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TOPICAL REVIEW

Climate-aware decision-making: lessons for electric grid infrastructure planning and operations

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Abstract

Climate change poses significant risks to large-scale infrastructure systems and brings considerable uncertainties that challenge historical planning approaches. Here we focus on how climate awareness might be better incorporated into planning and decision-making in the electric power sector. To do so, we consider lessons from decision science literature where researchers have specifically focused on how to make better decisions under uncertainty. We perform a three-part review: of decision science literature on best practices for decision-making under uncertainty, of industry practice documents to understand how new uncertainties may affect the types of decisions electric utilities are making today, and of literature on electricity sector planning under climate change to assess how lessons from decision science might fit into sector-specific analyses. We discuss how characterizations of uncertainty from the decision science literature might guide approaches in the electricity sector to appropriately capture climate-related uncertainties. We also distill three key ideas from the decision science literature that can be incorporated into electricity sector planning to manage these new uncertainties: robustness, adaptive planning, and multi-stakeholder engagement. We offer example recommendations for how these key ideas might be incorporated into one essential type of planning activity, capacity expansion.

1. Introduction

Changing climate patterns have already begun to strain society's infrastructure systems, and projected trends in ambient and extreme conditions portend significant stresses in the coming years. Billions of people worldwide rely on large-scale infrastructure systems, such as electric power, water, and transportation, for their daily needs. Despite considerable attention on documenting the mechanisms and potential impacts of climate change on these systems, more work is needed to incorporate climate awareness into actual planning decisions, which today often rely on historical data and outdated assumptions (Gerlak *et al* 2018).

We focus here on electric power systems, which are affected by climate and weather patterns in myriad ways and face ongoing and acute stresses from changing conditions (Ward 2013, Chandramowli and Felder 2014, Panteli and Mancarella 2015, Craig *et al* 2018, Brockway and Dunn 2020, Perera *et al* 2020). Centralized electric grids consist of generation and delivery infrastructure that supplies electricity to end-use customers. Recent events—such as widespread service interruptions and price spikes due to cold weather in Texas in February 2021 (Busby *et al* 2021, Doss-Gollin *et al* 2021); in California, heat-related rolling blackouts in August 2020 as well as grid-caused wildfires and associated power shutoffs intended to prevent additional fires from 2017 to 2021 (Dale *et al* 2018, Abatzoglou *et al* 2020, Wolak 2021); and extensive storm-induced outages in New Orleans in late summer 2021 (Blau *et al* 2021)—demonstrate that system planning and operational practices have not adequately accounted for climate change. Such events jeopardize the electric sector's core goals of safety, reliability, and cost-effectiveness. We define resilience here broadly, as the ability to preserve these goals without significant disruption and/or impact on customers, and to return to safe, reliable, and cost-effective operation quickly if disruptions occur.

Building climate awareness into electricity sector planning and decision-making is far from straightforward. Current planning processes commonly focus on predicting a likely future in terms of electricity demand, weather conditions, and technology options, and identifying investments that are expected to achieve specified reliability targets under those planning assumptions. Changing climate conditions and associated uncertainties—including those related to infrastructure impacts, policy and regulatory actions, and consumer behavior—challenge this underlying deterministic premise (Grubler *et al* 2011, Chattopadhyay *et al* 2016, Moallemi and Malekpour 2018). Yet openings may now exist to rethink planning approaches, as high-profile service disruptions have focused public, regulatory, and legal scrutiny on electricity sector planning and preparedness (Lacommare *et al* 2017, Gundlach 2020). In response, some electric utilities have begun producing vulnerability assessments to evaluate where their systems may face specific threats (PG&E 2016, Ralff-Douglas 2016, ConEd 2019c, McMahan and Gerlak 2020).

A major barrier to change is that the uncertainties inherent in future climate trajectories and their implications require a deeper grappling with the unknown than is present in electricity sector planning today. While electricity sector planners have always had to make decisions in the context of uncertain future conditions (e.g. those related to demand growth, technological innovation, fuel prices, etc), existing practices to account for uncertainty rely extensively on historical trends and expert intuition honed in the context of previous climate conditions (Kuhn and Madanat 2005). In the face of climate uncertainty, these approaches will no longer hold. Making better decisions in the face of these uncertainties will require taking stock of the available science and integrating it into planning processes, evaluating existing baked-in assumptions and revising where needed, considering compounding impacts, and reviewing expectations about acceptable levels of risk and resilience (Linkov *et al* 2014, Craig *et al* 2018, Brockway and Dunn 2020). Separately, decision science researchers have focused on how we can make better decisions even with significant uncertainties, and concepts from decision science can help provide systematic ways of accounting for them. Here, we review their insights in the context of advancing climate-aware planning in the electricity sector.

We perform a three-part literature review with the goal of making pragmatic recommendations on how climate awareness can be better incorporated into electricity sector planning today. First, we review academic and grey literature in decision science and its applications to assess best practices for decision-making under climate-induced uncertainties as well as tools to manage uncertainty in planning processes. Next, we review industry practice documents from two electric utilities to ground ourselves in the types of decisions made now and consider how potential new uncertainties created by climate change may impact those decisions. Then, we review literature on electricity planning under climate change to assess how decision science insights may be implemented in this space.

We assess how climate-induced uncertainties in the electricity sector fall within decision science frameworks used to categorize uncertainties. Such frameworks provide insights about how these uncertainties may be appropriately captured in planning models, and indicate that methods designed for handling deep uncertainty should be employed. We further distill three key ideas from the decision science literature: robustness, adaptive planning, and multi-stakeholder engagement, and assess how these build on current practices in the electricity sector. We discuss how the electricity sector could incorporate these ideas into industry practices, and highlight existing approaches that can form a scaffolding for climate-aware planning. Further, we focus in on one category of electricity sector decision-making—capacity expansion planning—and provide tangible examples of how climate awareness can be better incorporated via the key ideas identified from decision science. We suggest that embracing the concept of multiple plausible futures, setting up signposts that identify tipping points as the future evolves, and involving boundary organizations to help translate insights between climate science and electricity planning can help electricity sector decision-makers better plan for the future. In doing so, we bring together insights from three fields: decision science, electricity systems, and climate science, to advance how decision-makers in critical infrastructure sectors might rethink planning processes to better prepare for climate change.

2. Methodology

2.1. Decision science review

Decision science refers to the process of how individuals and organizations make decisions based on available information. It is an interdisciplinary field that draws on theories from economics, operations research, forecasting, behavioral science, and statistics. Growing complexities in infrastructure planning due to climate uncertainties have spurred the development of planning approaches that borrow theories from this field (Kwakkel and Van Der Pas 2011). The new planning approaches aim to provide planners with a more holistic view and assist in solving 'wicked' problems in infrastructure planning.

We reviewed both academic and grey literature on decision-making processes related to climate adaptation and resilience policy across critical infrastructure sectors. We focus on how uncertainty can be incorporated during the modeling process, rather than on how these frameworks might be implemented within regulatory entities.

For the academic literature, we used 14 combinations of search terms in Scopus (supplementary table 1). This yielded a total of 1018 peer-reviewed journal papers. We then removed duplicates and reviewed the abstracts using the following inclusion criteria, keeping only papers that met all of the criteria:

(a) The paper considers climate as a source of uncertainty.
(b) The paper is related to planning for an uncertain future or adaptation strategies in a critical infrastructure sector, or it is a review of decision-making frameworks in the context of critical infrastructure planning or adaptation planning.
(c) The paper was published after 2000 and is presented in English.

This selection process left us with 86 papers in our full text review, for which criterion (a) was a primary limiting factor. We then identified concepts and techniques used to handle uncertainty in each paper and categorized them into overarching concepts with associated techniques.

Our focus on decision-relevant planning approaches prompted us to also review the grey literature, where innovations by practitioners working in critical infrastructure sectors may be documented. We used four combinations of search terms (supplementary table 2) in three databases: Adaptation Clearinghouse, Climate-ADAPT and US Climate Resilience Toolkit. These databases contain a rich set of public documents produced by government agencies and nonprofits with a specific focus on climate adaptation. Down-selection was performed via the filtering functions embedded in each database rather than through keyword searches.

This search yielded 109 reports across the three databases. We then removed duplicates and reviewed report summaries using the following inclusion criteria, keeping only papers that met all of the criteria:

(a) The report considers climate as a source of uncertainty.
(b) The report is a planning or guidance document that discusses the decision-making process to address climate change for critical infrastructure planning (reports such as vulnerability assessments or climate impact studies are not included).
(c) The report was published after 2010.

This selection process left us with 15 reports for full text review. We then identified concepts and techniques used to handle climate uncertainty in each report and categorized them into overarching concepts with associated techniques.

2.2. Industry practice review

To better understand the ways that climate change may impact the electric power sector, we aim to document the types of decisions that electric utilities are making today. In the United States, roughly three-quarters of electricity customers are served by investor-owned utilities (IOUs) (Energy Information Administration 2019). IOUs operate as regulated monopolies, with their investment decisions and customer rates overseen by state public utility (or public service) commissions in general rate case (GRC) proceedings. These proceedings are rich sources of public information on how electric power systems are maintained, operated, and invested in today. As these documents are extensive, we select just two utilities to compare in order to keep our scope manageable. In selecting these utilities, our criteria include: (a) geographic diversity, (b) large utilities that serve a mix of customer types (including both urban and rural representation), and (c) utilities that have been heavily impacted by extreme weather events.

We focus here on two utilities: Pacific Gas and Electric (PG&E), which serves approximately 16 million customers in urban and rural Northern California, and Consolidated Edison (ConEd), which serves over 3 million customers in the New York City area. Notably, PG&E and ConEd have already been significantly impacted by climate change: increasing wildfire activity in California and Hurricane Sandy in New York have drawn scrutiny to utility operations and focused attention on electric system safety and resilience. Here, we review the 2020 GRC filings of both utilities, focusing attention on electric power system operation and energy delivery. The approved costs and rates in these GRC filings set utility spending and investment thresholds for 3 years, from 2020 to 2022.

For PG&E, we focus on the utility's filing requesting cost recovery for 2020 spending, as approved by the California Public Utilities Commission (CPUC) (CPUC 2020b). For ConEd, we focus on the joint proposal documenting the results of a settlement agreement on utility spending from the utility and other stakeholders (ConEd 2019b), expert testimonies that provide additional context about utility planning and investments (ConEd 2019a), a report documenting anticipated capital expenditures (ConEd 2020), and the approval from the New York State Public Service Commission (NYPSC 2020). For both utilities, we seek to identify where and how they propose to invest in their systems and the decisions they are making about them. We code investment decisions by activity area (see supplementary note 1), then summarize current utility practices within each space. For each activity area, we identify emerging uncertainties that will affect electric power system planning going forward.

2.3. Electricity sector planning under climate change review

We performed a literature review of papers related to electricity sector planning that also consider climate change. Search terms used are summarized in supplementary table 3 along with the number of papers these terms returned in Scopus. From the initial returned list of papers, we removed duplicates and papers written in a language other than English, which left us with 683 total papers. Then we reviewed the abstracts using the following inclusion criteria:

(a) We filtered out papers whose primary focus was not relevant to planning for electricity infrastructure and/or did not include some consideration of climate change or sustainability.
(b) We removed papers with a primary focus on modeling only one area of energy systems (e.g. building energy use, energy demand, solar photovoltaic generation), or where electricity infrastructure was not a major focus of the paper.
(c) We removed papers that focused on describing climate change impacts rather than planning for them or on resource characterization (e.g. solar availability).
(d) We focused on electricity system planning in geographic areas with developed grid systems, though we did include some papers looking at decentralized electricity systems as an option.

Following this down-selection process, we were left with 168 papers. We then reviewed the papers to identify how the authors handle climate change and uncertainty and whether and how they incorporated the key concepts identified in the decision science review. While reviewing, we also sorted the papers into topic areas (table 5).

3. Results and analysis

Decision science researchers have developed approaches that can help advance how electricity sector decision-makers may consider and address climate-induced uncertainties. Here, we focus first on uncertainty characterization (section 3.1), then evaluate how different types of uncertainties may emerge in the electricity sector (section 3.2) and how they may impact electric utility practices and decisions (section 3.3). Then, we consider key concepts from decision science that may be used to manage uncertainty in planning processes (section 3.4) and evaluate the extent to which these show up in literature on electricity sector planning (section 3.5). Sections 3.1 and 3.4 are based on our review of the decision science literature (section 2.1); sections 3.3 and 3.5 are based on our review of the industry practice (section 2.2) and electricity sector planning (section 2.3) literatures, respectively. Section 3.2 draws from our review of all three areas of literature.

3.1. Characterizing climate-related uncertainties

There are many different classifications of uncertainty and debates about their characterization and importance (Kujala *et al* 2013), so a standard framework or taxonomy for uncertainty in the context of climate change and infrastructure planning does not exist[5]. This lack of distinction leads to confusion and impedes clear communication about uncertainty to decision-makers. Climate uncertainty is also often perceived differently by decision-makers and scientists (Berkhout *et al* 2014, Döll and Romero-Lankao 2017). We aim to reconcile some differences in interpretation by classifying uncertainties in a decision-relevant context. Specifically, we approach uncertainty from a modeling perspective and distinguish the technical methods used to treat uncertainties. We expand upon work done by Hawkins and Sutton (2009) and Kwakkel *et al* (2010) and frame uncertainties in a grid planning context.

Uncertainty is generally defined as incomplete knowledge and/or disagreement about what is known or even knowable (Walker *et al* 2010, Kunreuther *et al* 2014). Five levels of uncertainty were proposed by Kwakkel *et al* (2010) (figure 1). These levels correspond to different degrees of numerical certainty, which constrain how information can be appropriately represented in models and analyses.

- Level 1 uncertainty (shallow) represents a situation when a reasonable estimate of the outcome is possible. This uncertainty may be appropriately captured with a point estimate and a range of possible deviations (e.g. tomorrow's electricity demand will peak at 5:30 p.m., +/− 5 min).
- Level 2 uncertainty (shallow) refers to an uncertainty that can be reliably described through statistical terms. One can capture level 2 uncertainty through forecasting techniques (scenarios) with associated probabilities (e.g. a new generation plant is 70% likely to be operational this year, 30% likely to be delayed). Analyses may appropriately assume that historical data can be used to develop reliable future forecasts.
- Level 3 uncertainty (shallow) are situations with known multiple alternatives where it is possible to rank the alternatives by perceived likelihood, but no probabilities can be reliably assigned

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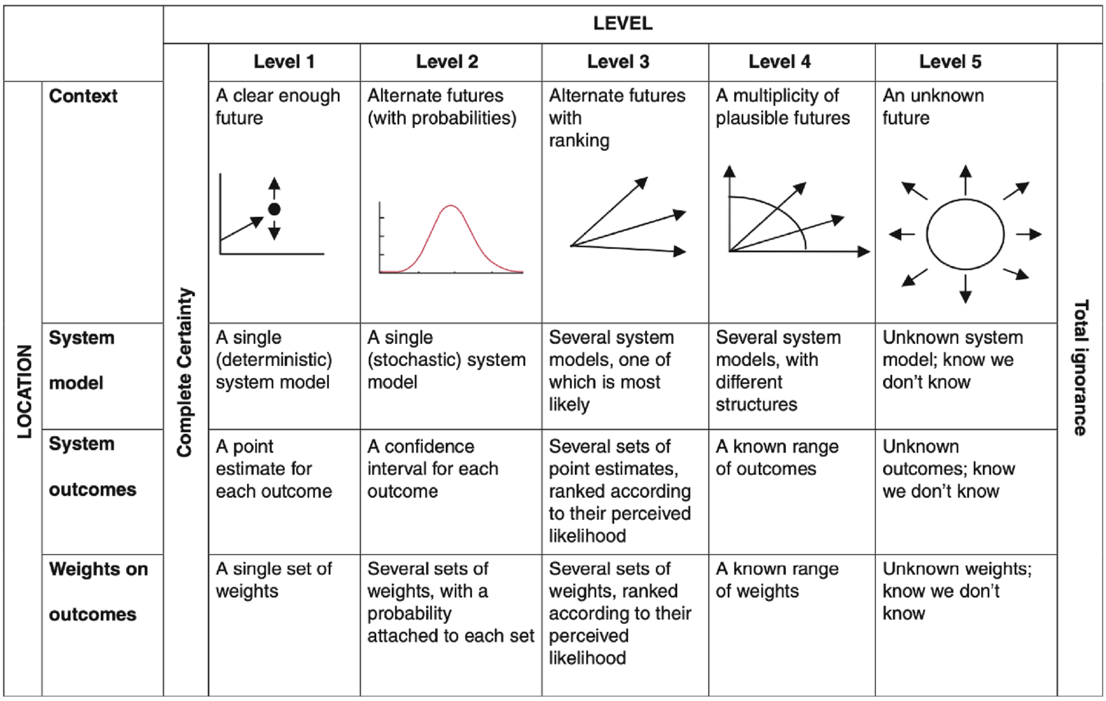
[5] Uncertainties are commonly categorized as either aleatory (random variability in the system) or epistemic (lack of knowledge about the system) across different disciplines (Kunreuther *et al* 2014). However, this categorization may not offer an adequate delineation in the context of climate-aware decision making as their distinctions are blurry, and many uncertainties have characteristics of both (Fletcher *et al* 2018).



		LEVEL						
		Complete Certainty	Level 1	Level 2	Level 3	Level 4	Level 5	Total ignorance
LOCATION	Context		A clear enough future	Alternate futures (with probabilities)	Alternate futures with ranking	A multiplicity of plausible futures	An unknown future	
	System model		A single (deterministic) system model	A single (stochastic) system model	Several system models, one of which is most likely	Several system models, with different structures	Unknown system model; know we don't know	
	System outcomes		A point estimate for each outcome	A confidence interval for each outcome	Several sets of point estimates, ranked according to their perceived likelihood	A known range of outcomes	Unknown outcomes; know we don't know	
	Weights on outcomes		A single set of weights	Several sets of weights, with a probability attached to each set	Several sets of weights, ranked according to their perceived likelihood	A known range of weights	Unknown weights; know we don't know	

Figure 1. Levels of uncertainty. Reproduced from Walker *et al* (2013b), with permission of Springer Nature.

(Patt and Dessai 2005). One can appropriately capture level 3 uncertainty with trend-based scenarios that reflect different assumptions of the driving force (e.g. three trend-based scenarios of electric vehicle demand, based on three different assumptions about product costs).

- Level 4 uncertainty (deep) are situations with known multiple alternatives but where ranking the alternatives in terms of likelihood is not possible, potentially due to inadequate data or decision-makers' disagreement on the rankings (e.g. an optimal location for building new generation in 2030, given demand patterns, population growth and movement, community impacts, and land-use change). Analysts may struggle to specify the appropriate models, select the probability distributions to represent uncertainty about key parameters in the models, and/or to value the desirability of alternative outcomes (Lempert *et al* 2003).
- Level 5 uncertainty (deep) represents the deepest level of recognized uncertainty. We can only acknowledge that we do not know.

These levels can be simplified to two levels: 'shallow uncertainty' and 'deep uncertainty'. Shallow uncertainty can be treated through probabilities or assigned likelihood for different future alternatives, whereas deep uncertainty refers to conditions where parties do not know and/or cannot agree on the probabilities or likelihood of different future alternatives. These levels map onto different ways of representing parameter uncertainty, which may range from probabilistic information, to bounds on a range, to trend estimation or effective ignorance (Kandlikar *et al* 2005). Lempert *et al* (2003) further define deep uncertainty as the condition where decision-makers cannot agree upon:

(a) the appropriate models to describe interactions among a system's variables,
(b) the probability distributions to represent uncertainty about key parameters in the models, and/or
(c) how to value the desirability of alternative outcomes.

The electricity sector faces uncertainties that span each of these levels. Determining which uncertainties meaningfully impact various planning and decision contexts is critical for identifying the conceptual frameworks and analytic methods that are needed to effectively advance climate-informed practice.

3.2. Uncertainties in electricity sector planning

We can evaluate climate-induced uncertainties faced by the electricity sector through the framework discussed above. Figure 2 shows a conceptual mapping of how climate uncertainties may propagate through to impacts on the electricity system. This mapping broadly reflects the attributes of coupled natural and human systems under deep uncertainty discussed in Sharmina *et al* (2019). These uncertainties directly pertain to decisions made today (table 1) and should be accounted for in climate-aware planning and decision-making. To do so appropriately, we

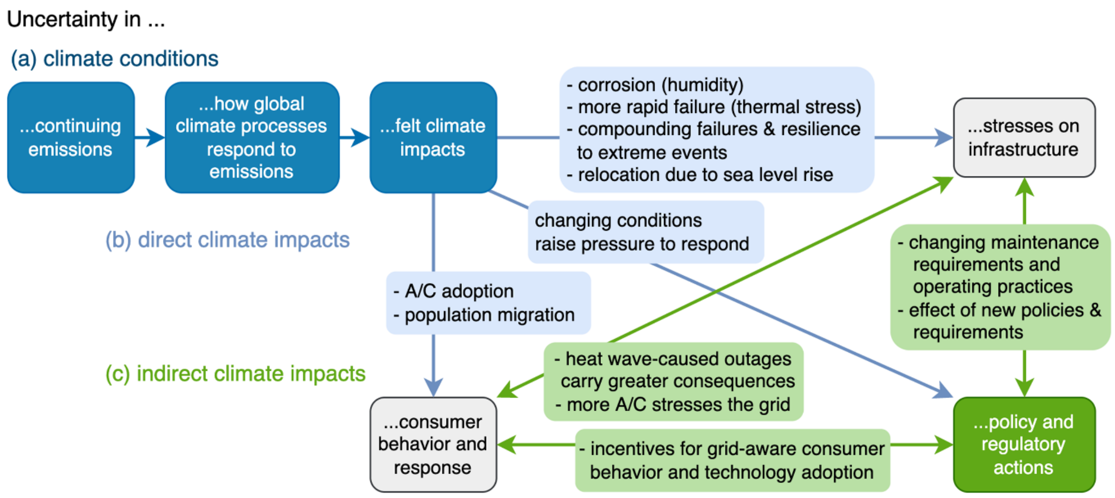


Figure 2. Conceptual mapping of progression of uncertainties in the electricity sector that are related to climate change. This figure is not meant to be exhaustive, but to illustrate the types of uncertainties and impacts that will emerge due to climate change.

must consider the nature of the uncertainties and how they might be represented to decision-makers.

3.2.1. Uncertainties in climate conditions

Climate scientists have made substantial progress in developing standard approaches to work with uncertainties related to climate conditions (figure 2(a)). Uncertainty in climate prediction comes from three sources: scenario uncertainty, model uncertainty, and internal variability (Hawkins and Sutton 2009, Lehner *et al* 2020), which have different impacts depending on the decision time and spatial scale. In the climate science space, *scenario uncertainty* corresponds to uncertainty in how greenhouse gas emissions will evolve. Uncertainties in continuing emissions are represented by scenarios (often, representative concentration pathways or RCPs, see van Vuuren *et al* 2011) that describe how emissions may evolve over the coming decades, and constitute a range of possible outcomes. Which scenario is realized depends upon societal characteristics, behavior, and climate policy, and so is constrained by future socioeconomic scenarios. These are often considered as shared socioeconomic pathways (SSPs) (O'Neill *et al* 2016, 2017), each of which is constructed around a self-consistent narrative describing plausible future outcomes for population, economic growth, etc. The SSPs enable a structured exploration of how alternative societal dynamics and decisions influence future climate outcomes. The range of future emissions can be loosely bounded by such plausible socioeconomic and policy scenarios, as well as by physical constraints on fossil fuel usage. However, the SSPs and RCPs are just a handful of the infinite possible futures that lie between and around them in the scenario space. It may be possible to qualitatively assign some expected likelihood to the class of similar scenarios represented by each emissions scenario based on expert judgment regarding the underlying factors that contribute to the scenarios (e.g. Hausfather and Peters 2020). However, assigning formal probabilities remains elusive, placing emissions scenario uncertainty at Level 3 or 4 from figure 1. The climate signatures of alternative emissions scenarios tend to broadly agree through approximately mid-century, so scenario uncertainty typically matters more for long-term planning decisions such as system expansion.

Uncertainties in how climate patterns might respond to continuing emissions are captured by global circulation models (GCMs), which take emissions scenarios as inputs. *Model uncertainty* refers to how these different models simulate changes in climate given the same amount of emissions. Each GCM constitutes a plausible representation of how future conditions may evolve. Model-based uncertainty is deep in the sense that these models are not randomly drawn from a space of possible models and their relative likelihoods cannot therefore be formally assigned probabilities. While certain model projections can be ruled out as less credible by examining their historic performance against observational benchmarks (e.g. Brunner *et al* 2020, Liang *et al* 2020, Tokarska *et al* 2020), it is often impossible to narrow the range to a single 'most likely' projection or 'most credible' model. Nor is it appropriate to think of models as equally likely since some models may share development histories and therefore common biases (Knutti *et al* 2013). Some researchers have developed credibility-based model weighting schemes, but in practice it is necessary to evaluate many metrics to build confidence that a particular weighting approach appropriately reduces uncertainty. Another reasonable strategy is to treat each projection that passes a skill-based screen as an equally plausible yet non-probabilistic outcome (i.e. corresponding to Level 4 from figure 1). GCMs describe climate impacts at large-scale resolution, and finer geographical resolution is desirable for actual planning decisions. Downscaling methods translate GCM outputs into regional climate impacts, and these methods also contain separate model uncertainties about how these large-scale outputs may be experienced locally (Barsugli *et al* 2013).

Climate projections are also subject to *internal variability*, or the natural fluctuation of the climate system even in the absence of emissions (Deser 2020). Internal variability is stochastic in nature and in principle can be estimated probabilistically through either observation or a sufficient number of simulated climate projections contingent on a given climate model and emissions scenario. However, the rarer an extreme event (e.g. a large storm or extreme heatwave) is, the more data is required to properly characterize its probability (Tebaldi *et al* 2021), presenting challenges when the historic record or future projections are limited. The recent advent of large climate projection ensembles (in which the same scenario is modeled dozens to hundreds of times) has led to better statistical resolution of extreme events (Kirchmeier-Young *et al* 2017), but still does not address the deep uncertainty arising from the choice of climate model itself or from alternative emissions scenarios.

3.2.2. Uncertainties in direct climate impacts

Changing climate conditions will directly impact infrastructure, consumer behavior, and decision-maker response (figure 2(b)). In particular, these may include how climate variables (e.g. humidity, temperature) impact power equipment performance and lifetimes, as well as the demands consumers put on that equipment (e.g. through increasing air conditioning use). Direct impacts will include those from changes in ambient conditions (i.e. trends in surrounding air temperature, precipitation, wind patterns, etc. that infrastructure is exposed to in routine operation), and in extreme conditions (i.e. increasing magnitude and frequency of events likely to cause disruptions). Researchers have estimated specific impacts from climate trends in these areas, and this ongoing work in conjunction with reasonable near-term confidence in felt local climate impacts (e.g. overall temperature trends) may make it possible to represent some uncertainties in these parameters through statistics. Yet such representations still rely on projecting the underlying climate impacts, which are nevertheless deeply uncertain (section 3.2.1). Climate conditions may also impact consumer and decision-maker responses that are more difficult to characterize empirically, such as population migration and/or political pressure.

3.2.3. Uncertainties in indirect climate impacts

Climate will also have additional indirect impacts on the electricity sector (figure 2(c)). These may include changing maintenance and operating practices, increasing danger for customers from heat-wave induced outages, and compounding stresses between consumer behavior and infrastructure performance. Policy actions in response to changing climate conditions may also prompt both increasing consumer actions (e.g. incentives for new technology adoption), and changing industry practices (e.g. decentralization). Adaptive responses by consumers and policymakers may pose further risks to electricity system stability and cost-effectiveness (Simpson *et al* 2021). These uncertainties emerge from the interrelationships among entities involved in electric power systems, infrastructure impacts, and climate conditions, and are compounded by feedback loops, including with other complex infrastructure sectors (e.g. water, transportation) (Reed *et al* 2022). Therefore, they are more difficult to estimate and capture through statistical approximations or modeling tools. Such uncertainties may thus be squarely considered deep, and require careful assessment that does not rely on predicting a deterministic future that may generate false confidence (Sharmina *et al* 2019).

3.3. Electric utility practices and emerging uncertainties

New uncertainties that arise from changing climate conditions are already disrupting the normal operation and performance of electric power systems. Accounting for these uncertainties in electricity sector planning will require evaluating how decisions are made today and how decision-making and planning processes will need to be updated for the future. From our review of the GRC filings of PG&E and ConEd (supplementary note 1), we identify six activity categories and 16 activity areas in which utilities are making decisions today that will be impacted by new uncertainties from a changing climate. We discuss each activity area in supplementary note 2 and summarize them in table 1.

These activity areas illustrate the range of practices that are exposed to new climate uncertainties. While the uncertainties discussed in section 3.2 and shown in figure 2 will impact all utility decisions, in table 1 we indicate specific climate uncertainties that may be particularly relevant to each activity area. These are meant to be illustrative rather than comprehensive:

(a) *Severe events* refers to uncertainties in the magnitude and frequency of events with the potential to disrupt day-to-day operations (e.g. strong storms, heat waves, droughts, etc).
(b) *Ambient conditions* refers to uncertainties in how average conditions (e.g. temperature, precipitation, humidity, etc) will change over time.
(c) *Speed of changes* refers to uncertainties in the rate of relevant changes in both severe and ambient conditions.
(d) *Demand changes* refers to uncertainties in changing consumer demand patterns and the

Table 1. Summary of utility activity areas and relevant climate-induced uncertainties (see supplementary note 2 for more).

	Activity area	Description	Climate uncertainties
Real-time operations	System operations	Activities performed in real time to manage system operation and respond to current conditions.	Severe events
	Monitoring and situational awareness	Inspection and monitoring of infrastructure readiness and grid performance, either through special equipment (e.g. sensors) or human attention (e.g. patrols).	Ambient conditions; Speed of changes
	Emergency response	Response to emergency events and real-time repair work to restore service.	Severe events; Demand changes
Maintenance	System maintenance	Maintenance of electric power system equipment and associated infrastructure, costs may include those related to labor, capital, and permitting.	Ambient conditions; Demand changes
	Vegetation management	Inspection, identification, clearing, and removal of vegetation located near electric power equipment.	Ambient conditions; Severe events
Planning	System planning	Ongoing projects to evaluate system condition and day-to-day needs and to plan for the future.	Ambient conditions; Demand changes
	Preparatory planning	Investments in planning specifically for emergency events, which may include technology, communication, human capital, and coordination with other responders.	Severe events; Demand changes
Investments	System expansion	Deployment of new equipment and infrastructure designed to accommodate new demand on the system.	Severe events; Demand changes
	Repairs and replacements	Repairing or replacing equipment that has reached the end of its useful life, or where investment is needed to maintain an appropriate level of performance.	Ambient conditions; Speed of changes; Demand changes
	Grid hardening	Upgrading or reinforcing equipment with the goal of mitigating a specific and emerging threat that would not have originally been planned for, or to improve performance under non-standard operating conditions.	Severe events; Speed of changes
	System awareness and security	Developing new capabilities to maintain system awareness, improve safety and resiliency, and enable coordination, with a focus on non-power assets (e.g. system mapping, security upgrades, threat and vulnerability detection).	Changing regulatory and policy landscape
Performance	Performance assessment	Development and implementation of systems and processes to evaluate and measure utility performance (e.g. reliability metrics, customer satisfaction).	Changing regulatory and policy landscape
	Customer programs	Direct consumer engagement related to outage management, demand response, time-of-use rates, etc	Demand changes
Business operations	Regulatory standards and compliance	Permitting and implementation of required technical or process standards, licenses, or environmental management practices.	Changing regulatory and policy landscape
	Internal operations	Costs required to perform core duties (e.g. labor, training, management, tools, office space, and land maintenance).	Changing regulatory and policy landscape
	Cost management	Accounting programs for managing infrastructure and operational costs (e.g. expenditures that are uncertain in time, decommissioning, recovery of cancelled projects).	Changing regulatory and policy landscape; Severe events

resulting impacts to customers of disruptions (e.g. increasing electrification will mean greater reliance on the electricity grid for new loads, such as heating).

(e) *Changing regulatory and policy landscape* refers to uncertainties about how decision-makers will respond, including potential new requirements for utilities with regards to risk and cost management (e.g. insurance).

In real-time operations, increasing frequencies of extreme events and changing ambient conditions may stress existing approaches to system operation, data collection and monitoring, as well as the ability of

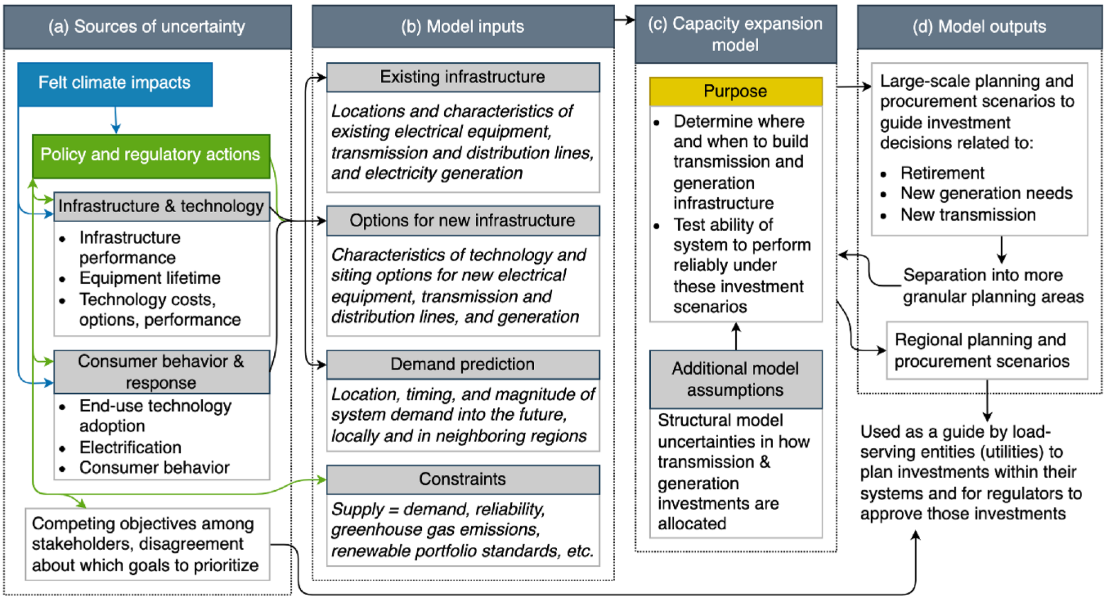


Figure 3. Uncertainties, inputs, and outputs of capacity expansion models. Part (a) builds on figure 2.

crews to effectively restore power after outages. In system maintenance, changing ambient conditions may alter the expected lifetime of system components (e.g. through corrosion or thermal stress) and necessitate more frequent maintenance and labor needs to ensure satisfactory operation. Further, while new climate patterns (e.g. drought) may place more stress on vegetation management practices, such practices will become increasingly important to preserve operation in light of extreme events and severe storms. In performance and business operations, changing regulatory and policy practices, including direct-to-customer incentives for new technologies, may also continue to drive changes in how utilities operate. Further, new insurance risks may threaten existing accounting practices.

Here, we focus on two activity categories—planning and investments—in which utilities make and execute long-term decisions about their systems. Activities in these areas will need to contend with the impacts to technology of changing ambient conditions and increasing severe events, changing consumer demands for electricity, and a changing regulatory and policy landscape (effectively, all uncertainties depicted in figure 2). To illustrate how these new uncertainties may challenge current utility planning and decision-making practices, we focus here on capacity expansion planning, which is widely used in the electricity sector to evaluate the need for investments in electricity generation and delivery infrastructure to serve new and changing demand patterns (Gacitua *et al* 2018, Miara *et al* 2019). These planning activities rely heavily on capacity expansion models, which incorporate information about existing infrastructure and make technology, market, and policy assumptions to determine where and when system investments should be made to accommodate load growth at least cost (figure 3). The extent to which the results of these models represent the real world depends on how they incorporate uncertainties in climate and its direct and indirect impacts and stakeholder objectives (figure 3(a)), as well as how well the model itself represents the electricity system (i.e. *model uncertainty*, figure 3(c)).

Current implementations of capacity expansion models typically make assumptions about these uncertainties to create a single plausible future to plan for. In California and New York, the capacity expansion planning models that feed into and inform infrastructure investments are primarily deterministic, i.e. they seek to make the best possible predictions of a single plausible future given current information, assume that uncertainties can be treated probabilistically, and then plan for that future (Brockway and Dunn 2020). While scenario planning approaches are used, investments are still tailored to one (typically median) scenario. Further, while in some cases such models take in weather and climate data directly (e.g. using temperature to predict electricity demand), they also contain embedded assumptions that implicitly incorporate climate conditions (e.g. equipment lifetimes). Feedback loops are also necessary to consider: for example, increasing consumer adoption of air conditioning due to increasing temperatures will increase demand on the grid at the same time as hotter days reduce line capacity and generation efficiency.

The potential impact that climate uncertainties may have on the results of these models is unknown until such uncertainties are more formally and systematically explored. Certainly, not all climate uncertainties will matter equally for all decisions, but relying on historical weather data as well as historical performance neglects the impact of climate as a source of uncertainty. Moreover, relying on historical weather data means, in practice, accepting the full risk of impacts due to climate change rather than preparing appropriately. Building climate awareness into capacity expansion planning is critical, and literature that evaluates the impacts of planning with climate considerations consistently show that it is better to plan for climate impacts upfront rather than after the fact (e.g. Miara *et al* 2019, Peter 2019, Sridharan *et al* 2019, Fonseca *et al* 2021). By not accounting for climate uncertainty, we are planning for an inaccurate future, which may compound existing grid inadequacies.

3.4. Key concepts from decision science for managing uncertainties

Traditional decision-making approaches that use the framework of expected utility theory (Savage 1972, Weitzman 2009), such as benefit-cost analysis (Boardman *et al* 2005), and cost-effectiveness analysis (Garber and Phelps 1997), hinge on the ability to assign a probability density function to future events and assume all uncertainties are quantifiable. However, any single projection of the future is likely to be inaccurate (Bishop *et al* 2007). Moreover, planning for climate change is a case of deep uncertainty, where long-term climate uncertainties in infrastructure planning are hard to quantify and futures are hard to predict. Therefore, these traditional approaches cannot provide planners with a holistic view, adequately integrate climate uncertainty, or grapple with the long-term multiplicity of plausible climate futures (Lempert *et al* 2003, Ackerman *et al* 2009, Hallegatte 2009, Ranger 2010, Masur and Posner 2011, Dittrich *et al* 2016). Relatedly, oft-cited reasons for not including climate data in decision-making processes include the perceived poor reliability of climate forecasts and difficulty in assessing the credibility of climate projections (Rayner *et al* 2005, Barsugli *et al* 2013). These reasons may also stem from the need to optimize under a single future and treat climate uncertainty in a probabilistic manner.

To address the limitations of the traditional decision-making approaches and climate uncertainty in policy making, a growing body of literature within the climate-aware decision science space uses concepts from decision-making under uncertainty and decision-making under deep uncertainty across different infrastructure sectors (table 2). These concepts are not new (Morgan *et al* 1990), particularly within the water and transit sectors, but they have not significantly factored into work by practitioners in grid infrastructure planning.

Table 2. Summary of sector identified in review of papers related to decision making under climate uncertainty.

Sector	*N* (academic)	*N* (grey)
Water	37	7
Transit	12	3
Climate adaptation	11	4
Energy	7	1
Conservation	2	0
Telecommunication	1	0
Nexus	1	0
N/A (conceptual review paper)	15	0
Total	86	15

A majority of this literature is targeted at water resources planning. The relatively high prevalence of these concepts in the water resources planning sector might be due to the early introduction by Matalas and Fiering in 1977 (National Research Council 1977, Herman *et al* 2015, Dittrich *et al* 2016, Giuliani and Castelletti 2016). However, the similarities between water resource and grid planning (e.g. high likelihood of path-dependence, sensitivity on both demand and supply to climate impacts, long infrastructure lifetime, investment irreversibility) make these concepts transferable. As discussed in section 3.2, climate uncertainties significantly affect all decision activities (e.g. system planning, investment, maintenance) and create compounding uncertainties (e.g. policy response, consumer behavior, infrastructure performance). In particular, long-term decisions such as capacity expansion planning may need a different approach to incorporate uncertainty in the decision-making. Three key concepts that emerged from our review could offer an alternative approach to the traditional methods:

(a) **Robustness.** Rather than an optimal outcome for a single future, a robust outcome performs reasonably well in a wide range of plausible future climate scenarios.
(b) **Adaptive planning.** Uncertainties in climate conditions evolve over time, and adaptive planning refers to setting up the institutional capacity to take actions over extended time horizons. This can include identifying short-term actions, developing different long-term options, and performing continuous monitoring to assess appropriate long-term paths.
(c) **Multi-stakeholder engagement.** Tensions between conflicting perspectives and policy objectives may be resolved through an iterative multi-stakeholder engagement process.

Table 3 shows a summary of those concepts with associated techniques and papers. The following sections provide deeper dives into each of those concepts and discuss opportunities to implement them into organizational decision-making.

Table 3. Summary of key concepts and their associated techniques.

Key concepts	Key Techniques	Example Papers
Robustness: ensuring the outcome is insensitive to errors and uncertainties in the parameter assumptions and performs reasonably well in a wide range of possible future scenarios.	• **Exploratory modeling or scenario discovery:** developing a set of scenarios in a systematic manner to expand the understanding of how the future might unfold and trade-offs between different prioritization of objectives. • **Vulnerability assessment:** Leveraging the systematic scenario discovery process to evaluate when a chosen policy performs poorly using a set of predefined metrics.	Herman *et al* (2015), Taner *et al* (2017), Lempert (2019), Bartholomew and Kwakkel (2020), Workman *et al* (2021)
Adaptive planning: identifying short-term actions, but also developing different long-term options for implementation based on continuous monitoring.	• **Signpost & tipping points:** Identifying the point (signpost) when a policy outcome would become inadequate and tracking specific indicators (tipping point) that inform future actions. • **Monitoring plan:** A formalized plan that provides instruction on how to monitor signposts and tipping points and map out long-term actions to take when thresholds for the signpost are triggered.	Haasnoot *et al* (2013, 2018), Hamarat *et al* (2013), Beh *et al* (2015), Wall *et al* (2015)
Multi-stakeholder engagement: facilitating interactions of different actors within and across sectors, at different levels, and within different organizations to incorporate their perspectives and priorities.	• **Participatory modeling and scoping process:** Having 'knowledge brokers' or 'boundary spanners' to translate jargon and knowledge among different stakeholders in an interactive workshop. It is most effective when engagement is conducted iteratively throughout planning process.	Kwakkel *et al* (2016a), Lawrence and Haasnoot (2017), Roelich and Giesekam (2019), Rădulescu *et al* (2020), Lempert and Turner (2021), Stanton and Roelich (2021)

Table 4. Number of times the key concepts appeared in literature review.

Concept	*N* (academic)	*N* (grey)
Robustness	48	5
Adaptive planning	27	4
Multi-stakeholder engagement	27	6

Table 4 shows the prevalence of key concepts in the literature. Robustness is more commonly discussed in academic literature compared to adaptive planning and multi-stakeholder engagement. However that prevalence did not translate over to practice in the grey literature. The lack of prevalence in implementing robustness concept is perhaps due to the technical complexity and knowledge gap on how uncertainties may impact planning outcomes, particularly in the context of climate change.

3.4.1. Robustness

The concept of robustness originated in ecology during the 1970's, when it was introduced to water resources planning in the context of climate change by Matalas and Fiering (National Research Council 1977). They defined a robust design as one that may not be the optimal choice under any one scenario, but that performs reasonably well under a variety of possible climate scenarios. Robustness further refers to the insensitivity of system design to any potential errors in assumptions affecting decision performance (National Research Council 1977). Although the mathematical backbone of robustness has evolved, the definition is still broadly valid. Forgoing the optimal choice may seem counterintuitive, but decision-makers are often willing to sacrifice optimality for robustness (Clímaco 2004, Difrancesco and Tullos 2015, Herman *et al* 2015, Rosenhead *et al* 2017). This preference for robustness is at odds with traditional decision-making approaches, where the goal is to produce the optimal outcome under the assumption that uncertainty is well-characterized (i.e. shallow uncertainty). Given the irreducibility and depth of climate uncertainty and irreversibility of infrastructure investment, approaching planning with the robustness concept enables decision-makers to identify viable solutions that work across many possible futures without needing to predict which of those futures is most likely.

In recent years, an increasing number of decision frameworks are integrating robustness concepts into their approach, including Decision Scaling (Brown *et al* 2012), robust decision making (RDM) (Lempert *et al* 2003), Information-Gap (Ben-Haim 2004), many-objective robust decision-making (Kasprzyk *et al* 2013), and Epoch–Era analysis (Curry and Ross 2015). Other authors have compared these methods (Hall *et al* 2012, Matrosov *et al* 2013, Roach *et al* 2016, Kwakkel *et al* 2016b, Marchau *et al* 2019, Bartholomew and Kwakkel 2020, Moallemi *et al* 2020), and developed a common taxonomy of robustness across those frameworks (Herman *et al* 2015, McPhail *et al* 2018). Here, we focus on extrapolating robustness concepts and techniques that may be relevant to the electricity sector.

The exact definition of robustness is dynamic depending on the decision context and stakeholders' attitudes (Giuliani and Castelletti 2016). However, the underpinning technique to achieve a robust outcome is by exploring how different policy alternatives perform in a wide range of plausible scenarios and evaluating trade-offs among multiple performance measures (Moallemi *et al* 2020). There are four distinct components within a robust decision analysis: a set of decision alternatives, a range of plausible scenarios, performance measures or robustness metrics, and vulnerability assessment or robustness controls. We will provide a simplified overview of each component, refer to Herman *et al* (2015) for a more comprehensive discussion.

(a) **A set of discrete policy alternatives.** These are the different decision options that may be implemented based on future scenarios and current institutional constraints. They may be pre-specified by decision-makers or developed through a computational search. For example, a discrete policy alternative might be a set of investment choices generated by a capacity expansion model under a particular set of inputs, including a given climate scenario. This policy alternative may then be evaluated alongside other alternatives developed by running the same model with different inputs (see (b) range of plausible scenarios). In practice, the set of decision alternatives is more likely to be pre-specified due to resource constraints. A multi-stakeholder engagement process may be effective in ensuring different objectives are incorporated into the initial policy alternatives and determining whether adaptive planning is necessary or possible.

(b) **A range of plausible scenarios** that considers all uncertainties and translates them into parameters in the model. For example, uncertainties around the change of temperature or precipitation in the next decade would become parameters with assigned plausible ranges. The different scenarios are different combinations of those uncertainties. A multi-stakeholder engagement process may be effective to create a comprehensive list of uncertainty factors and agree on plausible ranges for uncertainty parameters. The goal is not to predict future scenarios rather to explore what could happen. Each policy alternative is evaluated in each of the scenarios using robustness metrics.

(c) **Performance measures or robustness metrics** for each policy alternative are a list of criteria that policy alternatives are evaluated against in each scenario. Stakeholders and analysts may co-develop multi-objectives and robustness metrics. Robustness metrics are developed in a similar manner to traditional decision-making approaches, where decision-makers choose specific metrics to evaluate policy performance based on the decision context (i.e. properties of the problem space such as regulatory environment and technical constraints). Example robustness metrics are GHG emissions, system reliability, and investment cost. The performance of one policy alternative may be evaluated using a combination of several robustness criteria. Robustness is commonly assessed using two methods, least-regret or satisficing. Least-regret quantifies each policy alternative's deviation from expected performance based on robustness metrics and identifies the policy that deviates the least over a wide range of plausible futures (Lempert and Collins 2007). Satisficing evaluates each policy alternative against the robustness metrics and identifies the policy that performs reasonably well compared to the alternatives over a wide range of plausible futures (Hall *et al* 2012). Robustness metrics provide decision-makers with a systematic approach to evaluate and compare each policy under a wide range of climate futures.

(d) **Vulnerability assessment or robustness controls** refer to the process of isolating the uncertain factors most responsible for system vulnerabilities and examining where policies could fail (i.e. produce unacceptable outputs with respect to the performance metrics). A common technique is scenario discovery, which simulates the performance of different policy alternatives under a wide range of plausible futures and identifies where some policy alternative may fail (Bryant and Lempert 2010). This is similar to sensitivity analysis in traditional decision-making approaches. The goal is to help decision-makers target specific vulnerabilities and develop adaptive strategies to address them (Haasnoot *et al* 2013).

In the grey literature, robustness is discussed as an overarching concept but it is rare for planners to conduct and implement robustness concept in the standard decision-making process. Some reports acknowledge the need to move away from deterministic and definitive prediction about future climate conditions and the importance of incorporating uncertainty by planning for wide range of futures (Means *et al* 2010a, US Department of Energy 2016, World Association for Waterborne Transport Infrastructure 2020). However, this is often not operationalized; there are only several pilot projects in the water resources sector that leverage RDM to test its technical capability and value of running a wide range of future scenarios. One notable example is the work done by the Bureau of Reclamation in the Colorado River (Groves *et al* 2019, Smith *et al* 2022). Other examples include work done in water utilities and water planning (Means *et al* 2010b, Zeff *et al* 2014, Herman *et al* 2016, Gorelick *et al* 2018, Gold *et al* 2019). Both academic and grey literature suggest that the barriers to implementing the robustness concept center on the difficulty in changing the conventional decision-making process and planners' unfamiliarity (Means *et al* 2010b, Bhave *et al* 2016, Roelich and Giesekam 2019).

3.4.2. Adaptive planning

Adaptive planning is another tool used to cope with uncertainties in long-term infrastructure planning. Adaptive plans are designed to be iteratively updated with newly available information, leading to more resilience against uncertainties and more effectiveness in guiding future actions. Similar to the concept of robustness, adaptive plans also examine a wide range of uncertainties and plausible futures (Walker *et al* 2013a). In addition, adaptive planning refers to the flexibility of a policy alternative to change course based on the evolving environment through continuous learning (Rosenhead *et al* 2017, Haasnoot *et al* 2018). The objectives are to reduce path dependencies due to technological, institutional, and behavioral lock-ins (Fouquet 2016, Maier *et al* 2016) and increase tolerance to future uncertainties (Jeuken *et al* 2015). To achieve those objectives, adaptive planning identifies short-term actions and long-term options by systematically monitoring the environment, gathering information, and iteratively adjusting strategies to new circumstances (Yzer *et al* 2014). The literature presents several frameworks that encourage adaptive planning, such as Assumption Based Planning (Dewar and Wachs 1993), Adaptive Policy Making (Kwakkel *et al* 2010), Engineering Options Analysis (Smet 2017), and Dynamic Adaptive Policy Pathways (Haasnoot *et al* 2013). The fundamental idea across those frameworks is that coping with uncertainty involves a robust short-term strategy and monitoring for changes that indicate a need to develop new strategies. Here, we again focus on the common and essential components of adaptive planning.

Adaptive planning can either be static or dynamic. Static adaptive planning aims to protect a basic policy from failing through contingency actions and monitoring (Walker *et al* 2001, Haasnoot *et al* 2013). Dynamic adaptive planning goes beyond contingency planning and aims to monitor policy performance over time and develop alternative policies to switch to when certain thresholds are met (Wall *et al* 2015). The success of any adaptive plan depends on monitoring and anticipating ongoing developments such as changing climate and social context. Both approaches consist of two crucial components: a monitoring plan and a list of signposts (Maier *et al* 2016). We provide a simplified overview of those two components. Refer to Herman *et al* (2015) and Haasnoot *et al* (2018) for a comprehensive discussion.

(a) **A monitoring plan** aims to learn and continuously improve the existing policy based on new information (Preston *et al* 2011). Specifically, it monitors assumptions or uncertainty factors that affect policy performance and iteratively evaluates whether the current policy is at risk of failing given the changing environment. Multi-stakeholder engagement may be an effective way to develop a monitoring plan. The central goals of a monitoring plan are identifying what variables to monitor and establishing methods to analyze the information to get timely and reliable signals that indicate a change of action. Furthermore, a monitoring plan may also include flexible long-term planning options based on the changing environment and formalize stakeholder engagement activities to iteratively improve the long-term planning actions.

(b) **Signposts** are a list of variables to track to evaluate policy performance over time and are a central component of the monitoring plan. Each signpost is accompanied by critical values or thresholds that indicate when new actions are needed. An effective signpost consists of three quality criteria: salience, credibility, and legitimacy (Cash *et al* 2005). Salience refers to how decision-relevant a signpost is. A salient signpost will provide insights to address policy concerns and is measurable, timely, and reliable. Credibility refers to how scientifically sound are the critical values assigned to each signpost and how convincing they are at motivating potential changes needed. Legitimacy refers to the acceptability of the technical process around data gathering.

In grey literature, planners discuss the idea of adaptive plan within the context of adaptive capacity. It is often defined as the ability to adjust to change via building redundancy, resilience or recoverability (Johnson 2012, US Department of Energy 2016, World Association for Waterborne Transport Infrastructure 2020). The water sector is most advanced in incorporating ideas of monitoring plan and triggers when discussing adaptive planning.

3.4.3. Multi-stakeholder engagement

Multi-stakeholder engagement is an essential component for incorporating uncertainties into the planning process. Successfully developing a robust outcome and an adaptive plan relies on gathering decision-relevant information and considering perspectives from different stakeholders throughout the planning process (Babovic *et al* 2018). Conducting multi-stakeholder engagement is especially crucial in the context of climate planning because misrepresentations of future scenarios may exacerbate negative climate impacts on marginalized populations (Jafino *et al* 2021).

The literature presents many different frameworks of conducting multi-stakeholder engagement for infrastructure planning (Tompkins *et al* 2008, Gardner *et al* 2009, Herman *et al* 2014, Mok *et al* 2015, Bourne 2016, Cuppen *et al* 2016). A 'one size fits all' approach for multi-stakeholder engagement does not exist, since it is highly dependent on the decision context and planning stage (Rountree *et al* 2021). Moreover, there are discrepancies around the exact definition of a 'stakeholder' (Carney *et al* 2009).

Here, we use the IPCC's definition: stakeholders are individuals or groups that can influence or may be affected by the decision outcome. They might be policy-makers, scientists, communities, and/or managers in the sectors and regions most vulnerable to infrastructure failure (Rowe and Frewer 2000, Conde *et al* 2004). Stakeholder engagement is broadly defined as any activity such as a survey, interview, or interactive workshop with the purpose of information exchange between analysts, decision-makers, and stakeholders. There are some common frameworks infrastructure planners use to conduct stakeholder engagement. Delphi Method is commonly used to generate parameter bounds for climate scenarios (Grime and Wright 2016). Approaches such as the rapid assessment process and participatory planning are also common ways to understand different stakeholders' perspectives and generate scenarios (Meadow *et al* 2015). There is much room for improvement to increase input from affected stakeholders, engage with diverse values, and examine conflicting objectives during the planning process to ensure procedural equity (Cradock-Henry *et al* 2020, Leal Filho *et al* 2021). Stakeholder engagement in the energy sector can take different forms. Currently, these include intervention by non-profit and community organizations in regulatory proceedings, public comments on infrastructure siting decisions, and technical advisory groups established by regulators on specific topics (Baldwin *et al* 2018, Solman *et al* 2021). A full review of stakeholder engagement practices is out-of-scope here, but this topic deserves additional attention in the context of questions about procedural and distributional equity that have been documented by other researchers in infrastructure planning efforts (Sovacool *et al* 2016, Heffron and McCauley 2017, Fletcher *et al* 2022). Procedural equity starts with considering how to represent perspectives of affected community members by selecting a wide range of stakeholders and ensuring they are involved throughout the planning process. We offer some additional thoughts on this in section 4.3.

Although multi-stakeholder engagement takes many forms, the common objectives for engaging stakeholders in the context of climate-aware decision making are fourfold:

(a) Co-produce decision-relevant metrics to measure robustness and monitoring plan performance;
(b) Increase transparency to the planning process with greater input and feedback from stakeholders regarding their preferences;
(c) Seek active support and build consensus from stakeholders for the decisions which are made; and
(d) Incorporate diverse perspectives from different stakeholders.

Infrastructure planners cannot effectively implement the concepts of robustness and adaptive planning without multi-stakeholder engagement. Inputs from stakeholders are critical for defining policy success or failure. Many frameworks for decision-making under uncertainty include stakeholder engagement as an important step of the planning process. Ideally, analysts and decision-makers would engage different stakeholders to understand various priorities and develop decision-relevant performance criteria at the beginning of the planning stage (Ranger *et al* 2013, Stanton and Roelich 2021). Then analysts would translate those insights into parameters and constraints during the modeling process (Bhave *et al* 2016). Once modeling is complete, stakeholders are brought back for deliberation to build consensus and iteratively improve the decision outcome (Lempert *et al* 2003). Moreover, having a boundary spanner or boundary organization during the engagement process may help to increase effectiveness of the co-production process. The role of boundary organization is to facilitate the engagement process by allowing scientists and decision makers to maintain their independence and objectivity while also creating some permeability of the boundary to co-produce robustness metrics and monitoring plans (Clark *et al* 2011).

The grey literature suggests that multi-stakeholder engagement is already ubiquitous in large-scale long-term infrastructure projects as a way to manage risk and obtain public buy-in. However, there is a literature gap in how to conduct stakeholder engagement to effectively incorporate uncertainties and reconcile competing priorities (Stanton and Roelich 2021).

Table 5. Summary of topic areas identified in review of papers related to electricity sector planning under climate change. While some papers may span multiple topic areas, each was assigned to a single topic for organizational ease.

Topic area	N (papers)
Adaptive capacity	7
Capacity expansion	18
Climate impacts on power systems	12
Climate policy	9
Community energy systems	10
Complex systems	5
Decision support	18
Multi-sector optimization	10
Power system modeling	8
Resilience in power systems	23
Risk optimization	13
Robustness	9
Socio-technical transition	26
Total	168

3.5. Electricity sector planning under climate change

Researchers studying electricity systems in the context of climate change have taken a variety of approaches to this subject. To facilitate our review, we first sorted the identified papers into topic areas based on an initial survey of their titles, abstracts, and keywords (table 5). These topic areas formed clusters of papers with some commonality in their perspective, scope, approach, and/or methodology. We reviewed papers in each topic area to understand how the authors considered climate change and uncertainty, and assessed to what extent the three key concepts identified in the decision science review (robustness, adaptive planning, and stakeholder engagement) showed up in this literature. A full review of modeling methodologies used in the energy sector is out of scope here, but we direct readers to Keirstead *et al* (2012), Bale *et al* (2015), Li *et al* (2015), Ioannou *et al* (2017), Sellak *et al* (2017), Sharmina *et al* (2019), Witt *et al* (2020), Hanna and Gross (2021) for more discussion on the types of models used.

3.5.1. Climate change and uncertainty

Uncertainties, including those inherent in climate predictions as well as those stemming directly and indirectly from climate change (see section 3.2), have been considered in various ways at different stages of analyses. Researchers acknowledge the presence and potential impact of uncertainties such as technical system characteristics (e.g. generator performance, line capacity), policy goals (e.g. renewable energy targets, carbon prices), and consumer behavior (e.g. rates of technology adoption, demand growth). However, to capture these uncertainties, there is widespread reliance on tools that would only be appropriate for shallow uncertainty. These include directly estimating individual values, perhaps with some sensitivity (appropriate for Level 1 uncertainty; see Li *et al* 2015, Hanna and Gross 2021), assuming a probabilistic distribution of possible values (appropriate for Level 2 uncertainty; see Bessani *et al* 2019, Willems *et al* 2019, Ji *et al* 2020b), and employing scenario approaches with known alternatives (appropriate for Level 3 uncertainty; see Kichonge *et al* 2015, Chen *et al* 2016, Moksnes *et al* 2019, Peter 2019). Some researchers instead set a bounded interval or range of values without assuming a probabilistic distribution, which would fall between Levels 3 and 4 (Heinrich *et al* 2007, Cao *et al* 2010, Lin *et al* 2017, Ji *et al* 2020a).

Relying on value estimation and/or probabilistic estimates may further enable researchers to resolve parameter uncertainty within their analyses and report a sole solution. This raises the concern of seeking an optimized solution, which may inadvertently suggest to decision-makers that it is possible to model perfect knowledge (i.e. fully settle uncertainty) when the future is not deterministic (Chattopadhyay *et al* 2016). An alternative is to depict uncertainty directly in results, for example by presenting a possible range of outcomes (Willems *et al* 2019, Bloomfield *et al* 2021). Such results may more appropriately convey the continued need to consider uncertainty when presented for discussion in multi-stakeholder engagement processes.

Further, few researchers acknowledge model uncertainty (see structural uncertainty in Sharmina *et al* 2019). Model uncertainty is present in all types of modeling exercises, including climate models (section 3.2.1) and capacity expansion models (section 3.3), but, unlike in the climate modeling literature, little attention is paid in the electricity planning literature to systematically evaluating a diversity of structural assumptions in model design.

Authors who explicitly use climate information in their analyses also take a variety of approaches. In some cases, a limited set of climate information (e.g. one emissions scenario and GCM) are used as a case study (Chen *et al* 2021). Others include more climate information to explicitly represent possible futures, for example by using several GCMs with one emissions scenario (Miara *et al* 2019, Peter 2019), or several emissions scenario with one GCM (Santos da Silva *et al* 2021). In some cases, climate model outputs are aggregated (for example, by averaging their results) (Miara *et al* 2019). Other researchers evaluate climate models as distinct plausible futures, often as a set with the goal of creating a reasonable range on the phenomena of interest alongside several emissions scenarios (Parkinson and Djilali 2015, Spalding-Fecher *et al* 2017, Sridharan *et al* 2019, Voisin *et al* 2020, Figueiredo *et al* 2021, Fonseca *et al* 2021).

Importantly, authors in the reviewed literature commonly focus on specific types of uncertainty within a particular analysis rather than capturing the full range of uncertainties that may exist within a particular decision-making or planning process. For example, some authors use a range of GCMs and emissions scenarios while holding other assumptions constant (Li *et al* 2014, Miara *et al* 2019, Peter 2019, Voisin *et al* 2020, Fonseca *et al* 2021), while others use no or limited climate information but vary assumptions related to socioeconomic factors (Chen *et al* 2016). Such approaches emulate the concept of controlled experiments and may provide valuable scoping or case study information. However, they do not account for the full range of plausible scenarios that should be considered in a robust process.

3.5.2. Robustness

Relatively few reviewed papers focus on ensuring robustness in their decision outcomes (for an example, see Nahmmacher *et al* 2016). However, electricity sector researchers have developed computational techniques that capture components of the robustness concept. These techniques are designed with the acknowledgement that a single prediction of a possible future is inadequate, multiple plausible trajectories exist, and it is therefore worthwhile to consider how a policy or decision may perform across those potential futures. Techniques include:

(a) Stochastic programming tools may incorporate different plausible futures and weight them by specified probabilities. The overall objective is then to minimize the expected system cost across all futures (Chattopadhyay *et al* 2016, Ji *et al* 2020b).
(b) Robust optimization is frequently used to determine the best (or, least-worst) solution for a given scenario, but such tools may also consider multiple futures, with the optimal solution then defined as one that demonstrates satisfactory performance (or, avoids the worst outcomes) across alternative scenarios (Li *et al* 2014, Parkinson and Djilali 2015).
(c) Trade-off approaches start from the development of a vast possible solution set, then iteratively screen out inferior approaches as evaluated by predefined metrics (Heinrich *et al* 2007). A final solution set is evaluated against all proposed futures.

Beyond these techniques, authors in the electricity planning literature selectively employ components of robustness approaches. For example, authors commonly include the development of multiple plausible scenarios and performance metrics. Some also include a vulnerability assessment or robustness controls (Chen *et al* 2016). It is less common in the electricity sector literature that we reviewed to explicitly incorporate multiple policy alternatives within the design of a set of scenarios (for examples, see Moallemi and Malekpour 2018, Bloomfield *et al* 2021). While few authors incorporate all elements of the robustness concept as discussed in the decision science literature, these frameworks nevertheless present scaffolding on which additional components of robustness could be integrated. It is important to note that these approaches may quickly become computationally intensive with the generation of additional scenarios and incorporation of policy alternatives.

3.5.3. Adaptive planning

Planning in the electricity sector is heavily influenced by decisions that have already been made; for example, existing investments will impact where new investments will need to go. Recognizing the importance of long planning timescales with multiple decision points, researchers have made use of multistage modeling tools to create the foundation for evaluating system conditions and resolving uncertainties over time (Szolgayová *et al* 2012, Ji *et al* 2017, 2020a, Peter 2019). For example, models may be run once to a selected point in time, then evaluated again based on new information about how conditions have evolved (Chattopadhyay *et al* 2016). Such two-stage processes are particularly useful for uncertainties that have definite dates of resolution.

Other modeling tools may prioritize maintaining flexibility throughout a given timeline, for example, by selecting scenarios that maintain flexibility towards long-term uncertainties (see stochastic programming with recourse in Heinrich *et al* 2007) or by incorporating feedback signals for real-time adaptability (Hung and Chang 2017). Other authors discuss adaptation options but do not explicitly incorporate them into analyses (Nierop 2014, Burillo *et al* 2019).

Such approaches differ from the adaptive planning methodologies proposed in the decision science literature as they do not necessarily incorporate a monitoring plan or signposts, rather relying on discrete points in time and/or metrics of flexibility. However, they may provide a computational basis for incorporating those components to improve planning resiliency.

To some extent, current electricity sector practices do incorporate elements of adaptive planning, specifically via regulatory proceedings that require utilities to evaluate and justify their investment needs every 3 years (section 2.2). However, these short timescales do not facilitate looking ahead at future climate conditions, and may thereby further path dependence and technology lock-in. This could occur, for example, by investment in conventional grid hardening at the expense of building flexibility into the electricity system through distributed assets. Moreover, planning on short timelines neglects the impact of long-term climate trends (e.g. sea level rise) that may threaten technology investments with long implementation and performance timelines (e.g. new generating facilities built near coastlines). Instead, adaptive planning principles call for proactively tracing out the different long-term options when certain trigger points are met, thereby giving signals to electricity sector participants to lay the groundwork for new approaches (e.g. legislative or regulatory actions that create markets for energy storage).

3.5.4. Multi-stakeholder engagement

We encountered relatively few papers that explicitly consider multi-stakeholder engagement. In some cases, authors consider assumptions about risk tolerance or other decision-maker preferences (Szolgayová *et al* 2012, Ji *et al* 2017, 2020a), or formulate solutions to be decision-relevant (Burillo *et al* 2019, Voisin *et al* 2020, Santos da Silva *et al* 2021), but do not actually show evidence of having consulted stakeholders. Other papers involve stakeholders at the beginning or end of a particular analysis, whether to assist in scoping or to present results (Spalding-Fecher *et al* 2017, Willems *et al* 2019, Yang *et al* 2019). Extensive stakeholder engagement is present but somewhat rare (see Moallemi and Malekpour 2018, Panula-Ontto *et al* 2018, Pereira *et al* 2018, Sharmina *et al* 2019).

Other authors have considered stakeholder involvement theoretically, such as by developing frameworks for engagement (Araújo and Shropshire 2021), simulating preferences via agent-based models (Hoekstra *et al* 2017, Teixeira *et al* 2018, Hanna and Gross 2021), or evaluating computational approaches capable of accounting for various perspectives by solving for multiple objectives and/or including appropriate uncertainty ranges on parameters (Heinrich *et al* 2007). Authors have also proposed that stakeholder engagement can be used to determine where to focus within a solution space once a set of solutions are obtained, and, as each individual view is necessarily a simplification of all considerations, to provide a check on other perspectives by helping ensure that a planning exercise accounts for needed nuances (Bollinger *et al* 2014, Nierop 2014).

4. Recommendations

We have identified three key concepts from decision science—robustness, adaptive planning, and multi-stakeholder engagement—that can be directly incorporated into electricity system planning and decision-making. Here, we return to capacity expansion planning (see section 3.3) as a concrete example to illustrate how these key ideas could be incorporated into electricity sector activities.

4.1. Improving robustness in capacity expansion planning

Current capacity expansion models used in industry practice do not adequately account for the range of uncertainties and plausible futures created by changing climate conditions (section 3.3). The electricity planning literature (section 3.5) contains ample examples of approaches to uncertainty that would be appropriate if those uncertainties were shallow. However, deep uncertainties present in climate change impacts and responses make even stochastic approaches inadequate.

Fully embracing robustness methodologies from the decision science literature would involve running capacity expansion models with a full range of climate, policy, behavior, and technology scenarios to identify the wide range of plausible futures, then evaluating the performance of investment options to identify those that perform acceptably well across those futures. Such an effort could involve thousands of relevant scenario combinations, and extensive computational and human effort to create scenarios, track performance, and interpret outputs. This approach would undoubtedly present electricity sector decision-makers with valuable information, but may face practical barriers to implementation. A more incremental approach may help ensure buy-in and enable learning (as well as minimize mistakes) while implementing modifications to current industry practices. Alongside this initial incremental approach, there is an opportunity for the research community to investigate a much broader range of scenarios and develop recommended approaches for electricity sector decision-makers to utilize richer information in decision-making.

A key step towards building robustness into capacity expansion planning is to embrace the concept of multiple plausible futures rather than planning for one possible (however well-justified) future. In practice, this could mean that electricity sector planners:

(a) Develop scenarios of plausible climate change futures on the basis of projections from multiple climate models (without averaging). Consider that plausible futures may be more diverse than just low/medium/high climate change scenarios. (For example, of the ten climate projections recommended for use in California, four labeled as 'priority models' represent qualitatively different futures, including 'warm/dry' and 'cool/wet', see CalAdapt (2021).)
(b) Develop combined scenarios where different climate futures are considered alongside scenarios that account for uncertainties in demand growth, market, policy, and technology options (see also Giudici *et al* 2020). Risk mitigation options (e.g. greater deployment of batteries, demand response, operating reserves, and other strategies that contribute to system robustness) could also be included in combined scenarios.
(c) Select several of these combined scenarios that may complement and/or form a plausible range when evaluated in conjunction with a median combined scenario.
(d) Run capacity expansion models with a median and several range scenarios and evaluate investment needs for each.

(e) For each set of calculated investment needs, assess how these investments would perform under all other scenarios to identify vulnerabilities in investment choices (i.e. evaluate the counterfactual impacts or unmitigated risks of planning for a lower demand and climate impact scenario if instead a higher demand and climate impact scenario is realized).
(f) Evaluate thresholds for acceptable risks to how investments will perform and incorporate those thresholds into planning decisions.

Planners may also consider identifying which uncertainties are most consequential to the outcomes of interest and using those as a feedback loop to identify dimensions to explore further with additional scenarios. Such an approach, while limited in the number of scenarios assessed, would still create measurable progress towards building climate awareness and working with irreducible uncertainties.

4.2. Incorporating adaptive planning principles into capacity expansion decisions

Ranges of plausible outcomes can be defined for a variety of uncertainties, and adaptive planning principles can be used to refine those ranges as the future evolves. To aid this effort, decision-makers should develop a monitoring plan with input from modelers and stakeholders to identify signposts that signal when we need to take certain actions or change our planning assumptions. Notably, such adaptive planning principles were considered, though not ultimately prescribed, for inclusion in a recent CPUC decision requiring California's IOUs to publish climate vulnerability assessments (CPUC 2020a).

We offer three examples of signposts that could be applied to electricity sector planning in California:

(a) When California's Sierra Nevada snowpack reaches <30% of historical baseline for 3 continuous years (Siirila-Woodburn *et al* 2021), stop counting on late summer hydropower resources in future models and deploy battery storage instead.
(b) Define planning scenarios for low, medium, and high demand growth; if air conditioning adoption reaches >5% of households annually, know that we are in the high demand growth scenario.
(c) If wintertime peak electricity use due to heating electrification hits >80% of summertime peak, know that we need to start evaluating climate scenarios for their impact on cold months.

We stress that these are just example criteria. While the specific implementations of these signposts will vary, the key concept here is that setting signals now can aid which plausible futures are assessed and which assumptions are made in capacity expansion models over time. Furthermore, there may be organizational barriers to incorporate and implement adaptive planning. Decision-makers may need to formalize this concept at the beginning of the planning process and provide institutional support to reduce resistance for the potential adaptive measures. For example, the decision-making entity may establish a working group with stakeholders and experts, assign specific personnel to gather and analyze the data, and build stakeholder consensus on the specific adaptive measures.

4.3. Multi-stakeholder engagement in capacity expansion

Capacity expansion planning for regulated utilities occurs within public rate cases that provide opportunities for stakeholder involvement. However, the complexity of growing climate impacts on utility operations will require increased attention on multi-stakeholder engagement as a tool to identify and refine uncertainties, plausible futures, and paths forward. Decision-making entities such as utilities and regulatory bodies could consult boundary organizations to translate technical climate science information and complex planning processes between different stakeholders.

Broad stakeholder input and increased transparency is necessary at every step of the capacity expansion planning process:

(a) Determining appropriate inputs (climate data, demand data, infrastructure data).
(b) Identifying relevant uncertainties and appropriate numerical ranges for uncertain parameters.
(c) Developing salient robustness metrics to evaluate different capacity expansion policy outcomes under a range of plausible climate futures.
(d) Establishing consensus on planning goals.
(e) Evaluating each policy alternative's performance for different objectives and discussing tradeoffs among objectives.

Joint deliberation on how best to implement infrastructure plans must happen throughout the process in an iterative manner. At each step, key questions about the scope and mechanisms of stakeholder engagement efforts must be considered. For example: Who are the right set of participants to include, and how should conveners ensure they equitably represent necessary perspectives? Who will decide how stakeholder input should be weighted, resolve tensions, and balance the relative influence of different voices? What if some stakeholders do not want to engage and/or consensus is not possible? Further, what is the appropriate mechanism of and limits to stakeholder engagement, to ensure deliberations are not unduly sidetracked or prolonged at each step? These questions have been more thoroughly explored in the water sector than in the electricity sector, and evidence exists that insights from this work are not necessarily transferable between resource contexts (Rountree *et al* 2021). More foundational work is therefore needed here. Answering these questions is beyond the scope of the present review, but they merit additional focus in the context of climate-aware electricity sector planning.

5. Conclusions

Current planning processes in the electricity sector are not equipped to account for the stresses or uncertainties posed by a changing climate. Recent extreme weather events and service disruptions make it clear that climate change will continue to challenge electricity sector performance and operating practices. To better address these impacts, utility decision-making and planning approaches must incorporate a greater awareness of climate change and associated uncertainties. Here, we perform a three-part literature review to distill lessons from decision science researchers and assess how they might be incorporated into electricity sector planning to better account for the uncertainties posed by climate change.

First, we refer to the decision science literature to characterize climate-related uncertainties as shallow and deep uncertainties. This framework provides insights on how quantitative approaches may appropriately capture uncertainty. For example, shallow uncertainties (levels 1–3), where reasonable estimates of the relative likelihoods of different outcomes are possible, may be appropriately represented through probabilistic or trend-based scenarios. Deep uncertainties (levels 4–5), where multiple alternatives cannot be ranked by likelihood, cannot be reduced to statistical treatments.

Climate-induced uncertainties that must be considered in electricity sector planning include uncertainties in climate conditions as well as their direct and indirect impacts on electricity infrastructure, consumer behavior, and decision-maker responses. Efforts to characterize these uncertainties must consider complex interrelationships and deeply uncertain climate futures. Therefore, incorporating climate awareness into electricity sector planning will require making use of decision science practices that are equipped to handle deep uncertainty.

We distill three key ideas from decision science—robustness, adaptive planning, and multi-stakeholder engagement—that have been developed to deal with deep uncertainty and may help incorporate climate awareness into electricity sector planning and decision-making. Robustness requires considering multiple plausible futures and identifying planning approaches that perform acceptably well across them. Adaptive planning uses signposts and monitoring plans to refine plausible futures in time, building the institutional capacity to respond as climate conditions evolve. Multi-stakeholder engagement offers the potential to iteratively consider policy objectives and possible responses to adapt to new conditions, as well as to reconcile competing objectives.

Existing literature on electricity sector planning under climate change incorporates these key ideas to varying—but often only limited—degrees. However, existing tools that have been developed for use in the electricity sector, such as robust optimization and multi-stage modeling, can provide a scaffolding for implementing relevant insights from decision science.

Further, these three key ideas can guide action-oriented steps to build climate awareness in the electricity sector. We offer recommendations for how insights from these key ideas can be implemented within capacity expansion planning, a key area of decision-making in the electricity sector that is affected by all levels of uncertainty posed by climate change. Specifically, embracing the concept of multiple plausible futures, setting up signposts that signify tipping points as the future evolves, and including boundary organizations during stakeholder engagement can help electricity sector decision-makers better plan for the future.

Future work is needed to better connect lessons from decision science to industry practice. In particular, we suggest that social science research may provide insights on institutionalizing concepts of robustness and adaptive planning by decision-makers, and more effectively communicating uncertainty to and involving stakeholders in planning processes.

Climate change poses significant and ongoing challenges for critical infrastructure systems. Here, we offer some initial steps that can be taken today to help decision-makers incorporate climate awareness into electricity sector planning.

Data availability statement

No new data were created or analysed in this study.

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References

Abatzoglou J T, Smith C M, Swain D L, Ptak T and Kolden C A 2020 Population exposure to pre-emptive de-energization aimed at averting wildfires in Northern California *Environ. Res. Lett.* **15**

Ackerman F, DeCanio S J, Howarth R B and Sheeran K 2009 Limitations of integrated assessment models of climate change *Clim. Change* **95** 297–315

Araújo K and Shropshire D 2021 A meta-level framework for evaluating resilience in net-zero carbon power systems with extreme weather events in the united states *Energies* **14** 4243

Babovic F, Mijic A and Madani K 2018 Decision making under deep uncertainty for adapting urban drainage systems to change *Urban Water J.* **15** 552–60

Baldwin E, Rountree V and Jock J 2018 Distributed resources and distributed governance: stakeholder participation in demand side management governance *Energy Res. Soc. Sci.* **39** 37–45

Bale C S, Varga L and Foxon T J 2015 Energy and complexity: new ways forward *Appl. Energy* **138** 150–9

Barsugli J J *et al* 2013 The practitioner's dilemma: how to assess the credibility of downscaled climate projections *Eos* **94** 424–5

Bartholomew E and Kwakkel J H 2020 On considering robustness in the search phase of robust decision making: a comparison of many-objective robust decision making, multi-scenario many-objective robust decision making and many objective robust optimization *Environ. Modelling Softw.* **127** 104699

Beh E H, Maier H R and Dandy G C 2015 Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty *J. Am. Water Resour. Assoc.* **51** 1529–51

Ben-Haim Y 2004 Uncertainty, probability and information-gaps *Reliab. Eng. Syst. Safety* **85** 249–66

Berkhout F, van den Hurk B, Bessembinder J, de Boer J, Bregman B and van Drunen M 2014 Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments *Reg. Environ. Change* **14** 879–93

Bessani M, Massignan J A, Fanucchi R Z, Camillo M H, London J B, Delbem A C and Maciel C D 2019 Probabilistic assessment of power distribution systems resilience under extreme weather *IEEE Syst. J.* **13** 1747–56

Bhave A G, Conway D, Dessai S and Stainforth D A 2016 Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world *Clim. Risk Manage.* **14** 1–10

Bishop P, Hines A and Collins T 2007 The current state of scenario development: an overview of techniques *Foresight* **9** 5–25

Blau M, Waldman A and Wendland T 2021 Energy resisted upgrading New Orleans' power grid. Residents paid the price (NPR) (available at: www.npr.org/2021/09/22/1039110522/entergy-resisted-upgrading-new-orleans-power-grid-residents-paid-the-price)

Bloomfield H C, Brayshaw D J, Troccoli A, Goodess C M, De Felice M, Dubus L, Bett P E and Saint-Drenan Y M 2021 Quantifying the sensitivity of European power systems to energy scenarios and climate change projections *Renew. Energy* **164** 1062–75

Boardman A E, Greenberg D H, Vining A R and Weimer D L 2005 *Cost-Benefit Analysis: Concepts and Practice* (Cambridge: Cambridge University Press)

Bollinger L A *et al* 2014 Climate adaptation of interconnected infrastructures: a framework for supporting governance *Reg. Environ. Change* **14** 919–31

Bourne L 2016 Targeted communication: the key to effective stakeholder engagement *Proc. - Soc. Behav. Sci.* **226** 431–8

Brockway A M and Dunn L N 2020 Weathering adaptation: grid infrastructure planning in a changing climate *Clim. Risk Manage.* **30** 100256

Brown C, Ghile Y, Laverty M and Li K 2012 Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector *Water Resour. Res.* **48** 2011WR011212

Brunner L, Pendergrass A G, Lehner F, Merrifield A L, Lorenz R and Knutti R 2020 Reduced global warming from CMIP6 projections when weighting models by performance and independence *Earth Syst. Dyn.* **11** 995–1012

Bryant B P and Lempert R J 2010 Thinking inside the box: a participatory, computer-assisted approach to scenario discovery *Technol. Forecast. Soc. Change* **77** 34–49

Burillo D, Chester M V, Pincetl S and Fournier E 2019 Electricity infrastructure vulnerabilities due to long-term growth and extreme heat from climate change in Los Angeles County *Energy Policy* **128** 943–53

Busby J W, Baker K, Bazilian M D, Gilbert A Q, Grubert E, Rai V, Rhodes J D, Shidore S, Smith C A and Webber M E 2021 Cascading risks: understanding the 2021 winter blackout in Texas *Energy Res. Soc. Sci.* **77**

CalAdapt 2021 About climate projections and models (available at: https://cal-adapt.org/help/get-started/about-climate-projections-and-models)

Cao M F, Huang G H and Lin Q G 2010 Integer programming with random-boundary intervals for planning municipal power systems *Appl. Energy* **87** 2506–16

Carney S, Whitmarsh L, Nicholson-Cole S A and Shackley S 2009 A dynamic typology of stakeholder engagement within climate change research (available at: www.tyndall.ac.uk/sites/default/files/wp128.pdf)

Cash D, Clark W, Alcock F, Dickson N, Eckley N and Jäger J 2005 Salience, credibility, legitimacy and boundaries: linking research, assessment and decision making (https://doi.org/10.2139/ssrn.372280)

Chandramowli S N and Felder F A 2014 Impact of climate change on electricity systems and markets - a review of models and forecasts *Sustain. Energy Technol. Assess.* **5** 62–74

Chattopadhyay D, Spyrou E, Mukhi N, Bazilian M and Vogt-Schilb A 2016 Building climate resilience into power systems plans: reflections on potential ways forward for Bangladesh *Electr. J.* **29** 32–41

Chen H, Liu S, Liu Q, Shi X, Wei W, Han R and Küfeoglu S 2021 Estimating the impacts of climate change on electricity supply infrastructure: a case study of China *Energy Policy* **150** 112119

Chen Y, Lu H, Li J, Huang G and He L 2016 Regional planning of new-energy systems within multi-period and multi-option contexts: a case study of Fengtai, Beijing, China *Renew. Sustain. Energy Rev.* **65** 356–72

Clark W C, Tomich T P, van Noordwijk M, Guston D, Catacutan D, Dickson N M and McNie E 2011 Boundary work for sustainable development: natural resource management at the Consultative Group on Int. Agricultural Research (CGIAR) *Proc. Natl Acad. Sci.* **113** 4615–22

Clímaco J C 2004 A critical reflection on optimal decision *Eur. J. Oper. Res.* **153** 506–16

Conde C, Lonsdale K, Nyong A and Aguilar Y 2004 Engaging stakeholders in the adaptation process *Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures* (Cambridge: Cambridge University Press) pp 49–66

ConEd 2019a Electric case testimonies vol 3 *Technical Report* (Consolidated Edison Company of New York, Electric Infrastructure and Operations Panel)

ConEd 2019b Joint proposal in the proceeding on motion of the commission as to the rates, charges, rules and regulations of consolidated Edison Company of New York, Inc. for electric service *Technical Report* (Consolidated Edison Company of New York) (available at: https://documents.dps.ny.gov/public/MatterManagement/CaseMaster.aspx?MatterCaseNo=19-E-0065&submit=Search)

ConEd 2019c Climate change vulnerability study *Technical Report* (Consolidated Edison Company of New York) (available at: www.coned.com/en/our-energy-future/our-energy-vision/storm-hardening-enhancement-plan)

ConEd 2020 Report on 2019 capital expenditures and 2020-2024 electric capital forecast *Technical Report* (Consolidated Edison Company of New York)

CPUC 2020a Decision on energy utility climate change vulnerability assessments and climate adaptation in disadvantaged communities (phase 1, topics 4 and 5) *Technical Report* (California Public Utilities Commission) (available at: www.cpuc.ca.gov/industries-and-topics/electrical-energy/climate-change)

CPUC 2020b Decision addressing the test year 2020 general rate case of pacific gas & electric company *Technical Report* (California Public Utilities Commission) (available at: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M354/K486/354486687.PDF)

Cradock-Henry N A, Blackett P, Hall M, Johnstone P, Teixeira E and Wreford A 2020 Climate adaptation pathways for agriculture: insights from a participatory process *Environ. Sci. Policy* **107** 66–79

Craig M T, Cohen S, Macknick J, Draxl C, Guerra O J, Sengupta M, Haupt S E, Hodge B M M and Brancucci C 2018 A review of the potential impacts of climate change on bulk power system planning and operations in the United States *Renew. Sustain. Energy Rev.* **98** 255–67

Cuppen E, Bosch-Rekveldt M G, Pikaar E and Mehos D C 2016 Stakeholder engagement in large-scale energy infrastructure projects: revealing perspectives using Q methodology

Curry M D and Ross A M 2015 Considerations for an extended framework for interactive epoch-era analysis *Proc. Comput. Sci.* **44** 454–65

Dale L, Carnall M, Wei M, Fitts G and Lewis McDonald S 2018 Assessing the Impact of wildfires on the California electricity grid *Technical Report* (California Energy Commission) (available at: www.climateassessment.ca.gov/techreports/energy.html)

Deser C 2020 Certain uncertainty: the role of internal climate variability in projections of regional climate change and risk management *Earth's Future* **8** e2020EF001854

Dewar J A and Wachs M 1993 Transportation planning, climate change, and decision making under uncertainty *Technical Report* (RAND Corporation)

Difrancesco K N and Tullos D D 2015 Assessment of flood management systems' flexibility with application to the Sacramento River basin, California, USA *Int. J. River Basin Manage.* **13** 271–84

Dittrich R, Wreford A and Moran D 2016 A survey of decision-making approaches for climate change adaptation: are robust methods the way forward? *Ecol. Econ.* **122** 79–89

Döll P and Romero-Lankao P 2017 How to embrace uncertainty in participatory climate change risk management—a roadmap *Earth's Future* **5** 18–36

Doss-Gollin J, Farnham D J, Lall U and Modi V 2021 How unprecedented was the February 2021 Texas cold snap? *Environ. Res. Lett.* **16**

Energy Information Administration 2019 Investor-owned utilities served 72% of U.S. electricity customers in 2017 *Today in Energy* (available at: www.eia.gov/todayinenergy/detail.php?id=40913)

Figueiredo R, Nunes P and Brito M C 2021 The resilience of a decarbonized power system to climate variability: Portuguese case study *Energy* **224** 120125

Fletcher S, Hadjimichael A, Quinn J, Osman K, Giuliani M, Gold D, Figueroa A J and Gordon B 2022 Equity in water resources planning: a path forward for decision support modelers *J. Water Resour. Plan. Manage.* **148** 02522005

Fletcher S, Strzepek K, Alsaati A and De Weck O 2018 Learning and flexibility for water supply infrastructure planning under groundwater resource uncertainty *Doctoral Dissertation* Massachusetts Institute of Technology

Fonseca F R *et al* 2021 Effects of climate change on capacity expansion decisions of an electricity generation fleet in the southeast U.S. *Environ. Sci. Technol.* **55** 2522–31

Fouquet R 2016 Path dependence in energy systems and economic development *Nat. Energy* **1** 16098

Gacitua L, Gallegos P, Henriquez-Auba R, Lorca N-P M, Olivares D, Valenzuela A and Wenzel G 2018 A comprehensive review on expansion planning: models and tools for energy policy analysis *Renew. Sustain. Energy Rev.* **98** 346–60

Garber A M and Phelps C E 1997 Economic foundations of cost-effectiveness analysis *J. Health Econ.* **16** 1–31

Gardner J, Dowd A M, Mason C and Ashworth P 2009 A framework for stakeholder engagement on climate adaptation. CSIRO climate adaptation flagship working paper No.3 (availabel at: www.csiro.au/resources/CAF-working-papers.html)

Gerlak A K, Weston J, McMahan B, Murray R L and Mills-Novoa M 2018 Climate risk management and the electricity sector *Clim. Risk Manage.* **19** 12–22

Giudici F, Castelletti A, Giuliani M and Maier H R 2020 An active learning approach for identifying the smallest subset of informative scenarios for robust planning under deep uncertainty *Environ. Modelling Softw.* **127** 104681

Giuliani M and Castelletti A 2016 Is robustness really robust? How different definitions of robustness impact decision-making under climate change *Clim. Change* **135** 409–24

Gold D F, Reed P M, Trindade B C and Characklis G W 2019 Identifying actionable compromises: navigating multi-city robustness conflicts to discover cooperative safe operating spaces for regional water supply portfolios *Water Resour. Res.* **55** 9024–50

Gorelick D E, Zeff H B, Characklis G W and Reed P M 2018 Integrating raw water transfers into an eastern United States management context *J. Water Resour. Plan. Manage.* **144** 05018012

Grime M M and Wright G 2016 Delphi method *Wiley StatsRef: Statistics Reference Online* pp 1–6

Groves D G, Molina-Perez E, Bloom E and Fischbach J R 2019 Robust decision making (RDM): application to water planning and climate policy *Decision Making Under Deep Uncertainty: From Theory to Practice* (Cham: Springer International Publishing) ch 7, pp 135–63

Grubler A, Fuss S, McCollum D, Krey V and Riahi K 2011 Technology portfolios: modelling technological uncertainty and innovation risks *Energy Technology Innovation: Learning From Historical Successes and Failures* (Cambridge: Cambridge University Press) pp 89–102

Gundlach J 2020 Climate risks are becoming legal liabilities for the energy sector *Nat. Energy* **5** 94–97

Haasnoot M, Kwakkel J H, Walker W E and ter Maat J 2013 Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world *Glob. Environ. Change* **23** 485–98

Haasnoot M, van't Klooster S and van Alphen J 2018 Designing a monitoring system to detect signals to adapt to uncertain climate change *Glob. Environ. Change* **52** 273–85

Hall J W, Lempert R J, Keller K, Hackbarth A, Mijere C and Mcinerney D J 2012 Robust climate policies under uncertainty: a comparison of robust decision making and info-gap methods *Risk Anal.* **32** 1657–72

Hallegatte S 2009 Strategies to adapt to an uncertain climate change *Glob. Environ. Change* **19** 240–7

Hamarat C, Kwakkel J H and Pruyt E 2013 Adaptive robust design under deep uncertainty *Technol. Forecast. Soc. Change* **80** 408–18

Hanna R and Gross R 2021 How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity?

Implications for policy and practitioners *Energy Policy* **149** 111984

Hausfather Z and Peters G P 2020 Emissions - the 'business as usual' story is misleading *Nature* **577** 618–20

Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* **90** 1095–107

Heffron R J and McCauley D 2017 The concept of energy justice across the disciplines *Energy Policy* **105** 658–67

Heinrich G, Howells M, Basson L and Petrie J 2007 Electricity supply industry modelling for multiple objectives under demand growth uncertainty *Energy* **32** 2210–29

Herman J D, Reed P M, Zeff H B and Characklis G W 2015 How should robustness be defined for water systems planning under change? *J. Water Resour. Plan. Manage.* **141** 04015012

Herman J D, Zeff H B, Lamontagne J R, Reed P M and Characklis G W 2016 Synthetic drought scenario generation to support bottom-up water supply vulnerability assessments *J. Water Resour. Plan. Manage.* **142** 04016050

Herman J D, Zeff H B, Reed P M and Characklis G W 2014 Beyond optimality: multistakeholder robustness tradeoffs for regional water portfolio planning under deep uncertainty *Water Resour. Res.* **50** 7692–713

Hoekstra A, Steinbuch M and Verbong G 2017 Creating agent-based energy transition management models that can uncover profitable pathways to climate change mitigation *Complexity* **2017** 1967645

Hung S P and Chang S L 2017 The simulation and management of adaptive smart grid oriented power mix based on evolutionary dynamic mechanism under high percentage of renewable energy policy *PICMET 2016—Portland Int. Conf. on Management of Engineering and Technology: Technology Management For Social Innovation* (*Honolulu, HI, USA, September 2016*) pp 3017–45

Ioannou A, Angus A and Brennan F 2017 Risk-based methods for sustainable energy system planning: a review *Renew. Sustain. Energy Rev.* **74** 602–15

Jafino B A, Kwakkel J H and Taebi B 2021 Enabling assessment of distributive justice through models for climate change planning: a review of recent advances and a research agenda *WIREs Clim. Change* **12** e721

Jeuken A, Haasnoot M, Reeder T and Ward P 2015 Lessons learnt from adaptation planning in four deltas and coastal cities *J. Water Clim. Change* **6** 711–28

Ji L, Huang G H, Niu D X, Cai Y P and Yin J G 2020a A stochastic optimization model for carbon-emission reduction investment and sustainable energy planning under cost-risk control *J. Environ. Inform.* **36** 107–18

Ji L, Huang G H, Xie Y L, Niu D X and Song Y H 2017 Explicit cost-risk tradeoff for renewable portfolio standard constrained regional power system expansion: a case study of Guangdong Province, China *Energy* **131** 125–36

Ji L, Zhang B, Huang G, Cai Y and Yin J 2020b Robust regional low-carbon electricity system planning with energy-water nexus under uncertainties and complex policy guidelines *J. Clean. Prod.* **252** 119800

Johnson I 2012 Adapting Vermont' s transportation infrastructure to the future impacts of climate change *Technical Report* (Vermont Transportation Agency)

Kandlikar M, Risbey J and Dessai S 2005 Representing and communicating deep uncertainty in climate-change assessments *C. R. Geosci.* **337** 443–55

Kasprzyk J R, Nataraj S, Reed P M and Lempert R J 2013 Many objective robust decision making for complex environmental systems undergoing change *Environ. Modelling Softw.* **42** 55–71

Keirstead J, Jennings M and Sivakumar A 2012 A review of urban energy system models: approaches, challenges and opportunities *Renew. Sustain. Energy Rev.* **16** 3847–66

Kichonge B, John G R and Mkilaha I S 2015 Modelling energy supply options for electricity generations in Tanzania *J. Energy South. Afr.* **26** 41–57

Kirchmeier-Young M C, Zwiers F W and Gillett N P 2017 Attribution of extreme events in Arctic Sea ice extent *J. Clim.* **30** 553–71

Knutti R, Masson D and Gettelman A 2013 Climate model genealogy: generation CMIP5 and how we got there *Geophys. Res. Lett.* **40** 1194–9

Kuhn K D and Madanat S M 2005 Model uncertainty and the management of a system of infrastructure facilities *Transp. Res.* C **13** 391–404

Kujala H, Burgman M A and Moilanen A 2013 Treatment of uncertainty in conservation under climate change *Conserv. Lett.* **6** 73–85

Kunreuther H *et al* 2014 Integrated risk and uncertainty assessment of climate change response policies *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) ch 2, pp 151–206

Kwakkel J H, Haasnoot M and Walker W E 2016b Comparing robust decision-making and dynamic adaptive policy pathways for model-based decision support under deep uncertainty *Environ. Modelling Softw.* **86** 168–83

Kwakkel J H and Van Der Pas J W G 2011 Evaluation of infrastructure planning approaches: an analogy with medicine *Futures* **43** 934–46

Kwakkel J H, Walker W E and Haasnoot M 2016a Coping with the wickedness of public policy problems: approaches for decision making under deep uncertainty *J. Water Resour. Plan. Manage.* **142** 01816001

Kwakkel J H, Walker W E and Marchau V A 2010 Classifying and communicating uncertainties in model-based policy analysis *Int. J. Technol. Policy Manage.* **10** 299–315

Lacommare K, Larsen P and Eto J 2017 Evaluating proposed investments in power system reliability and resilience: preliminary results from interviews with public utility commission staff *Technical Report* LBNL-1006971 (Lawrence Berkeley National Laboratory) (https://doi.org/10.2172/1342947)

Lawrence J and Haasnoot M 2017 What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty *Environ. Sci. Policy* **68** 47–57

Leal Filho W, Stringer L C, Totin E, Djalante R, Pinho P, Mach K J, Carril L R F, Birkmann J, Pandey R and Wolf F 2021 Whose voices, whose choices? Pursuing climate resilient trajectories for the poor *Environ. Sci. Policy* **121** 18–23

Lehner F, Deser C, Maher N, Marotzke J, Fischer E M, Brunner L, Knutti R and Hawkins E 2020 Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6 *Earth Syst. Dyn.* **11** 491–508

Lempert R J and Collins M T 2007 Managing the risk of uncertain threshold responses: comparison of robust, optimum and precautionary approaches *Risk Anal.* **27** 1009–26

Lempert R J, Popper S W and Bankes S C 2003 *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis* (Santa Monica, CA: RAND Corporation) (https://doi.org/10.7249/MR1626)

Lempert R J and Turner S 2021 Engaging multiple worldviews with quantitative decision support: a robust decision-making demonstration using the lake model *Risk Anal.* **41** 845–65

Lempert R J 2019 Robust decision making (RDM) *Decision Making Under Deep Uncertainty: From Theory to Practice*, ed V A W J Marchau, W E Walker, P J T M Bloemen and S W Popper (Cham: Springer International Publishing) pp 23–51

Li F G, Trutnevyte E and Strachan N 2015 A review of socio-technical energy transition (STET) models *Technol. Forecast. Soc. Change* **100** 290–305

Li S, Coit D W, Selcuklu S and Felder F A 2014 Electric power generation expansion planning: robust optimization considering climate change *Proc. Industrial and Systems Engineering Research Conf.* pp 1049–58

Liang Y, Gillett N P and Monahan A H 2020 Climate model projections of 21st century global warming constrained using the observed warming trend *Geophys. Res. Lett.* **47** 1–10

Lin Q G, Zhai M Y, Huang G H, Wang X Z, Zhong L F and Pi J W 2017 Adaptation planning of community energy systems to climatic change over Canada *J. Clean. Prod.* **143** 686–98

Linkov I *et al* 2014 Changing the resilience paradigm *Nat. Clim. Change* **4** 407–9

Maier H R, Guillaume J H, van Delden H, Riddell G A, Haasnoot M and Kwakkel J H 2016 An uncertain future, deep uncertainty, scenarios, robustness and adaptation: how do they fit together? *Environ. Modelling Softw.* **81** 154–64

Marchau V, Walker W, Bloemen P and Popper S 2019 *Decision Making Under Deep Uncertainty. From Theory to Practice* (Cham: Springer International Publishing) (https://doi.org/10.1007/978-3-030-05252-2)

Masur J S and Posner E A 2011 Climate regulation and the limits of cost-benefit analysis *California Law Rev.* **99** 1557

Matrosov E S, Padula S and Harou J J 2013 Selecting portfolios of water supply and demand management strategies under uncertainty-contrasting economic optimisation and 'robust decision making' approaches *Water Resour. Manage.* **27** 1123–48

McMahan B and Gerlak A K 2020 Climate risk assessment and cascading impacts: risks and opportunities for an electrical utility in the U.S. Southwest *Clim. Risk Manage.* **29** 100240

McPhail C, Maier H R, Kwakkel J H, Giuliani M, Castelletti A and Westra S 2018 Robustness metrics: how are they calculated, when should they be used and why do they give different results? *Earth's Future* **6** 169–91

Meadow A M, Ferguson D B, Guido Z, Horangic A, Owen G and Wall T 2015 Moving toward the deliberate coproduction of climate science knowledge *Weather Clim. Soc.* **7** 179–91

Means E G, Laugier M C, Daw J A and Owen D M 2010a Impacts of climate change on infrastructure planning and design: past practices and future needs *J. Am. Water Works Assoc.* **102** 56–65

Means E, Laugier M, Daw J, Kaatz L and Waage M 2010b Decision support planning methods: incorporating climate change uncertainties into water planning *Technical Report* (Water Utility Climate Alliance)

Miara A, Cohen S M, Macknick J, Vörösmarty C J, Corsi F, Sun Y, Tidwell V C, Newmark R and Fekete B M 2019 Climate-water adaptation for future US electricity infrastructure *Environ. Sci. Technol.* **53** 14029–40

Moallemi E A, Elsawah S and Ryan M J 2020 Robust decision making and Epoch–Era analysis: a comparison of two robustness frameworks for decision-making under uncertainty *Technol. Forecast. Soc. Change* **151** 119797

Moallemi E A and Malekpour S 2018 A participatory exploratory modelling approach for long-term planning in energy transitions *Energy Res. Soc. Sci.* **35** 205–16

Mok K Y, Shen G Q and Yang J 2015 Stakeholder management studies in mega construction projects: a review and future directions *Int. J. Proj. Manage.* **33** 446–57

Moksnes N, Rozenberg J, Broad O, Taliotis C, Howells M and Rogner H 2019 Determinants of energy futures—a scenario discovery method applied to cost and carbon emission futures for South American electricity infrastructure *Environ. Res. Commun.* **1** 025001

Morgan M G, Henrion M and Small M 1990 *Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis* (Cambridge: Cambridge University Press)

Nahmmacher P, Schmid E, Pahle M and Knopf B 2016 Strategies against shocks in power systems—an analysis for the case of Europe *Energy Econ.* **59** 455–65

National Research Council 1977 *Climate, Climatic Change and Water Supply* (Washington, DC: The National Academies Press) (https://doi.org/10.17226/185)

Nierop S C 2014 Envisioning resilient electrical infrastructure: a policy framework for incorporating future climate change into electricity sector planning *Environ. Sci. Policy* **40** 78–84

NYPSC 2020 Order adopting terms of joint proposal and establishing electric and gas rate plan *Technical Report* (State of New York Public Service Commission) (available at: https://documents.dps.ny.gov/public/MatterManagement/CaseMaster.aspx?MatterCaseNo=19-E-0065&submit=Search)

O'Neill B C *et al* 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 *Geosci. Model Dev.* **9** 3461–82

O'Neill B C *et al* 2017 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* **42** 169–80

Panteli M and Mancarella P 2015 Influence of extreme weather and climate change on the resilience of power systems: impacts and possible mitigation strategies *Electr. Power Syst. Res.* **127** 259–70

Panula-Ontto J *et al* 2018 Cross-impact analysis of Finnish electricity system with increased renewables: long-run energy policy challenges in balancing supply and consumption *Energy Policy* **118** 504–13

Parkinson S C and Djilali N 2015 Robust response to hydro-climatic change in electricity generation planning *Clim. Change* **130** 475–89

Patt A and Dessai S 2005 Communicating uncertainty: lessons learned and suggestions for climate change assessment *C. R. Geosci.* **337** 425–41

Pereira G I, Specht J M, Silva P P and Madlener R 2018 Technology, business model and market design adaptation toward smart electricity distribution: insights for policy making *Energy Policy* **121** 426–40

Perera A T, Nik V M, Chen D, Scartezzini J L and Hong T 2020 Quantifying the impacts of climate change and extreme climate events on energy systems *Nat. Energy* **5** 150–9

Peter J 2019 How does climate change affect electricity system planning and optimal allocation of variable renewable energy? *Appl. Energy* **252** 113397

PG&E 2016 Climate change vulnerability assessment and resilience strategies *Technical Report* (November Pacific Gas & Electric Company) (available at: www.pgecurrents.com/wp-content/uploads/2016/02/PGE_climate_resilience.pdf)

Preston B L, Westaway R M and Yuen E J 2011 Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations *Mitig. Adapt. Strateg. Glob. Change* **16** 407–38

Rădulescu M A, Leendertse W and Arts J 2020 Conditions for co-creation in infrastructure projects: experiences from the overdiepse polder project (The Netherlands) *Sustainability* **12** 7736

Ralff-Douglas K 2016 Climate adaptation in the electric sector: vulnerability assessments and resiliency plans 27 (available at: www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work/PPD_Work_Products_(2014_forward)/PPD - Climate Adaptation Plans.pdf)

Ranger N 2010 Adaptation in the UK: a decision-making process *Technical Report* (Grantham Research Institute on Climate Change and the Environment) (available at: www.cccep.ac.uk)

Ranger N, Reeder T and Lowe J 2013 Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project *EURO J. Decis. Process.* **1** 233–62

Rayner S, Lach D and Ingram H 2005 Weather forecasts are for wimps: why water resource managers do not use climate forecasts *Clim. Change* **69** 197–227

Reed P M *et al* 2022 MultiSector dynamics: advancing the science of complex adaptive human-Earth systems *Earth's Future* **10** 1–18

Roach T, Kapelan Z, Ledbetter R and Ledbetter M 2016 Comparison of robust optimization and info-gap methods for water resource management under deep uncertainty *J. Water Resour. Plan. Manage.* **142** 04016028

Roelich K and Giesekam J 2019 Decision making under uncertainty in climate change mitigation: introducing multiple actor motivations, agency and influence *Clim. Policy* **19** 175–88

Rosenhead J, Elton M and Gupta S K 2017 Robustness and optimality as criteria for strategic decisions *J. Oper. Res. Soc.* **23** 413–31

Rountree V, Baldwin E and Hanlon J 2021 A review of stakeholder participation studies in renewable electricity and water: does the resource context matter? *J. Environ. Stud. Sci.* **12** 232–47

Rowe G and Frewer L J 2000 Public participation methods: a framework for evaluation *Sci. Technol. Human Values* **25** 3–29

Santos da Silva S R, Hejazi M I, Iyer G, Wild T B, Binsted M, Miralles-Wilhelm F, Patel P, Snyder A C and Vernon C R 2021 Power sector investment implications of climate impacts on renewable resources in Latin America and the Caribbean *Nat. Commun.* **12** 1276

Savage L J 1972 *The Foundations of Statistics* 2nd edn (New York: Dover Publications, Inc.)

Sellak H, Ouhbi B, Frikh B and Palomares I 2017 Towards next-generation energy planning decision-making: an expert-based framework for intelligent decision support *Renew. Sustain. Energy Rev.* **80** 1544–77

Sharmina M, Abi Ghanem D, Browne A L, Hall S M, Mylan J, Petrova S and Wood R 2019 Envisioning surprises: how social sciences could help models represent 'deep uncertainty' in future energy and water demand *Energy Res. Soc. Sci.* **50** 18–28

Siirila-Woodburn E R *et al* 2021 A low-to-no snow future and its impacts on water resources in the western United States *Nat. Rev. Earth Environ.* **2** 800–19

Simpson N P *et al* 2021 A framework for complex climate change risk assessment *One Earth* **4** 489–501

Smet K S M 2017 Engineering options: a proactive planning approach for aging water resource infrastructure under uncertainty *Doctoral Dissertation* Harvard University

Smith R, Zagona E, Kasprzyk J, Bonham N, Alexander E, Butler A, Prairie J and Jerla C 2022 Decision science can help address the challenges of long-term planning in the Colorado River Basin *J. Am. Water Resour. Assoc.* 1–11

Solman H, Smits M, van Vliet B and Bush S 2021 Co-production in the wind energy sector: a systematic literature review of public engagement beyond invited stakeholder participation *Energy Res. Soc. Sci.* **72** 101876

Sovacool B K, Heffron R J, McCauley D and Goldthau A 2016 Energy decisions reframed as justice and ethical concerns *Nat. Energy* **1** 16024

Spalding-Fecher R, Joyce B and Winkler H 2017 Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: system-wide impacts and policy implications *Energy Policy* **103** 84–97

Sridharan V *et al* 2019 Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation *Nat. Commun.* **10** 1–9

Stanton M C B and Roelich K 2021 Decision making under deep uncertainties: a review of the applicability of methods in practice *Technol. Forecast. Soc. Change* **171** 120939

Szolgayová J, Fuss S, Khabarov N and Obersteiner M 2012 Robust energy portfolios under climate policy and socioeconomic uncertainty *Environ. Model. Assess.* **17** 39–49

Taner M U, Ray P and Brown C 2017 Robustness-based evaluation of hydropower infrastructure design under climate change *Clim. Risk Manage.* **18** 34–50

Tebaldi C, Dorheim K, Wehner M and Leung R 2021 Extreme metrics from large ensembles: investigating the effects of ensemble size on their estimates *Earth Syst. Dyn.* **12** 1427–501

Teixeira B, Pinto T, Silva F, Santos G, Praça I and Vale Z 2018 Multi-agent decision support tool to enable interoperability among heterogeneous energy systems *Appl. Sci.* **8** 328

Tokarska K B, Stolpe M B, Sippel S, Fischer E M, Smith C J, Lehner F and Knutti R 2020 Past warming trend constrains future warming in CMIP6 models *Sci. Adv.* **6** eaaz9549

Tompkins E L, Few R and Brown K 2008 Scenario-based stakeholder engagement: incorporating stakeholders preferences into coastal planning for climate change *J. Environ. Manage.* **88** 1580–92

US Department of Energy 2016 Climate change and the electricity sector: guide for assessing vulnerabilities and developing resilience solutions to sea level rise *Technical Report*

van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

Voisin N, Dyreson A, Fu T, O'Connell M, Turner S W, Zhou T and Macknick J 2020 Impact of climate change on water availability and its propagation through the Western U.S. power grid *Appl. Energy* **276** 115467

Walker W E, Haasnoot M and Kwakkel J H 2013a Adapt or perish: a review of planning approaches for adaptation under deep uncertainty *Sustainability* **5** 955–79

Walker W E, Lempert R J and Kwakkel J H 2013b Deep Uncertainty *Encyclopedia of Operations Research and Management Science* ed S I Gass and M C Fu (Boston, MA: Springer US) pp 395–402

Walker W E, Marchau V A and Swanson D 2010 Addressing deep uncertainty using adaptive policies: introduction to section 2 *Technol. Forecast. Soc. Change* **77** 917–23

Walker W E, Rahman S A and Cave J 2001 Adaptive policies, policy analysis and policy-making *Eur. J. Oper. Res.* **128** 282–9

Wall T A, Walker W E, Marchau V A and Bertolini L 2015 Dynamic adaptive approach to transportation-infrastructure planning for climate change: San-Francisco-Bay-Area case study *J. Infrastruct. Syst.* **21** 05015004

Ward D M 2013 The effect of weather on grid systems and the reliability of electricity supply *Clim. Change* **121** 103–13

Weitzman M L 2009 On modeling and interpreting the economics of catastrophic climate change *Rev. Econ. Stat.* **91** 1–19

Willems S, Labeau P E, Maun J C, Vergnol A and Sprooten J 2019 Probabilistic Transmission Expansion Planning: on the effects of outcome variability on decision-making *Proc. 29th European Safety and Reliability Conf.* pp 3453–9

Witt T, Dumeier M and Geldermann J 2020 Combining scenario planning, energy system analysis and multi-criteria analysis to develop and evaluate energy scenarios *J. Clean. Prod.* **242** 118414

Wolak F A 2021 Long-term resource adequacy in wholesale electricity markets with significant intermittent renewables *SSRN Electron. J.* (available at: www.nber.org/system/files/chapters/c14586/c14586.pdf)

Workman M, Darch G, Dooley K, Lomax G, Maltby J and Pollitt H 2021 Climate policy decision making in contexts of deep uncertainty—from optimisation to robustness *Environ. Sci. Policy* **120** 127–37

World Association for Waterborne Transport Infrastructure 2020 Climate change adaptation planning for ports and inland waterways *Technical Report*

Yang Y, Ng S T, Xu F J, Skitmore M and Zhou S 2019 Towards resilient civil infrastructure asset management: an information elicitation and analytical framework *Sustainability* **11** 4439

Yzer J R, Walker W E, Marchau V A and Kwakkel J H 2014 Dynamic adaptive policies: a way to improve the cost-benefit performance of megaprojects? *Environ. Plan.* B **41** 594–612

Zeff H B, Kasprzyk J R, Herman J D, Reed P M and Characklis G W 2014 Navigating financial and supply reliability tradeoffs in regional drought management portfolios *Water Resour. Res.* **50** 4906–23