of market liberalisation on the sensitivity of generators to profit	future mlg	0.001 – 0.03 (–)
External effect of market liberalisation on the sensitivity of distributors to profit	future mls	0.001 – 0.4 (–)
External effect of market liberalisation on the sensitivity of generators to payment security	future mld	0.001 – 0.55 (–)
Impact of the internal performance of the system on the rate of FIT	constant wif	0.01 – 0.05 (–)
Impact of the internal performance of the system on the rate of RPO	constant wir	0.01 – 0.05 (–)
Impact of the internal performance of the system on the rate of AD	constant wia	0.01 – 0.09 (–)

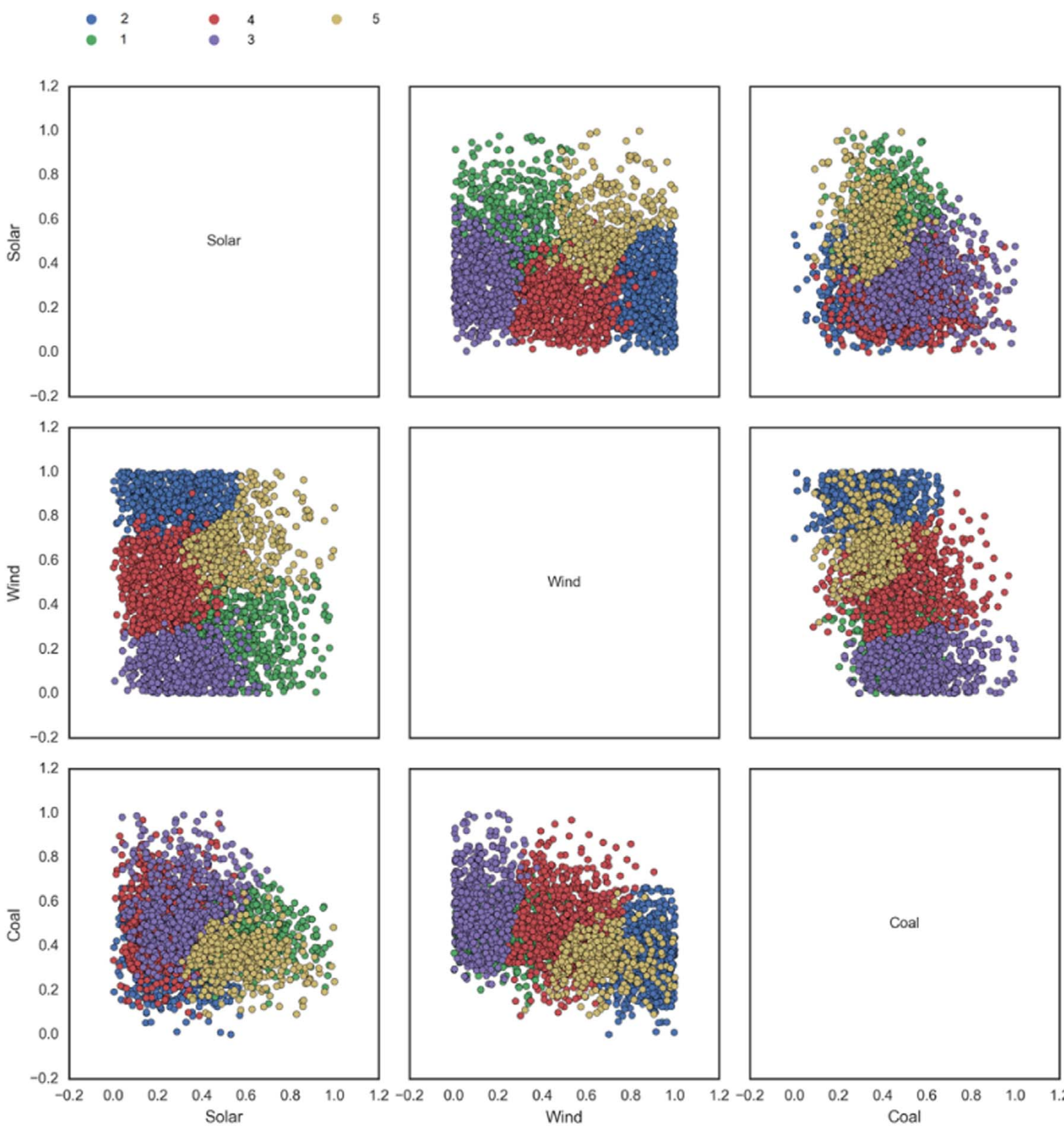

Fig. 6. Pairwise scatter plot showing the position of classes (in different colours) with respect of the installed capacity of coal, wind and solar.

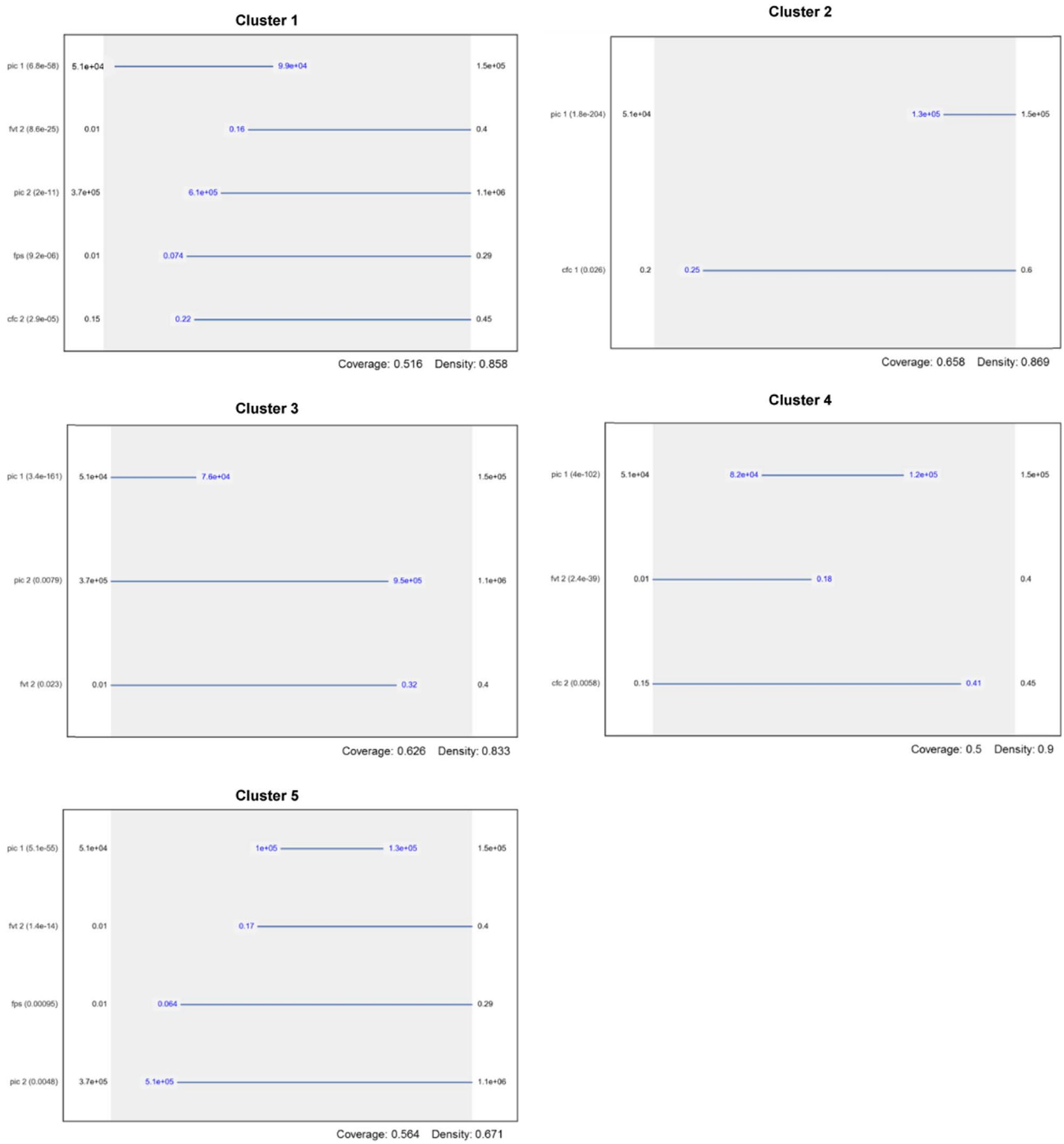

Fig. 7. PRIM results representing the uncertainty conditions in each cluster.

significantly in this scenario, but it can still be considered an established system because of its share in total installed capacity. Wind growth can be achieved to some extent while it will remain a marginal energy source compared to solar. In terms of the satisfaction of the societal needs, the electricity demand would not be satisfied completely as the renewable capacity factors (and the renewable generation subsequently) are much less than the capacity factors (and generation) of conventional sources. However, the emissions and fuel imports are expected to be low due to more renewable and less fossil electricity generation. This scenario depends on some uncertainty conditions. One is that solar needs to become competitive to wind (as the current prior source of renewable) and to coal (as the current regime of the sector). To make solar competitive, wind should not have a high potential installed capacity (i.e. pic 1). This makes the further exploitation of wind costly (or impossible) and gives more chance to solar to use the limited budget and investment resources and to grow. Second, the effect of fossil fuel price shocks (i.e. fps) on conventional systems should be high. This increases the investment cost of coal compared to solar. Third, the solar capacity factor (i.e. cfc 2) and potential installed capacity (i.e. pic 2) should take high values within their ranges of uncertainty. This improves solar generation and the profit for generators and allows the maximum exploitation of the resource. The government should also lead the transition by setting ambitious targets and actively intervening in the development of solar electricity through funding and investment (i.e. fvt 2).

5.3.2. Highly-utilised wind pathway

Cluster 2 is a 'highly-utilised wind pathway'. Wind installed capacity can grow significantly though it cannot be the dominated system as the wind maximum installed capacity is substantially lower than the coal and solar potential capacities (See Table 2). Coal and solar can vary from a minimum to a moderate level of installed capacity depending on uncertainties. In terms of the satisfaction of societal needs, a higher wind capacity factor (compared to solar) results in more generated electricity (compared to Cluster 1). The emissions and fuel imports are low as the sector is not primarily dependent on conventional sources. The main conditions contributing to this scenario is that the wind potential installed capacity (i.e. pic 1) and the wind capacity factor (i.e. cfc 1) take high values in their range of uncertainties in order to keep wind electricity competitive to solar and coal.

5.3.3. Coal-dominated pathway

Cluster 3 is a 'coal-dominated pathway'. Coal will remain the main source of electricity generation with the highest installed capacity. Wind and solar will be marginal sources of energy although solar is more likely to have higher installed capacity compared to wind due to the higher potential installed capacity. In the coal-dominated pathway, generation will be high, but fuel imports and emissions remain high too. The main uncertainties responsible for this scenario are low values for wind and the solar potential installed capacities (i.e. pic 1 and pic 2), less government investment, and less direct support for solar electricity (i.e. fvt 2). This condition keeps the electricity sector in the status quo where coal dominates other generation sources.

5.3.4. Coal-dominated pathway with wind moderate penetration

Cluster 4 is a 'coal-dominated pathway with the moderate penetration of wind'. This is a situation similar to Cluster 3, but with the possibility of having wind as an established system too. Generation, emissions, and fuel imports will be less in this scenario in comparison to a coal-dominated sector. One necessary condition is not to have high government support in favour of solar (i.e. fvt 2) as well as a high solar capacity factor (i.e. cfc 2) in the future. This allows coal and wind to compete with solar on a level playing field, to be economically efficient, and to grow in the electricity sector. Other conditions are to have a moderate range of potential installed capacity for wind (i.e. pic 1).

5.3.5. Renewable-dominated pathway

Cluster 5 is a 'renewable-dominated pathway'. Solar will be the dominant source of electricity generation followed by highly utilised wind. Coal will not be significant in comparison to the share of renewables. In terms of satisfaction of societal needs, due to dependency on renewable sources, generation cannot be high. However, emissions and fuel imports are expected not to be high too. This scenario is more likely to happen if the impact of fossil fuel's price shock on coal is high (i.e. fps). There should also be supportive government interventions (i.e. fvt 2) and high potential installed capacity (i.e. pic 2) for solar. The potential installed capacity for wind (i.e. pic 1) needs to be in the moderate range of uncertainty.

6. Conclusions

Deep uncertainty surrounding future transition pathways can challenge the success of government interventions which are designed under deterministic assumptions. This paper argued that energy transition pathways under deep uncertainty should be analysed from a narrative-informed exploratory analysis approach to address this challenge. Three potential contributions of narratives to exploratory analysis of transition pathways were discussed: narratives as underlying conceptual framework for transitions models; narratives for framing the exploration of the future; and narratives for interpreting exploratory modelling results and for better transmitting policy insights.

The suggested approach was applied to a case study of possible transitions in India's electricity sector. The results from the case study can inform energy policy makers in India about the plausible futures of electricity sector and solar electricity as the currently most promising renewable option of this country. Through the exploration of computational experiments, we showed that the government 100 GW solar target could not be met by 2022 although it is most likely to be achieved around 2028. This implies that the government target for solar electricity is not realistic. The government should be informed of this likely delay and to reduce this delay by confronting it with proactive measures. The government, however, could be able to meet the solar target earlier than 2028 if it leads and coordinates the transition by active interventions rather than by relying only on market forces and if it directs the transition towards the satisfaction of sustainability and security needs prior to equity need. The higher efficacy of a government-led transition (over market-led transitions) can be explained by governmental mission-oriented programs which bring faster localisation of global technological progress and larger cost reductions. This efficacy is also because of the stronger commitment to the fulfilment of targets and the presence of direct government investment. The priority of sustainability and security needs (over equity) is because of their emphasis on the clean and less fuel import-dependent generation of electricity rather than only the stable and abundant generation of electricity for the growing demand.

Based on the open-ended exploration of future pathways, we showed that even under the current government policy settings, which are designed to be supportive of renewables, several divergent scenarios could dominate the future of India's electricity sector. This implies the importance of taking proactive measures by the government for directing energy transitions towards a desired destination, dominated by solar electricity. The results of PRIM analysis suggested these measures to be around: making solar electricity a more attractive option for investment compared to other renewable sources (especially wind), supporting solar electricity against cheap conventional sources by removing price control and subsidies for fossil fuels, and localising technological progress and improving the capacity factor and efficiency of solar installed capacity to increase the generation profit.

This study faced some limitations. The first methodological limitation of this study was that the narratives of future scenarios did not take into account policy makers' opinion in a participatory process. Policy makers provide important perspective and have insight into additional sources of relevant information. In our application, narratives were developed based on the results of exploratory modelling and using concepts from sustainability transitions. Policy maker participation is possible in various steps of our suggested approach, such as in delineating the transition process in model development, identifying critical uncertainties and their potential ranges of variation, validating outcomes, and interpreting the generated quantitative results. Policy makers are also a key audience for exploratory modelling outcomes. Engaging policy makers in the implementation process enhances the trust in suggested decision insights and encourages deliberation and learning from different perspectives among actors.

Another limitation of this study was in the implementation of our approach in the case study. Historical narratives helped us to inform model structure and to guide the exploration process, but they could also constrain the assumptions that we included in the model structure. Different historical narratives can result in various assumptions, and relying on only one historical narrative can simplify exiting uncertainties. By the exclusion of uncertainty in historical narratives, some plausible transition pathways, which could eventuate in the 'real' future, are ignored. In the same manner, uncertainty in the model structure (scenario generator) was not also considered in our exploratory modelling process. The same historical narrative could be modelled differently, for example based on different theoretical frameworks or with different modelling techniques. It is, therefore, suggested as future research to use assumptions from a variety of narratives and to develop different model structures (based on different theoretical frameworks and modelling techniques) to address these aspects of uncertainty better.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.08.019.

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