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UNCERTAINTY, SCENARIO ANALYSIS, AND LONG-TERM STRATEGIES: STATE OF PLAY AND A WAY FORWARD

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EXECUTIVE SUMMARY

Highlights

- The Paris Agreement invites countries to develop and communicate mid-century long-term low greenhouse gas (GHG) emission development strategies. Such strategies are subject to great uncertainty. This paper takes stock of how the long-term strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC) handle uncertainties.
- The most common sources of uncertainty involve future climate impacts, technological innovation and deployment, the availability of large-scale carbon removal solutions, and the reliability of current GHG emission data.
- Approaches to handling uncertainties include deferring full analysis of an uncertainty until more is known through research and data collection, making assumptions about uncertainty factors, and conducting sensitivity analysis or scenario analysis. Scenario analysis is the most diverse in its approaches to framing uncertainties.
- The use of scenario analysis in the submitted long-term strategies was reviewed and a model-assisted quantitative approach to improve scenario analysis was suggested. The paper examines the suggested approach through a quantitative model analysis and illustrates its benefits and applicability along with some limitations.
- Identifying and addressing material uncertainties can mitigate the vulnerability of long-term strategies. Scenario analysis is useful for that purpose and it can be strengthened with the model-assisted quantitative approach.

CONTENTS

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Context

The Paris Agreement invites countries to formulate and communicate mid-century long-term low GHG emission development strategies (LTSs) by 2020. Developing such strategies is a challenging task partly because the time frame extends across three decades and partly because of the need to deal with complex interactions among socioeconomic and biophysical systems. Despite the immense challenge, 11 countries had already submitted their LTSs to UNFCCC as of February 2019.

Review of the Long-Term Strategies

This working paper takes stock of the submitted LTSs to understand which uncertainties are perceived as important and how they are handled in developing the strategies. Countries perceive and acknowledge various uncertainties, including future climate impacts, technological innovations and deployment, the availability of large-scale carbon removal solutions, and the accuracy of current GHG inventory data. Countries' responses to those uncertainties vary. For example, some try to reduce uncertainty by gaining more knowledge, making simple assumptions about uncertainties, or applying sensitivity analysis or scenario analysis. This working paper builds on the assessment of the submitted 11 LTSs and a literature review to propose an analytical framework for diagnosing uncertainties and identifying their types and characteristics, thereby facilitating the choice of effective ways to handle them when developing an LTS.

Among the ways to handle uncertainties found in the assessment, scenario analysis is the most diverse in application. Nine out of 11 countries introduce scenarios to depict multiple future pathways that the countries might take in their LTSs. However, only two countries deliberately use scenarios to explore the impacts of material uncertainties, which is a common use of scenario analysis. In addition, most countries choose a handful of scenarios without clear explanations of how and why these are selected.

Experimenting with Quantitative Approach to Scenario Analysis

This paper suggests a model-assisted quantitative approach to scenario analysis as a way to improve scenario analysis for addressing uncertainty. When available data and modeling tools allow its use, the approach helps policymakers and analysts identify material uncertainties, a small set of policy-relevant scenarios, the vulnerability of policy options, and possible ways to mitigate the vulnerability. The method should thereby contribute to more robust and adaptive policies and strategies. To demonstrate its benefits and applicability, a quantitative scenario analysis was used to assess how policies designed to meet a defined target are affected differently when uncertainties are incorporated. The 2050 GHG emission targets of a hypothetical country were analyzed using the Energy Policy Simulator (EPS), a computer model developed by Energy Innovation LLC (Energy Innovation LLC 2019). To illustrate the effects of uncertainty in a manageable framework, the analysis was limited to five factors chosen to represent uncertainty in technological advances.

Identifying and addressing material uncertainties can mitigate the vulnerability of LTSs. Whether done quantitatively or, when data or models are lacking, qualitatively, scenario analysis is useful in addressing uncertainties. The approach suggested in this paper can improve and strengthen scenario analysis in exploring uncertainties and support the development of a more robust LTS.

Although the analysis demonstrates the effectiveness of the quantitative approach to scenario analysis, it also shows its limitations. The approach uses computerized models to experiment with a large number of scenarios, but models are not always available for some countries or sectors. In addition, the ability of models to represent reality may not be sufficient to make the analysis useful, and the variables in the models at hand may not be adequate to represent important uncertainties. More important, too much emphasis on model-assisted analysis may restrict the scope and the perspectives of the exploration of uncertainties to what is covered or represented by the available models. This could undermine the whole point of scenario analysis. To avoid too narrow a view, a well-thought-out combination of qualitative and quantitative approaches is important.

1. INTRODUCTION

The Paris Agreement (Article 4.19) and a decision by the 21st session of the Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC 2016 Decision 1/CP.21 [paragraph 35]) invite countries to formulate and communicate “mid-century, long-term low greenhouse gas emission development strategies” (LTSs) by 2020. Although a long-term strategy (LTS) is a valuable instrument in shaping a country’s low-emission development visions and the pathways to reaching them, as well as in informing near-term plans and actions, its development is inherently a challenging task.

One of the greatest challenges is uncertainty. Because LTSs have a long time horizon and economy-wide scope, fulfillment of the plans is subject to many factors that are uncontrollable, unpredictable, or even unknown. Nevertheless, as of February 2019, 11 countries had developed and communicated LTSs to UNFCCC.

This working paper is primarily intended for policy analysts who are developing or revising LTSs and may be interested in insights on how to address the challenges of uncertainty in LTS development. The paper may also be of interest to a wider audience, such as government officials and practitioners in international development organizations, civil society organizations, and consultancies who contribute to or advise governments on LTS development.

The paper reviews these LTSs to understand how uncertainties are perceived and addressed, and to develop insights that can inform the future development or revision of LTSs by countries. The review also examines the use of scenarios and pathways in LTSs as one means of incorporating uncertainties.

Building on the findings of the review of the strategies and a review of the literature, this paper suggests a way to improve the analysis of uncertainties. It proposes a framework to classify uncertainties and to guide the choice of how to handle them in the analysis for LTS development. It also makes a case for a quantitative approach to scenario analysis, when models and data are available, as a way to improve the effectiveness of scenario analysis to address uncertainty. To demonstrate its benefits and applicability, this paper develops an illustrative analysis based on a 2050 emissions reduction target for a hypothetical country. There is also a discussion of limitations to the quantitative approach to scenario analysis and of the importance of a good combination of qualitative and quantitative approaches.

Chapter 2 describes the review of the 11 LTSs submitted to UNFCCC that was made to understand how uncertainties have been perceived and addressed. It also reviews the use of pathways and scenarios that are used as ways to take uncertainties into account in LTSs. Chapter 3 proposes a framework to diagnose the characteristics of uncertainties as well as a quantitative approach to scenario analysis. Chapter 4 experiments with a quantitative approach to scenario analysis to demonstrate its applicability and potential value in identifying material uncertainties, developing policy-relevant scenarios, and providing insights for policy improvements. This is followed by a discussion of the limitations of the quantitative approach and a summary of findings.

2. REVIEW OF LONG-TERM STRATEGIES

A qualitative review of the LTSs communicated by 11 countries through the UNFCCC website[1] as of February 2019 was undertaken to examine the following aspects of those plans:

- Factors underlying perceived uncertainties explicitly acknowledged in LTSs
- Methods of handling uncertainties
- Use of future scenarios or pathways

“Uncertainty” can be interpreted differently. This paper follows the definition of the Intergovernmental Panel on Climate Change (2014, 155): “a cognitive state of incomplete knowledge that results from a lack of information and/or from disagreement about what is known or even knowable.” The review of LTSs looked for relevant key words, such as “uncertain,” “variability,” “unknown,” “not known,” “knowledge gap,” “poorly understood,” “not understood,” “lack of agreement,” and “lack of information/knowledge” as signs of perceived uncertainty. The scope of analysis includes only uncertainty that is perceived; that is, explicitly acknowledged in LTSs, as this serves as the basis for understanding the uncertainties of most concern to countries.

The terms “assume” or “assumption” may also imply perceived uncertainties. For example, there were references to the assumptions made about future fuel prices and gross domestic product (GDP) growth rates in the described analyses in LTSs of multiple countries. However, in many cases, assumptions seem to be made for the mixed reasons of addressing incomplete knowledge (i.e., uncertainty) and simplifying the analysis. For instance, the words "assume" and "assumption" are used 164 times in Fiji's LTS (Government of Fiji 2019), which includes references to factors of relatively minor importance, such as the average energy consumption of a television. Because this review was interested in countries' perceptions of important sources of uncertainties, the factors attached to the terms "assume" or "assumption" were not collected unless they were also accompanied by one of the other key words listed above.

2.1. Uncertainties Acknowledged in Long-Term Strategies

Table 1 summarizes the main uncertainties explicitly acknowledged in the LTSs, categorized into five broad issues: climate impacts, greenhouse gas (GHG) emissions, technological developments, carbon removal options, and socioeconomic variables. It also lists how the uncertainties were handled in developing the LTSs. The table is not meant to be a comprehensive or exhaustive list of uncertainties and the ways they are handled in LTSs; it is an attempt to capture the overall characteristics of perceived uncertainties that countries are concerned about as well as the main types of handling uncertainties. A more detailed list is provided in Appendix A.

Table 1 | **Uncertainties Acknowledged in the LTSs and How They Were Handled**

ISSUES	UNCERTAINTIES	HOW UNCERTAINTY WAS HANDLED IN LTS DEVELOPMENT
Climate impacts	New infectious diseases (Benin)	Noted
	Climate variability (impacting agriculture) (Benin)	Noted
	Numerous knowledge gaps in future physical changes, their impacts on economy and society, and feasibility and resource availability of adaptation options (Marshall Islands)	Full analysis deferred (prompting research and data collection)
GHG accounting and historical emissions	Amount of fugitive emissions from hydraulic fracturing to extract shale gas (Canada)	Full analysis deferred (prompting research and data collection)
	GHG emissions from land sector (forestry, agriculture) (Fiji, France, United Kingdom, United States)	Full analysis deferred (prompting research and data collection) or assumptions made
	Various current data, such as energy loss in power grid, fuel used for power generation and land, sea, and air transport (Fiji, Marshall Islands)	Full analysis deferred (prompting research and data collection) or assumptions made
Technological development, innovation, acceptance, and deployment	Growth of electricity grid storage capacity and future change in energy storage cost (Fiji)	Assumptions made or noted
	Household behaviors of vehicle choice (France)	Assumptions made
	Shift in consumer behavior toward more overnight electric vehicle (EV) charging (United Kingdom)	Full analysis deferred (prompting research and data collection)
	Role of electrification and hydrogen in emissions reduction from heating homes and businesses, and the transport system (United Kingdom)	Scenario analysis
	Growth of clean vehicles (United States)	Scenario analysis

Table 1 | **Uncertainties Acknowledged in the LTSs and How They Were Handled (Cont'd)**

ISSUES	UNCERTAINTIES	HOW UNCERTAINTY WAS HANDLED IN LTS DEVELOPMENT
Availability of carbon removal options	Feasibility of large-scale deployment of carbon removal technologies (Canada)	Full analysis deferred (prompting research and data collection)
	A lack of consensus about how many potential storage sites for carbon capture and storage (CCS) are available (Germany)	Noted
	Carbon removal potential of coastal wetland restoration ("blue carbon"), particularly mangroves (Fiji)	Full analysis deferred (prompting research and data collection)
	Input data for the analysis of the impacts of land use, land-use change, and forestry (LULUCF) sector policies on GHG emission dynamics (Ukraine)	Noted
	Role of bioenergy with carbon capture, usage, and storage (CCUS), making CCUS a viable option for industry (United Kingdom)	Scenario analysis
	Potential and economic viability of increased land sector carbon sequestration and carbon removal technologies (United States)	Scenario analysis
Socioeconomic variables	Current and future population in informal communities and the number of tourists (Fiji)	Assumptions made
	Changes in the renovation cost per dwelling over time (France)	Assumptions made
	Energy consumption by residential heating in energy consumption analysis (France)	Assumptions made
	The level of household borrowing for financing renovation work, the rate of building renovation in service sector, and an increase in energy efficiency in industry sector (France)	Sensitivity analysis
	Solar financing availability (Marshall Islands)	Full analysis deferred (prompting pilot actions)
	Fixed and variable costs, and demand projections, among others, in medium- and long-term electricity demand–supply planning (Mexico)	Full analysis deferred (prompting research and data collection)

Notes: Ways of handling uncertainties include the following categories:

- Noted: Uncertainties are acknowledged but no explicit indication of how to address them was found.
- Full analysis deferred (prompting research and data collection): The impacts of the identified uncertainty were not fully analyzed in the development of the current LTS. Future activities are intended to increase knowledge and understanding to reduce uncertainties.
- Assumptions made: Assumptions were made about the identified uncertainties to enable analysis.
- Scenario analysis: Scenarios were developed with deliberately differentiated assumptions about uncertainties to analyze the impacts and implications of the uncertainties.
- Sensitivity analysis: Analysis was conducted to test the sensitivity of outcomes of interest to variation in uncertainty factors.
- Full analysis deferred (prompting pilot actions): The impacts of the identified uncertainty were not fully analyzed in the development of the current LTS. Instead, future experimental activities are intended to test new technologies, practices, business models, etc., to gain knowledge and understanding and thereby reduce uncertainties and increase confidence.

A number of conclusions can be drawn from this table. First, climate impact uncertainties are acknowledged in developing countries' LTSs. Benin (Government of Benin 2016), Fiji (Government of Fiji 2019), the Marshall Islands (Government of Republic of the Marshall Islands 2018), and Mexico (Government of Mexico 2016) include adaptation in their LTSs and acknowledge uncertainties regarding physical changes and their impacts. For example, the Republic of the Marshall Islands notes overwhelming knowledge gaps in numerous areas of climate change impacts and considers filling those gaps to be a pressing issue. Benin expresses strong concern over climate variability, particularly variable precipitation and the consequences for agriculture.

Second, continued efforts are required to reduce uncertainty in GHG accounting. Fiji, France (Government of France 2017), the United Kingdom (Government of the United Kingdom 2018), and the United States (Government of the United States 2016) acknowledge significant uncertainty related to land sector GHG accounting because of its technical challenges, and they are all committed to further research to improve it. Canada identifies the fugitive emissions from hydraulic fracturing to extract shale gas as a source of uncertainty in GHG accounting. The government of the Marshall Islands perceives a lack of data on energy loss in the power grid and on fuel use for power generation and transport. Although such data would appear to be fairly basic, other developing countries may face similar challenges. Collecting data is fundamentally important in the effort to identify and quantify current sources of emissions and develop effective policies to reduce them.

Third, clean vehicle technologies are viewed as a key factor for decarbonization. Innovation and dissemination of any technology is always uncertain, but France, the United Kingdom, and the United States view the deployment of clean vehicle technologies, such as EV and fuel cell vehicles (FCVs), as a material uncertainty in their decarbonization pathways.

Fourth, large-scale carbon removal is an important element of strategies for decarbonization. The potential and feasibility of carbon removal through natural and technological approaches, such as bioenergy with carbon capture and storage (BECCS), are considered particularly important to achieve decarbonization, as carbon removal is referred to in all LTSs, and yet the availability of carbon removal at scale is viewed as uncertain by several countries. Notably, the United Kingdom and United States construct their pathways toward a low-carbon future with a range of assumptions about the availability of carbon removal options.

Fifth, lack of agreement can be a significant source of uncertainty. Stakeholders may disagree over their understanding of the current situation, future projections, and the preferability or effectiveness (or both) of policies. A lack of consensus can create major uncertainty in policy development and actions but it is little mentioned in the 11 country LTSs that were studied. However, Germany acknowledges a lack of consensus about how many potential storage sites for CCS are available (Government of Germany 2016).

2.2. Ways of Handling Uncertainties

Countries take different ways of addressing perceived uncertainties. These can be classified into the following categories. The classification below does not include those cases "noted" in Table 1, where uncertainties are merely noted or are acknowledged but the follow-up actions are not clearly stated in the LTS.

- Full analysis deferred (prompting reduction of uncertainty through research and data collection)
- Full analysis deferred (prompting pilot actions)
- Making assumptions
- Sensitivity analysis
- Scenario analysis

Countries may identify uncertainties but decide to defer full analysis of their impacts and prompt additional future research, data collection, and pilot actions to reduce uncertainty, which will improve the implementation of an LTS and future LTS updates. It is, however, not clear how these uncertainties were considered in developing the current LTS. They may not have been included in the scope of the analysis and therefore are not reflected in the current LTS, or some assumptions may have been made to enable its development. Actions to reduce uncertainty are useful when it can be reduced by gaining more information, which is not always the case. Because resources are limited, policymakers must decide how to set priorities and allocate resources toward reducing different uncertainties.

Assumptions are often made to prevent uncertainties from entirely stopping model-based analysis. Simplified assumptions are made about input data, model parameters, or relationships between variables in the face of a lack of information or knowledge of such factors. A model is, in a way, made of a set of assumptions, whether they be parameters, functional forms, or even exclusion of some parameters or functions, with different confidence levels. The assumptions referred to in Table 1 are by no means the only assumptions made in analyses of LTSs, but these are noteworthy because countries expressed perceived uncertainties about them. Making assumptions is a reasonable approach if the systems surrounding the uncertainty factors are reasonably well understood and if their impacts on the outcomes of interest are considered relatively small. Assumptions can lead to unwelcome surprises if they turn out to be wrong and their impacts are significant.

Some countries (France and the United Kingdom) use sensitivity analysis to examine the potential impacts of changes in uncertainty factors on the outcome of interest. Different methods of sensitivity analysis (Box 1) are available and care must be taken to choose the right method for the circumstances (Saltelli and Annoni 2010; Pianosi et al. 2016). If the level of understanding of the system is low and there is no model available, or if a model does not adequately represent real-world conditions, sensitivity analysis may not be useful (Pilkey and Pilkey-Jarvis 2007).

The United Kingdom and the United States use scenario analysis to demonstrate how uncertainty factors affect the course of actions implemented to attain the goals of LTSs. The use of scenario techniques in social policy issues as “a methodological tool for policy planning and decision making in complex and uncertain environment” dates back to the 1960s (Bradfield et al. 2005, 799) and it is now widely used for climate-related policy analyses (Trutnevyte et al. 2016). It enables the exploration of multiple possible futures, contingent on uncertainties, and the implications for policy planning. In the policy planning context, the scenario analysis is often used to analyze and demonstrate implications of alternative policy options, or to explore the impacts of uncertainties on policy options. It is a flexible tool applicable to diverse settings that can be applied with both quantitative and qualitative approaches, including with a combination of both. Quantitative approaches generally need reasonably reliable models and data in their application; qualitative approaches are less dependent on them.

Although sensitivity analysis focuses on quantifying the effects of changes in input factors on outputs, scenario analysis focuses on finding, quantitatively or qualitatively, meaningful sets of conditions that materially affect the outcome of interest. These two approaches are not mutually exclusive and can be applied in combination. For example, a multivariate sensitivity analysis technique can help a scenario analysis identifying material uncertainties and policy-relevant scenarios.

Box 1 | **Sensitivity Analysis**

- Sensitivity analysis is an analytical technique to examine and attribute the change in outputs of an analysis to the variation of input factors (e.g., data, parameters, and functional forms to relate variables). It is widely used. One example of a common application is found in economic analyses of investments where the technique is used to examine sensitivity of a cost-benefit indicator (e.g., net present value or economic internal rate of return) to variation in uncertain parameters, thereby evaluating the potential impact of uncertainty on the economic viability judgment of investments, and identifying the most influential uncertain parameter or parameters.
- The most common use of sensitivity analysis is as a one-factor-at-a-time approach that examines the impact of variation of one factor at a time, keeping other factors equal, and as a local sensitivity analysis that examines the impact of deviation from a particular set of input values (e.g., baseline or reference) (Ferretti et al. 2016). However, these approaches are not appropriate in many cases as they do not allow exploration of the full range of uncertainties (Saltelli and Annoni 2010) or examination of the effects of interactions of more than one factor.

2.3. Applications of Scenario Analysis

The previous section identified five ways of handling uncertainties, which can be employed in combination. Among those ways, the most detailed information provided and the most diverse approaches to framing uncertainties are observed for scenario analysis. This section reviews the applications of scenario analysis in the LTS to understand current practices in scenario analysis and explore potential for improvement. The review shows that scenarios are used to address the issue of uncertainty but also to highlight various other issues of importance in developing LTSs.

Mitigation scenarios

The mitigation scenarios sought in this review are projections of the future with regard to mid-century nationwide GHG emissions logically derived from assumptions and data. They have to be future projections rather than visions, objectives, targets, or plans. In other words, scenarios describe what may happen, instead of what to do or achieve. Nine out of the 11 LTSs describe scenarios or pathways to illustrate possible future GHG emissions trajectories. Table 2 summarizes characteristics of those scenarios and pathways (in this section, those scenarios and pathways are collectively referred to as "scenarios" unless otherwise noted). Additional descriptions of the scenarios are provided in Appendix B. The scenarios are neither predictions nor plans of the future. Rather, they are illustrations of possible futures that inform discussions on challenges, opportunities, and required measures to achieve a country's mid-century emission reduction goals or visions.

The Czech Republic (Government of Czech Republic 2018), Fiji (Government of Fiji 2019), and Ukraine (Government of Ukraine 2018) present scenarios that would achieve their national emissions reduction goals and visions and others that would not achieve them (Box 2). This approach shows that a broad range of policies and measures have to be applied in combination to achieve the emissions reduction goals.

Table 2 | **Characteristics of Mid-Century GHG Emission Scenarios Presented in LTSs**

COUNTRY	NO. OF SCENARIOS PRESENTED	STATED PURPOSES OF INTRODUCING SCENARIOS	DIFFERENCES AMONG SCENARIOS
Benin	0	n/a	n/a
Canada	6	Canada's LTS including the scenarios is meant "[t]o inform the conversation about how Canada can achieve a low-carbon economy," as well as "outlines potential GHG abatement opportunities, emerging key technologies, and identifies areas where emissions reductions will be more challenging and require policy focus in the context of a low-carbon economy by 2050." (Government of Canada 2016, 5)	Six scenarios are selected from those proposed by three organizations using different models. Projected domestic emissions reduction in 2050 of the six scenarios ranges from 50% (including process emissions) to 88% below 2015 level with different sector scopes. They differ in assumptions of the level of deployment of various technologies and other factors such as economic growth rate and oil price.
Czech Republic	8	To "show that the 2050 target cannot be achieved without the combination of many different measures, especially in the energy production and consumption." (Government of Czech Republic 2018, 9)	Eight scenarios are developed using the same model with varied levels of deployment of nuclear power, renewable energy (RE), energy efficiency (EE), energy imports, and CCS as well as economic conditions. Among the eight scenarios, one assumes business-as-usual (BAU) (as reference), four do not meet the emissions reduction target, and three meet the emissions reduction target.
Fiji	4	Not explicitly mentioned	Among four scenarios, the BAU unconditional and BAU conditional scenarios assume implementation of existing policies with existing technologies without or with external financial supports, respectively. The two other scenarios assume more ambitious policies with new technologies at different levels. Of those, only the very high ambition scenario is projected to achieve Fiji's vision of net zero GHG emissions by 2050.

Table 2 | **Characteristics of Mid-Century GHG Emission Scenarios Presented in LTSs (Cont'd)**

COUNTRY	NO. OF SCENARIOS PRESENTED	STATED PURPOSES OF INTRODUCING SCENARIOS	DIFFERENCES AMONG SCENARIOS
France	2	The reference scenario—the only presented scenario that can achieve the GHG emissions goal—is meant: ■ To illustrate "the magnitude of the efforts to be made as well as the expected transformations and co-benefits" ■ To present "a possible path for achieving" its objectives and "allow qualitative and quantitative analysis of any discrepancies over time" ■ To "enable short- and medium-term sector-specific recommendations" (Government of France 2017, Summary for decision-makers, 6)	One (trend-based) scenario assumes only current measures in place, which does not meet the emission reduction target, while the other (reference) scenario takes account of additional measures and is compatible with the emission reduction target. These two scenarios are compared not only in terms of their emissions reduction in 2050 but also of wider social and economic impacts, such as employment, economic growth, and investments.
Germany[a]	0	n/a	n/a
Mexico	3	The quantitative analysis that formed the basis of the scenarios is meant: ■ To "advance the understanding" of its "mitigation options" ■ To "guide long-term action, as it helps in identifying critical actions to scale-up mitigation" (Government of Mexico 2016, 71)	Three scenarios assume different sets of policy measures, resulting in different GHG emissions trajectories to 2050. One of the three is the baseline scenario, which assumes no climate or energy constraints are imposed, and it naturally will not achieve the 2050 vision.
Republic of the Marshall Islands (RMI)	3	■ To "provide illustrative examples of the range of options available, and the kind of measures that might need to be implemented to achieve them, as well as to suggest next steps" ■ To "provoke discussions as to what might be the best way forward for RMI to contribute to achieving the temperature goals of the Paris Agreement" ■ To "facilitate making progress towards achieving RMI's aspiration of net zero GHG emissions by 2050" (Government of Republic of the Marshall Islands 2018, 11)	Two sets of policy measures are assumed; one is more ambitious than the other, resulting in different levels of GHG emissions in 2050. The more ambitious set of policies is applied to two out of the three scenarios but with 15 years' difference in deployment, resulting in different emissions trajectories and levels in 2050 between the two scenarios.
Ukraine	Energy and industrial process sector: 5 LULUCF sector: 3	Not explicitly mentioned	For the energy and industrial process sector, the first scenario is BAU. The second scenario adds EE policies, and the third scenario adds RE policies on top of the second scenario. The fourth scenario adds a range of policies to bring technological advances to the energy sector (e.g., plant operation, nuclear, hydrogen, smart grid, energy storage) and the transportation sector to the third scenario. The fifth scenario adds various regulatory and market policies (e.g., carbon pricing, GHG disclosure mandate for firms, and eco-labeling) to the fourth scenario. In this way, the five scenarios illustrate the emissions reduction effects of additional policy packages. Three out of five scenarios are consistent with Ukraine's mid-century vision of reducing emissions in this sector to 31%–34% of the 1990 level. A similar approach is used to construct three scenarios for the LULUCF sector, which result in three different levels of projected carbon sequestration.

Table 2 | **Characteristics of Mid-Century GHG Emission Scenarios Presented in LTSs (Cont'd)**

COUNTRY	NO. OF SCENARIOS PRESENTED	STATED PURPOSES OF INTRODUCING SCENARIOS	DIFFERENCES AMONG SCENARIOS
United Kingdom	3	■ To "identify low-regrets steps" the UK "can take in the next few years common to many versions of the future, as well as key technologies and uncertainties" ■ To "demonstrate a range of practical ways in which emission reduction aims can be delivered with technology known today, and to underline some of the steps common to all" (Government of the United Kingdom 2018, 55, 56)	All three scenarios (pathways) are compatible with the UK emission reduction target in 2050 but adopt different assumptions as to the three material uncertainty factors identified in the LTS; i.e., the role of electrification, the role of hydrogen, and the role of BECCUS.
United States	7	The analysis that formed the basis of the scenarios is meant: ■ To "describe key opportunities and challenges associated with . . . illustrative pathways, and highlight findings that are robust across scenarios" ■ To "explore multiple low-GHG pathways consistent with the MCS [Mid-Century Strategy] vision" (Government of the United States 2016, 7, 30)	Among seven scenarios, six scenarios are constructed in such a way that their projected emissions in 2050 will be 80% below the 2005 level; the remaining scenario envisages more than 80% reduction. The first six scenarios differ in assumptions of three material uncertainty factors identified in the LTS; i.e., the potential and economic viability of increased land sector carbon sequestration, the potential and economic viability of carbon removal technologies, and growth in clean vehicles.

Note: n/a means not applicable.

[a] Germany's LTS was developed based on various existing scenarios (Wagner and Tibbe 2019), but those scenarios are not described in the LTS. Those existing scenarios include 2050 climate change scenarios by Öko-Institute and Fraunhofer ISI with 80% and 95% emissions reduction in 2050, and GHG-Neutral Germany 2050 by the German Federal Environment Agency with 95% emissions reduction by 2050 (Wagner and Tibbe 2019).

Scenarios in France's LTS provide detailed analysis of the potential effects of policies beyond GHG emissions reduction, including their projected effects on socioeconomic factors such as employment, levels of investment, and economic growth. Ukraine and the United Kingdom also provide some general descriptions of possible social and economic effects of delivering the LTS goals, but they are not linked to specific scenarios. Scenario-specific information on projected impacts related to multiple socioeconomic objectives would be valuable in engaging a broad range of stakeholders with different interests and to facilitate discussions on potential synergies and trade-offs among different objectives in the transition process toward decarbonization.

The Marshall Islands LTS describes two scenarios with the same policy package but with 15 years' difference in the start year to illustrate the differences in emissions trajectories and emission levels in 2050. The timing issue is important in long-term planning and experimenting with the effects of shifting deployment timing is a good use of scenario analysis.

The United Kingdom and the United States construct a set of scenarios with different assumptions about various material uncertainties. This is a typical way of using scenario analysis to explore the impacts of uncertainty. It enables the exploration of a range of potential impacts of uncertainty factors under policy options, and identifies common options across scenarios that are relatively unaffected by uncertainty, which indicates they are robust and low-regret options. It also provides insights into the factors that drive or divide emissions pathways and, therefore, should be monitored or targeted for efforts to influence their direction.

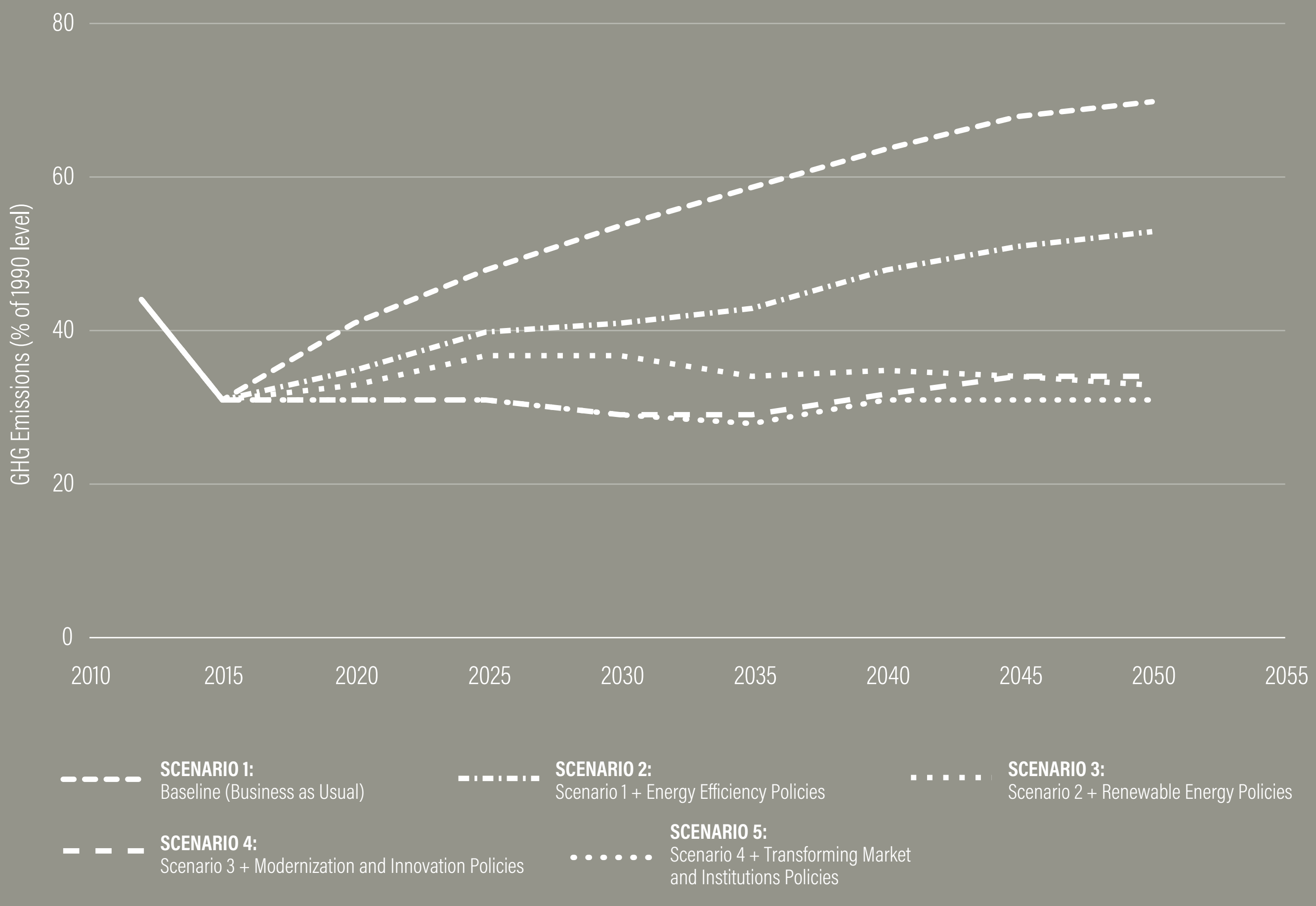
Canada selects six scenarios developed by three organizations using different models and assumptions (Government of Canada 2016). This is one way to assess structural uncertainties originating from models (DeCarolis 2011).

As noted, scenario analysis is often used to analyze and demonstrate implications of alternative policy options, or to explore the impacts of uncertainties on policy options. Although the use of scenarios in the LTSs of the Czech Republic, Fiji, France, Mexico, the Republic of the Marshall Islands, and Ukraine gives more emphasis to demonstrating the implications (particularly on GHG emissions) of alternative policy options, some of them also explore the impacts of external factors such as economic recession (Czech Republic) and availability of external support (Fiji). On the other hand, scenarios in the LTSs of Canada, the United Kingdom, and the United States illustrate what different assumptions about uncertain external factors affect the policy options that are to be adopted to achieve the set emission targets. The United States also explores the implications of alternative policy options by demonstrating the Beyond 80 scenario.

Box 2 | Scenario of Ukraine's Long-Term Strategy

Ukraine takes a systematic approach to scenario setting—four sets of emissions reduction policy packages in the energy and industrial process sectors are added one by one to create five scenarios to assess the effects of the additional policy package. The 2050 emissions projection in the third scenario, with two policy packages, is slightly lower than that of the fourth scenario, with three policy packages (third scenario plus a policy package to bring a range of advanced technologies to energy and transportation sectors), which is perhaps counterintuitive. The emissions trajectory of the fourth scenario shows fast emissions reduction until 2035 but emissions increase afterwards toward 2050. The Ukraine LTS mentions that the third scenario ends up with a higher share of renewable energy than the fourth scenario. The result indicates that policies may interfere with each other, reducing overall effectiveness in terms of emissions reduction, and demonstrates the usefulness of the model-assisted scenario analysis. The possibility of interference is difficult to identify otherwise, given the complexity of the systems involved.

FIGURE B2.1. UKRAINE'S PROJECTED EMISSIONS TRAJECTORIES



Source: Based on data from Ukraine's LTS (Government of Ukraine 2018), modified by the authors

Climate change scenarios and adaptation

Benin, Fiji, Mexico, and the Marshall Islands include adaptation in their LTSs. They all refer to climate change scenarios as the basis for their adaptation strategy. For instance, Benin describes projections of changes in precipitation patterns; Mexico explains its own climate change scenarios of changing temperature and precipitation and uses them for vulnerability analysis; and the Marshall Islands LTS refers to three sea-level-rise scenarios. These analyses qualitatively link climate scenarios and desired outcomes and are useful in identifying vulnerabilities and developing adaptation measures. However, they do not adequately address questions such as how effective planned adaptation measures would be in reducing vulnerabilities, how much more effort may be required, and which measures are more effective than others and therefore deserving of more resources.

Qualitative analysis of climate change impacts and adaptation strategies to respond to them contrasts with the quantitative mitigation scenario analysis countries undertake, where the effectiveness of mitigation measures is simulated by projecting GHG emissions after implementation of the measures. A major difficulty with developing quantitative models that can assess the effects of adaptation measures is that, in many cases, they involve complex interactions of socioeconomic and biophysical systems. Where resources and capacities are available to undertake such modeling, introducing model-assisted quantitative scenario analysis for adaptation would help advance development of long-term adaptation strategies.

3. OPPORTUNITIES TO IMPROVE SCENARIO ANALYSIS

Chapter 2 reviewed current practices for identifying uncertainties and described the use of scenario analysis as an approach to addressing uncertainties. This chapter discusses how to improve those practices, first by developing a framework to diagnose characteristics of uncertainties so as to consider adequate ways to handle them in LTS development, and then by proposing an approach for improving scenario analysis.

3.1. Framework for Better Understanding of Uncertainties

A systematic analytical framework could help identify material uncertainties and build effective strategies to mitigate their risks or take advantage of their opportunities. Although there are many conceptual frameworks proposed in different fields for different purposes, there is little agreement among them (Ascough et al. 2008; Walker et al. 2003). For example, frameworks designed to understand and handle uncertainties surrounding environmental modeling, environmental impact assessment, and environmental disaster management are different (Bodde et al. 2018), partly because aspects of uncertainty relevant to each field are different. Not surprisingly, the existing frameworks do not seem ideal for understanding and classifying uncertainties that countries often face in LTS development. In the absence of a readily available framework, this paper suggests a relatively simple framework that is built on those suggested by Walker et al. (2003) and Brugnach et al. (2008) (Box 3).

Table 3 shows the analytical framework proposed in this paper, which draws on the work described in Box 3. It consists of three dimensions: the level of understanding of the system, the nature of uncertainty, and the influence of the factor. The first two are equivalent to the “level” and “nature” dimensions of Walker et al. (2003), but “disagreement” is added to the nature of uncertainty, reflecting the view of Brugnach et al. (2008). The three types of uncertainty are not mutually exclusive. In other words, a factor of uncertainty can take the nature of any mix of the three. For example, the amount of carbon that can or should be sequestered over 20 years may be uncertain because it relies on technological innovations (unpredictability), there is not enough information on the availability of suitable storage sites (incomplete knowledge), and people may disagree on the preferability of CCS over other options (disagreement). Influence refers the potential magnitude of impact of the uncertainty on the outcomes of interest. The table also provides some points to consider when deciding the way to handle uncertainties. This framework is meant to be a heuristic guide for diagnosing uncertainties in LTS development.

Box 3 | Theoretical Background of Analytical Framework for Diagnosing Uncertainties

Walker et al. (2003) proposed a "three-dimensional concept" of uncertainty that consists of "location," "nature," and "level" dimensions. The framework is intended primarily for model-based decision analyses.

"Location" concerns where the uncertainty lies within the model—whether in the boundary setting of the system, the relationship of variables, the parameters, input data, or model outcomes. The "nature" dimension distinguishes between "epistemic" and "variability" uncertainty: the former stems from a lack of knowledge and information; the latter is caused by the intrinsic unpredictability of the system behaviors. An important implication of this distinction is that the epistemic uncertainty is at least possible to reduce through research and data collection; variability uncertainty is not, because it stems from natural randomness as well as from certain aspects of nonrational human choices and behaviors, and from complex socioeconomic dynamics.

The "level" dimension measures the degree of understanding of the system of interest. It grades the state of understanding within a range from "determinism" (perfect knowledge) at one end to "total ignorance" at the other.

Walker et al. (2003) caution that it is also necessary to assess the magnitude of influence of the uncertainty factors on the outcomes because even ignorance (high level of uncertainty) of a factor may have little influence on the outcomes of interest and, therefore, may not be relevant.

Brugnach et al. (2008) suggest a framework that distinguishes between "incomplete knowledge" and "unpredictability," which are similar to "epistemic" and "variability" uncertainties in the terminology of Walker et al., but adds another type of uncertainty: "multiple knowledge frames." This additional type of uncertainty can be observed in situations where there is no agreement among stakeholders on interpretations or projections of the system concerned. Even if the system concerned is well understood, stakeholders may express different yet equally legitimate opinions because of the differences in their beliefs, values, disciplinary perspectives, and so on. Separating this category from the other two is meaningful in policymaking contexts because disagreements require distinct coping strategies, such as extensive stakeholder dialogues.

On the basis of those considerations, an analytical framework for diagnosing uncertainties was developed that consists of three dimensions; i.e., level of understanding of the system, the nature of uncertainty, and the influence of the factor.

Table 3 | Proposed Analytical Framework for Diagnosing Uncertainty

DIMENSION	CHARACTERISTICS	POINTS TO CONSIDER IN DECIDING HOW TO HANDLE UNCERTAINTIES
Level of understanding of the system	High (able to make reliable projections)	■ Model-based analysis will be useful. ■ Although the level of understanding of the system is high, there may still be uncertainty in input data.
	Medium (able to make projections on the basis of facts, data, and reason but without high confidence)	■ There is a need to be cautious of the models' limitations and reliability when implementing model-based analysis. ■ There is a need to seek robust and adaptive policies. Robust policies are capable of achieving objectives regardless of uncertain factors.
	Low (unable to make projections on the basis of facts, data, and reason)	■ It is difficult to assess the impacts of uncertainties. ■ There is a need to invest in research to improve the level of understanding. ■ There is a need to seek robust and adaptive policies.
Nature of uncertainty	Incomplete knowledge	■ Gaining more information and knowledge may be able to reduce uncertainty.
	Unpredictability	■ Gaining more information and knowledge cannot reduce uncertainty.
	Disagreement	■ Stakeholder engagement, communication, dialogues, etc., are needed.
Influence of the factor	Influential or indeterminable	■ Making simple assumptions may be risky.
	Not influential	■ Making assumptions makes sense. ■ Investing resources in gaining more information and knowledge may not be worthwhile.

Source: Based on the frameworks suggested by Walker et al. (2003) and Brugnach et al. (2008).

3.2. Getting More Out of Scenario Analysis

It is clear that scenario analysis is widely used in LTSs and it is applied in different ways, reflecting issues of interest for each country. Although such flexibility is a strength of scenario analysis, this paper proposes some approaches that could increase the utility of scenario analysis. More specifically, countries could use scenario analysis to "stress test" their LTSs against multiple futures, to identify their potential vulnerability to uncertainties, and to find ways to make them more robust in achieving their objectives regardless of how the future unfolds (Lempert et al. 2003).

Design scenarios to explore the impacts of material uncertainties

Scenario analysis is a useful tool to explore the potential impacts of material uncertainties and develop effective strategies to address them. This purpose would be better served by designing scenarios with different assumptions regarding the material uncertainties. The United States and the United Kingdom take this approach in their scenario analysis, but other countries do not demonstrate explicit links between the uncertainty factors acknowledged and the scenario selected. This approach will yield additional policy insights and facilitate common understanding of the potential impacts of uncertainties among stakeholders involved in the development and implementation of the LTS.

Test policies against different futures

Figure 1 illustrates two conceptual boundaries of scenarios. External factors are beyond the direct control of policymakers, whereas policies are controllable. External factors and policies interact in the system and produce outcomes. In the context of developing a long-term mitigation strategy, for example, the system represents the socioeconomic and biophysical system of the country, and one of the outcomes of interest is the GHG emissions level in the future.

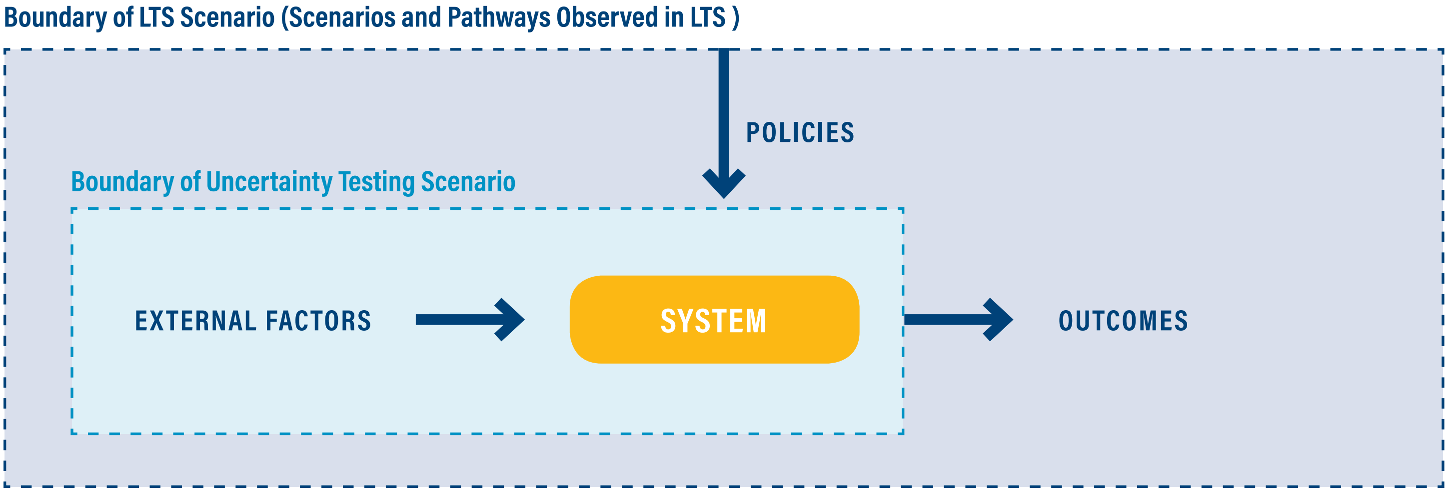
Note that uncertainty can exist in all components of Figure 1. Uncertainty in external factors results from the incomplete or insufficient quantity or quality of input data and parameters. This type of uncertainty is often referred to as "parameter uncertainty" or "parametric uncertainty." There can be uncertainty in the system because of incomplete knowledge or the intrinsic unpredictability and complexity of the system, which is often referred to as "system uncertainty" or "structural uncertainty." There may also be uncertainty in policies because not all policies can be fully implemented and policies themselves may unexpectedly shift over time. The uncertainty in outcomes is the principal object of interest in policy analyses, and scenario analysis can shed light on the relationship between the outcome uncertainty and the uncertainty in other components.

All scenarios or pathways found in LTSs (the "LTS scenario" in Figure 1) describe possible futures that would result from certain sets of policies, external factors, systems, and outcomes. In other words, they encompass all elements shown in Figure 1. However, the approach proposed here helps in exploring uncertainties and their impacts on outcomes of policies: for that purpose, it is more convenient to redefine the conceptual boundary of scenarios separated from policies and outcomes. This conceptual boundary of scenarios (the "uncertainty testing scenario" in Figure 1), aligns with those commonly found in the literature of scenarios analysis (Spaniol and Rowland 2018). The uncertainty testing scenario is defined here to represent a set of assumptions of external factors with different levels of uncertainty, and a system of interest. In other words, the uncertainty testing scenario deals with parameter uncertainty and system uncertainty.

By separating policies from scenarios that now consist of external factors and a system, and testing policies against different scenarios, the analysis can offer richer insights on the vulnerability and opportunities of policies against uncertainties as well as the way to improve them. This does not mean that policies do not involve any uncertainty. On the contrary, the implementation, future continuity, and evolution of policies also involve uncertainty. Nonetheless, the framework proposed here focuses on the analysis of the vulnerabilities of policies against uncertainties in external factors and systems. The implications of policy uncertainties can be analyzed in addition to the analysis suggested in this paper.

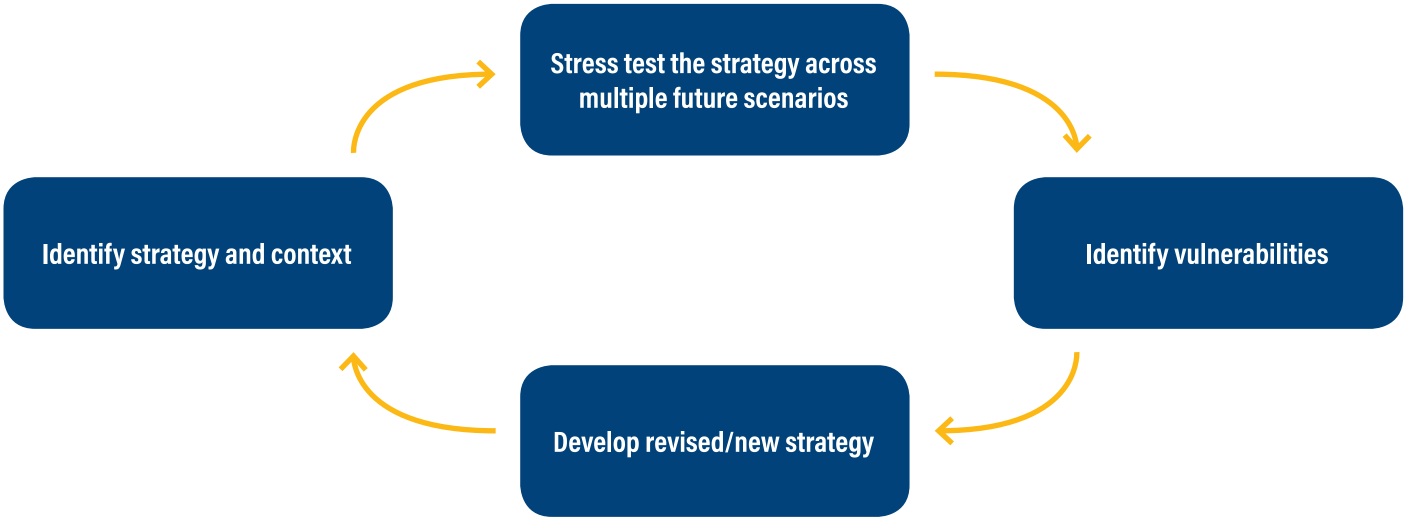
Figure 2 depicts the process of scenario analysis suggested in this paper which is based on the Robust Decision Making (RDM) framework (Lempert et al. 2003). It starts by identifying strategies and the context in which the strategies are assessed. This is different from a traditional planning approach of predicting the future first and then developing the optimal strategy under the predicted future, which is fraught with dangers when the future is deeply uncertain (Lempert et al. 2013). The next step is to stress test the strategies against multiple future scenarios and identify their potential vulnerabilities. The understanding of vulnerabilities leads to the development of revised or new strategies. Then the same process is repeated until robust strategies that would perform well under many future scenarios are identified.

Figure 1 | **Conceptual Boundaries of Scenarios**



Note: "System" here represents the socioeconomic and biophysical system of the country that produces the outcomes of interest.
Source: Based on Kwakkel (2017), modified by the authors.

Figure 2 | **Process of the Proposed Scenario Analysis**



Source: Based on Lempert (2018b), modified by the authors.

Explore a broader range of uncertainties and pursue multiple objectives

As Lempert (2018a) and Trutnevyte et al. (2016) indicate, scenario analysis can provide richer policy insights by exploring a broader range of uncertainties. The number of scenarios presented in the studied LTSs ranges from two to eight, but how each number of scenarios was selected from an infinite number of possible future scenarios is not explained. Some LTSs, such as those of France and the United States, mention that a larger set of scenarios was examined but the extent to which uncertainty was explored is not clear. The range of scenarios explored in current LTSs appears rather limited; expanding the range will make it possible to develop more robust and adaptive strategies that are able to attain the desired outcome across diverse future scenarios.

Scenarios that show only future GHG emissions levels may have little appeal to many stakeholders. To communicate effectively, engage with a broad range of stakeholders, and bolster support for the LTS, it is important that scenario analysis be able to show multiple socioeconomic outcomes that will benefit the country along with climate mitigation or adaptation outcomes. Such socioeconomic outcomes may include, for example, economic outputs, unemployment rate, international trade balance, and averted premature human deaths from air pollution.

Exploring a broader range of uncertainties while projecting impacts on multiple objectives is a complex task, but modern computing technologies make it possible (Kwakkel et al. 2016b; Kwakkel et al. 2016a; Matrosov et al. 2013; Guivarch et al. 2017). One of the key features of computer-assisted methods is the ability to help develop and apply a large number of diverse scenarios to each policy package, and boil them down to a small set of policy-relevant scenarios by identifying particular combinations of material uncertainties with their value ranges that are likely to affect the outcomes of interest (giving threats or good surprises) (Lamontagne et al. 2018; Trutnevyte et al. 2016). The scenarios are differentiated by material uncertainties to illustrate vulnerabilities and opportunities of each strategy and inform robust near-term policy options. Although many such quantitative approaches to scenario analysis have been proposed, they have not been widely applied yet and should be tested in a variety of cases (Guivarch et al. 2017). Partly because the development of LTSs has a short history, there is no literature known to the authors of case studies on the application of quantitative approaches to scenario analysis in LTS development.

4. A QUANTITATIVE APPROACH TO SCENARIO ANALYSIS

4.1. Process and Framing of the Analysis

The following analysis examines a model-assisted quantitative approach to scenario analysis to demonstrate its benefits and applicability and identify limitations. Uncertainty is, by definition, difficult to understand, present, and discuss among stakeholders. A number of sophisticated analytical and decision support methods that are potentially useful for this challenging task have been developed and discussed in the scientific community; for example, Maier et al. (2016) offer a systematic review of recent developments in decision analysis and support approaches under uncertainty. However, stakeholders involved in LTSs largely have not harnessed this advancement. The approach suggested here is a relatively simple and basic form of the RDM framework (Lempert et al. 2003), and yet it could help analysts assess, visually present, and facilitate the discussion and understanding of uncertainty among stakeholders involved in LTS development.

Take, as an example, a hypothetical country whose goal is to reduce net GHG emissions in 2050 by 80 percent relative to 2005 levels. Three policy packages that would equally achieve the goal under one default scenario are developed. The impacts of uncertainty on policy outcomes, including GHG emissions, are examined by applying 1,000 scenarios, each one involving different values of uncertainty factors. The intention is to analyze and demonstrate how the three equivalent policy packages may perform differently once uncertainties are taken into account. The analysis also attempts to identify material uncertainty factors, policy-relevant scenarios, and possible measures to increase the robustness of policy packages under those uncertainties.

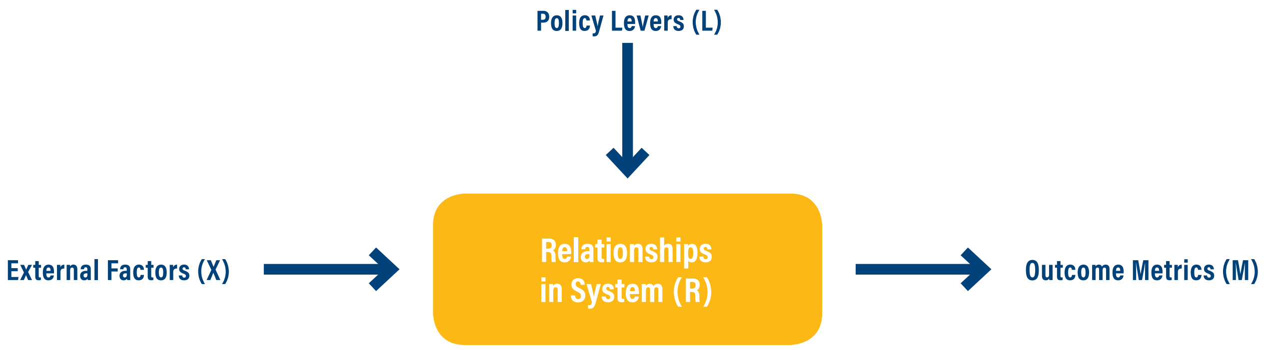
The analysis presented here is for demonstration purposes only and the policy packages were developed arbitrarily, without assessment of their plausibility. The results of this analysis should not be interpreted as policy recommendations.

The analysis uses the XLRM framework proposed by Lempert et al. (2003) (Figure 3). The factors of the XLRM framework used in the analysis are summarized in Table 4. And although the proposed approach of undertaking scenario analysis to assess uncertainty can take both parameter uncertainty and system uncertainty into account, the analysis of the hypothetical example deals only with parameter uncertainty.

Relationships in system (R)

"Relationships in system" refers to the mechanism that governs interactions of factors, including external factors and policy levers, and eventually produces outcomes of interest. Such relationships can be described in various scopes and forms. In this paper, a computerized model represents the relationship in order to harness the power of quantitative analysis. The model used is the EPS model developed by Energy Innovation: Policy and Technology LLC (2019). It was first released in October 2015 and has been continuously updated. The latest model can be downloaded from the company's website[2] and operates on a simulation software, Vensim. EPS had been developed for seven countries as of February 2019 and its coverage is expanding. This paper uses the EPS model version 1.4.2 (released on August 14, 2018) and the EPS default input data set for the United States to model the scenarios of the hypothetical country.

Figure 3 | **The XLRM Framework**



Source: Based on Kwakkel (2017), modified by the authors.

Table 4 | **XLRM Framework: Factors Used in the Analysis**

EXTERNAL FACTORS (X)	POLICY LEVERS (L)
Technological innovations: ■ Percentage reduction in battery EV cost ■ Percentage reduction in capital cost of onshore wind power generation ■ Percentage reduction in capital cost of offshore wind power generation ■ Percentage reduction in capital cost of solar photovoltaic (PV) system ■ Percentage reduction in CCS capital cost	■ Tax-oriented policy package ■ Intermediate policy package ■ Regulation-oriented policy package
RELATIONSHIPS IN SYSTEM (R)	**OUTCOME METRICS (M)**
■ Energy Policy Simulator (EPS), version 1.4.2	■ Net GHG emissions in 2050 ■ Net present value (NPV) of total expenditures on capital investment, fuels, and operation and maintenance relative to BAU

Source: Developed on the basis of the framework of Lempert et al. (2003).

EPS is a system dynamics model that is able to represent the entire economy, encompassing major sectors that affect net GHG emissions, such as transportation, electricity, industry, buildings, and LULUCF. It is an open-source, accessible, well-documented model. It does not require any special computing resources and can be run on ordinary personal computers. A default data set is provided along with the model; simulations can be undertaken without additional data collection.

Outcome metrics (M)

"Outcome metrics" refers to indicators used to assess the outcomes of interest. The primary outcome of interest is net GHG emissions in 2050, which can be compared with the hypothetical LTS target of an 80 percent reduction relative to the 2005 level. The 80 percent reduction brings the emissions level to 1,318 million metric tons of carbon dioxide equivalent (MtCO$_2$e), which is considered the benchmark value.

In the context of LTS development, net GHG emissions are rarely the only concern for countries, and multiple objectives need to be considered. EPS provides some economic and social outcome indicators such as emissions of non-GHG air pollutants, human lives saved through reduced particulate pollution, and various financial metrics. In this paper, the NPV of total expenditures in capital investments, fuels, and operation and maintenance (O&M), with a revenue-neutral carbon tax, relative to the BAU scenario (NPV total expenditures), is selected as the additional outcome metric. The reason behind this is, in part, that policy cost is one of the primary decision elements in any policy planning, and in part that other outcome indicators are more likely to be correlated to GHG emission indicators than policy cost indicators would be.

NPV total expenditures aggregates the capital costs, fuel costs, and O&M costs borne by all economic actors in the model—industry, consumers, and government—between 2017 and 2050, which is the duration of the simulation. In calculating NPV, EPS uses the discount rate of 3 percent by default. NPV total expenditures does not include subsidies paid by the government but does include taxes paid by industry and consumers, such as a fuel tax. However, a carbon tax is the exception; it is treated as revenue neutral; that is, the amount collected as carbon tax is subtracted from total expenditures.

Policy levers (L)

"Policy levers" refers to policy measures that policymakers can plan and implement. EPS provides numerous policy levers to test their impacts on outcomes. Here, these policy levers were combined to develop three sets of policy packages: "tax-oriented," "intermediate," and "regulation-oriented" (Table 5). The specific policy levers in each of the three packages are detailed in Appendix C. The "intermediate" policy package is so called because its policy levers are set between those of the other two policy packages. All these policy levers were arbitrarily set for the purpose of this analysis with no assessment of their plausibility. The authors do not endorse any particular combination of policies. Using the EPS default set of input data, the projected net GHG emissions in 2050 resulting from all three packages are roughly equivalent to the benchmark emission of 1,318 MtCO$_2$e. The intention here is to examine how the three policy packages—with equivalent performance in terms of projected net GHG emissions in 2050 under the default data set—may perform differently once uncertainties are taken into account.

Table 5 | **Characteristics of the Three Illustrative Policy Packages**

POLICY PACKAGE	CARBON TAX RATE	LEVEL OF REGULATORY STANDARDS
1. Tax-oriented	High	Low
2. Intermediate	Medium	Medium
3. Regulation-oriented	Low	High

External factors (X)

"External factors" generally represents exogenous factors that cannot be controlled directly by policymakers. For most external factors, values included in the EPS default data set are used as they are. External factors in question here are those representing uncertainties.

A number of exogenous factors may be regarded as uncertain, but this paper limits those included to those representing the uncertainty of technological innovations, which is one of the common types of uncertainty illustrated in Table 1.

Table 6 shows the uncertainty factors selected in this analysis and the projected average cost reductions before introducing uncertainty. By default, EPS calculates the capital cost reduction of some nascent technologies, including EVs, offshore and onshore wind power, solar PV, and CCS, on the basis of cumulative capacity installed or units deployed. This effect is often called "endogenous learning" or just "learning."[3] The EPS default data set includes learning rates for these technologies. The last column indicates the percentage of cost reduction by 2050 through endogenous learning, which is averaged across the three policy packages.

In principle, a plausible range of values should be set for each uncertainty factor, but for the demonstrative purpose of this analysis, the ranges are set arbitrarily for the sake of simplicity. To determine the value ranges, average cost reduction percentages in 2050, relative to the first year of the three policy packages for each technology (average reduction) were calculated with the EPS default data set (Table 6). Then the range of uncertainty was set in such a way that cost reduction percentages vary between −50% (lower limit) and +100% (upper limit) of the average reduction.[4]

Table 7 shows the calculated lower and upper limits of each factor. A negative percentage means a slowdown in the cost reduction from endogenous learning. To apply these five factors in the simulations, EPS policy levers representing the effects of research and development were used. In EPS, these policy levers are originally intended to represent technological progress because of research and development enabled by policies. In this paper, however, they represent unexpected accelerations or slowdowns of technology cost reductions that are not caused by policy interventions.

Table 6 | **Average Capital Cost Reduction of Different Technologies over Three Policy Packages Calculated by the EPS Model**

	FIRST-YEAR (2017) AVERAGE COST	LAST-YEAR (2050) AVERAGE COST	AVERAGE REDUCTION (%)[a]
EV (passenger light-duty vehicles) cost	$36,331	$29,267	19.4
Onshore wind capital cost[b]	$1.54 million	$1.20 million	22.3
Offshore wind capital cost[b]	$5.41 million	$3.90 million	27.8
Solar PV capital cost[b]	$1.20 million	$0.80 million	33.0
CCS capital cost[c] (electricity sector)	$ 41.9	$ 25.4	39.2
CCS capital cost [c] (industry sector)	$126.2	$ 76.7	39.2

Notes: All monetary values are expressed in 2012 U.S. dollars.

[a] Average reduction does not necessarily coincide with the reduction calculated with the first- and last-year average costs shown here because of the difference in rounding digits.

[b] Construction cost per unit capacity (MW)

[c] CCS capital cost to sequester one ton of CO_2 per year

Table 7 | **External (Uncertainty) Factors Analyzed**

UNCERTAINTY FACTORS	VALUE RANGE	
	LOWER LIMIT	UPPER LIMIT
1. Percentage of additional reduction in battery EV cost	−12.1%	24.1%
2. Percentage of additional reduction in capital cost of onshore wind power generation	−14.4%	28.7%
3. Percentage of additional reduction in capital cost of offshore wind power generation	−19.3%	38.5%
4. Percentage of additional reduction in capital cost of solar PV system	−24.6%	49.1%
5. Percentage of additional reduction in CCS capital cost	−32.2%	64.5%

Note: The value ranges are set arbitrarily for this illustrative analysis.

According to the functional relationships in the EPS, CCS capital cost reduction affects the NPV total expenditures but not GHG emissions.

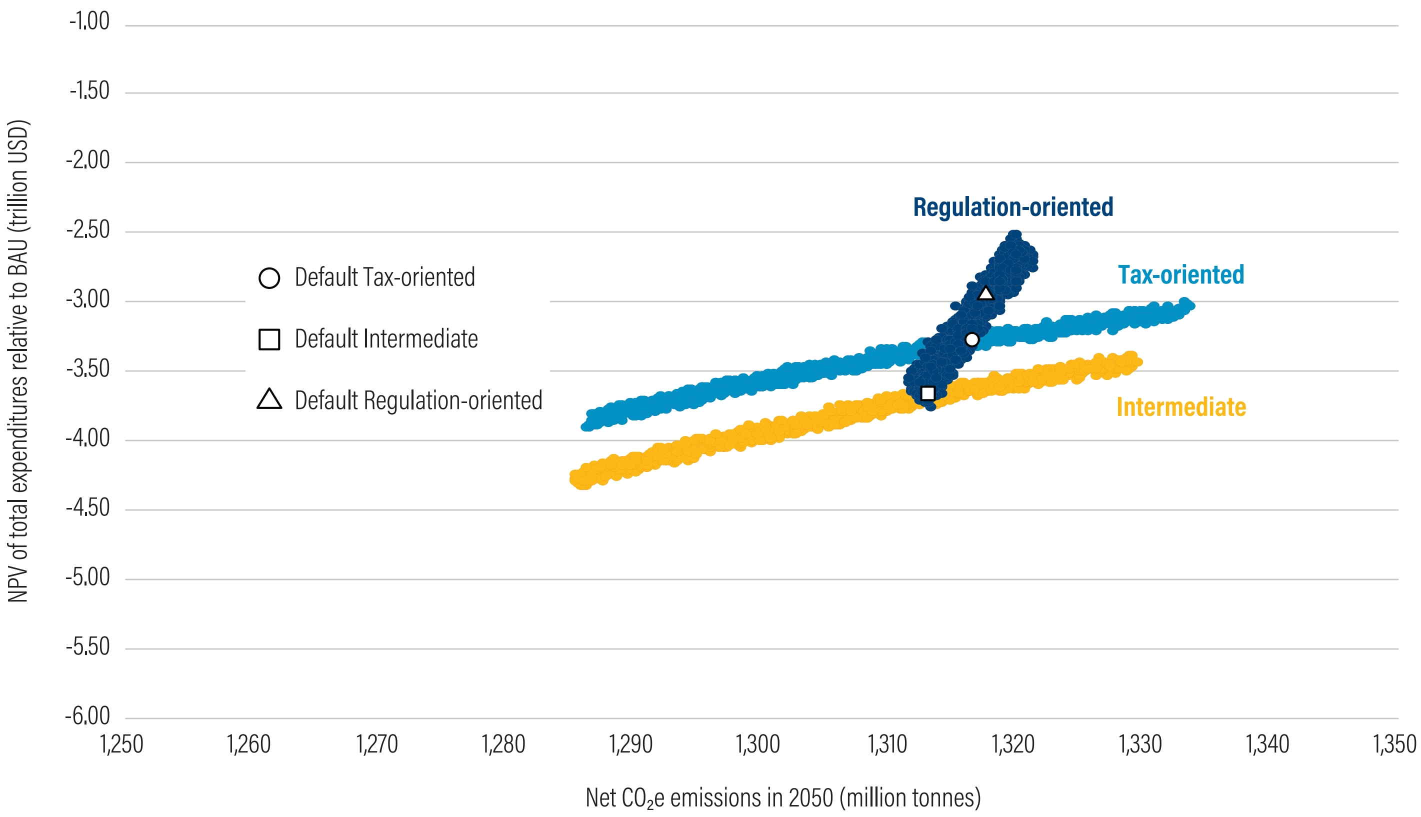
It should be noted that these factors represent uncertainty only in cost reductions for a handful of existing technologies. Uncertainty in technological innovations also includes emergence and deployment of less established technologies (e.g., FCVs and fuel cell generators) or currently nonexistent technologies, and this type of uncertainty may be more significant in terms of its level of uncertainty and influence. However, this paper does not analyze this type of uncertainty because variables representing such effects are not available in the EPS model. This is a limitation of the present analysis and it is often a limitation for quantitative approaches to scenario analysis.

4.2. Performance Projection of Three Policy Packages Using the EPS Default Data Set

The performance projections for the three policy packages are shown in Figure 4 with solid white plots. The net GHG emissions in 2050 resulting from all three policy packages are roughly equivalent to 80 percent below 2005 levels. The NPV total expenditure varies among the packages but takes huge negative values in all three because it is expressed as the change relative to a no-new-policies, BAU scenario. Significant fuel cost savings are projected relative to BAU.

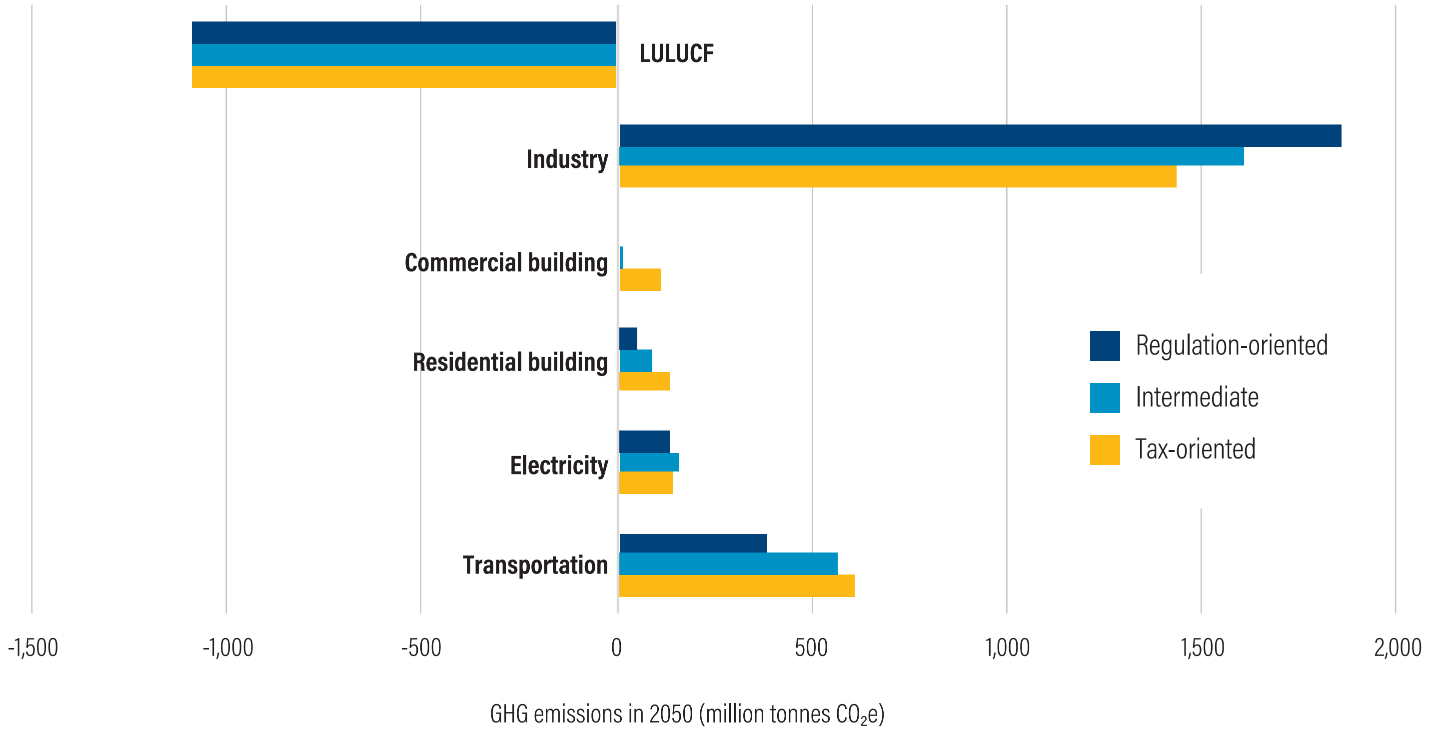
Although the economy-wide net GHG emissions in 2050 are roughly equal for the three policy packages, the sectoral share of emissions varies (Figure 5). Carbon removal via the LULUCF sector is the same across the packages.

Figure 4 | **Uncertainty in GHG Emissions and NPV Total Expenditures under 1,000 Scenarios**



Source: Authors.

Figure 5 | **GHG Emissions in 2050 by Sector for Illustrative Policy Packages**



Note: EPS sector categories include district heating as a sector, but it is excluded from this figure because its emissions are minimal across the three policy packages.
Source: Authors.

4.3. Impact Analysis of Uncertainties on Policy Performance

To assess the impacts of uncertainties on the projected policy performance of the three policy packages, authors constructed 1,000 future scenarios with varying values for the five uncertainty factors (technology costs) listed in Table 6. These correspond to the "uncertainty testing scenario" in Figure 1. The scenarios were generated using the Vensim software's built-in function of sensitivity analysis. It assigns a randomly generated value within the specified range for each factor of uncertainty. In generating the values, random uniform probability distribution (for sampling purposes only and not inferring the probability distribution of the real world) and the Latin hypercube sampling method were chosen.

The 1,000 scenarios were applied to each of the three policy packages to see their effects on the two outcome metrics of GHG emissions and NPV total expenditures. Figure 4 illustrates the result. Each plot represents the outcome of one of 1,000 scenarios applied to one of the three policy packages. The solid white plots represent the results of calculation with the EPS default data set without introducing uncertainty.

The dispersion of plots was relatively uniform across the range of distribution for all three policy packages and on both vertical and horizontal axes.

With regard to GHG emissions, the tax-oriented and intermediate packages are more sensitive to change in uncertainty factors than the regulation-oriented package; the ranges of the plots for these two policy packages are more widely distributed in terms of GHG emissions (Figure 4). This is consistent with an intuition that low-carbon technology cost fluctuations would affect tax-oriented policies more in terms of GHG emissions because the adoption of low-carbon technologies is more sensitive to price signals. However, the range of variance is not very significant in ratio (less than 5 percent deviation relative to the average) in this analysis. A small difference in emissions in 2050 can disguise a larger difference in cumulative emissions because the trajectory toward reaching the 2050 level can differ significantly. Cumulative emissions depend heavily on how early peak emissions are achieved. To take the case of the tax-oriented policy package as an example, when cumulative emissions between 2017 and 2050 are compared with the highest and lowest emission scenarios in 2050, the difference is 558.0 $MtCO_2e$ (although the difference is only 0.56 percent relative to the cumulative emissions with the EPS default data set under the tax-oriented policy package). This figure could become greater if differences in emissions after 2050 are counted (the model does not calculate emissions after 2050).

The regulation-oriented package is more wide-ranging than the other two packages in terms of NPV total expenditures. It is consistent with an intuition that low-carbon technology cost fluctuations would affect regulation-oriented policies more in terms of total expenditures because emission reduction targets and standards have to be met even when low-carbon technology costs are high.

The tax-oriented and intermediate packages have a very similar shape and slope of plot distributions, which is counterintuitive. Although the mechanism behind this similarity was not investigated, a possible explanation is that for those two policy packages, a carbon tax has dominant effects compared with other policy levers, and the relationship between GHG emissions and NPV total expenditures becomes similar in these packages because of the carbon tax dominance.

This result demonstrates that although countless policy packages could be projected to achieve a long-term emissions reduction target under a set of assumptions, they can perform very differently once the underlying assumptions change, and sensitivity to the same uncertainty may vary significantly across policy packages. All this implies the benefits of exploring the vulnerability of long-term strategies to perceived material uncertainties.

4.4. Identifying Material Uncertainties: Scenario Discovery

The previous section showed how the outcomes of policy packages could be affected by uncertainty factors, but it did not indicate which uncertainty, or what combination of uncertainties, is most influential on the outcomes of interest. The scenario discovery method (Bryant and Lempert 2010) was introduced to identify material uncertainties and the value ranges of those that are likely to collectively affect the outcomes of interest. The patient rule induction method (PRIM) is a common method of scenario discovery (Friedman and Fisher 1999). Ready-to-use computer program codes written in different languages are publicly available. In this paper, a Python-based stand-alone PRIM module provided by Hadka (n.d.) was used.

PRIM explores the multidimensional uncertainty universe defined by the ranges set for each uncertainty factor. For example, if five uncertainty factors are considered, the uncertainty universe has five dimensions. The 1,000 scenarios can be plotted in this uncertainty universe. In applying PRIM, the user must define a threshold criterion (e.g., GHG emissions of *x* million metric tons in year 2050 or lower) to judge whether the outcome of a scenario satisfies the threshold condition or not. PRIM explores the multidimensional universe by experimenting with various boxes that partition a part of the universe. The purpose is to find a subregion (or subregions) with a high concentration of scenarios that meet the criterion, which can be described by fewer factors. The rationale is that such a subregion identifies simple scenarios that are likely to affect the outcome of interest. (See Bryant and Lempert (2010) for a practical guide to PRIM.)

Figure 6 shows examples of the results of PRIM analysis applied to NPV total expenditures. The scatter plots show the images of the multidimensional universe viewed from different two-dimensional windows. Each dot in the graphs represents one of the 1,000 scenarios. Red dots indicate the cases that meet the criterion; blue dots indicate those that do not. The black frames are a part of the multidimensional box that PRIM framed.

In this analysis, the threshold was set as the NPV total expenditures with the EPS default data set for each policy package, multiplied by 1.15. In other words, the cases that exceed this threshold lead to a positive surprise of 15 percent more cost savings than the default case, thanks to unexpected technological innovations.

Take Figure 6A as an example. This set of graphs shows the box PRIM selected at the 40th step in a series of trying different dimensions of a box. Three uncertainty factors are shown in the figure. This indicates that those three factors are more influential than the other two factors (i.e., cost reduction of CCS and solar PV) on the outcome because, at each step in which PRIM adjusts the box dimensions, it compares the incremental influence of all five factors and picks up the most influential one. In the upper graphs, red dots (representing cases that meet the criterion) are concentrated in the frame sliced by the factor EV (i.e., the percentage of additional reduction in battery EV cost). The other two factors—that is, capital cost reduction of offshore and onshore wind—do not add much explanatory power in differentiating cases that meet the criterion from cases that do not. The figure suggests that, among the five uncertainty factors considered, the EV cost reduction dominates the cost-saving effects of the tax-oriented policy package and the other four factors do not have a significant effect as long as they take values within the range assumed in the analysis. The range chart (the bottom left chart in Figure 6A) shows the dimension of the box shown in the scatter plots. It suggests that if the additional EV cost reduction in 2050 is about 20 percent or more, compared with the default cost reduction, a positive surprise of 15 percent more in cost savings would be likely under the particular set of assumptions considered in this illustrative analysis.

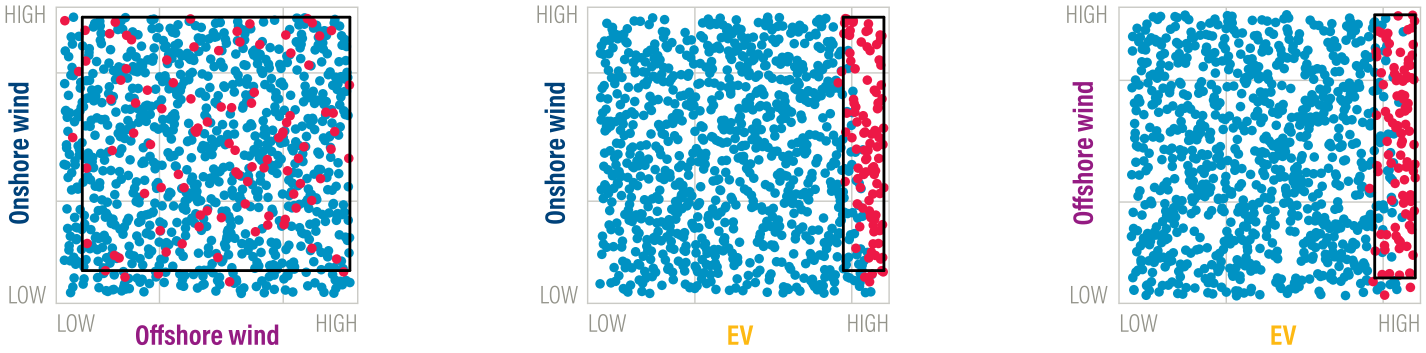
The EV cost reduction also dominates the effect on NPV total expenditures for the other two illustrative policy packages. The analysis of the intermediate policy package showed very similar results to the tax-oriented policy package and is not included here. The dominance of the EV cost reduction is even more prominent in the analysis for the regulation-oriented policy package (Figure 6B) where only the EV cost reduction is identified as the important factor. The explanatory power of the EV cost reduction is so strong that PRIM analysis stops without trying any additional factors.

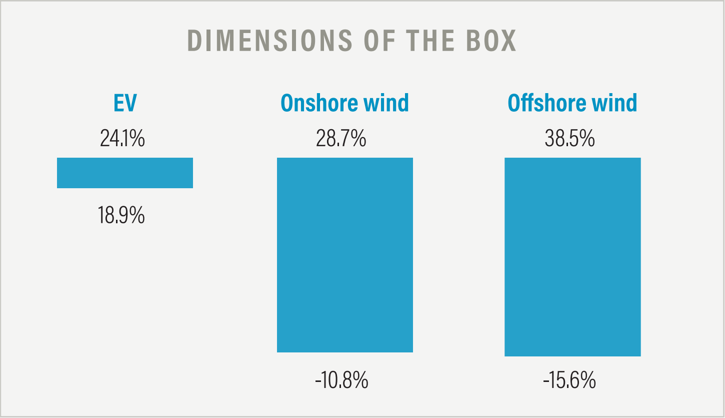
The EV cost reduction also has a strong influence on the possibility of negative surprise. Although not further discussed here, the PRIM analysis of the same policy packages with NPV total expenditures set more than 5 percent higher (meaning the cost savings is smaller than expected by the default simulation), revealed that EV cost reduction was the most significant factor. Solar PV cost reduction also showed some influence.

Figure 7 shows an example of the results of PRIM analysis applied to net GHG emissions with the tax-oriented policy package. This analysis is interested in scenarios where net GHG emissions in 2050 are reduced beyond the threshold value of 1,318 $MtCO_2e$ (i.e., 80 percent below economy-wide emissions of the hypothetical country in 2005). Compared with the analysis of NPV total expenditures, it demonstrates even more clearly the dominance of EV cost reduction in this particular set of illustrative policy packages. Here, the result can be interpreted to mean that as long as the EV cost reduction is about the same as, or higher than, the cost reduction to be achieved in the case without the introduction of uncertainty, the emissions goal is likely to be achieved, assuming there are no other surprises from other factors not considered as uncertain in this analysis. The same analysis with the other two illustrative policy packages shows very similar results. Although these results may be because of the constraints of this analysis, which does not incorporate other, possibly more important, uncertainty factors (and therefore should not be taken to have policy implications), these illustrative findings provide a useful demonstration of the ways in which scenario analysis can benefit policymakers.

Figure 6 | **Results of PRIM Analysis of NPV Total Expenditures with Illustrative Policy Packages**

A) Tax-oriented policy package

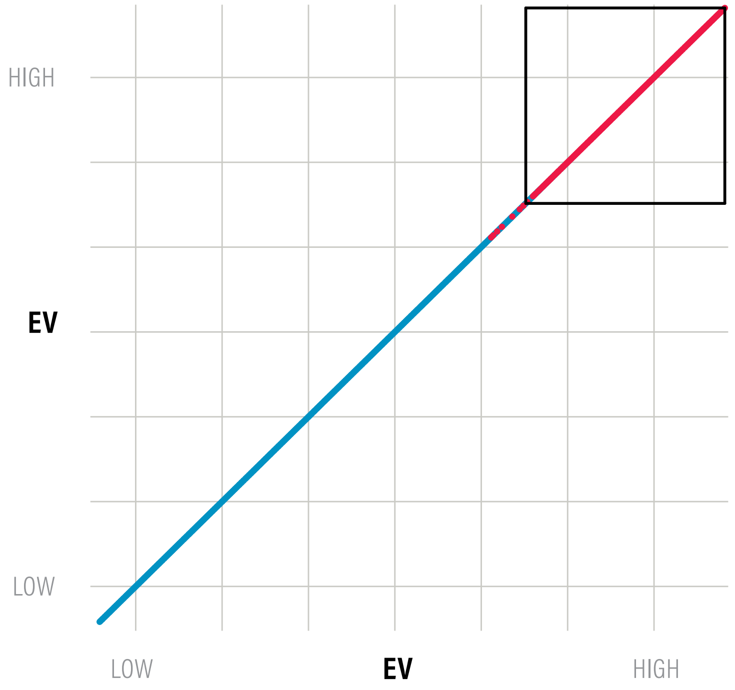


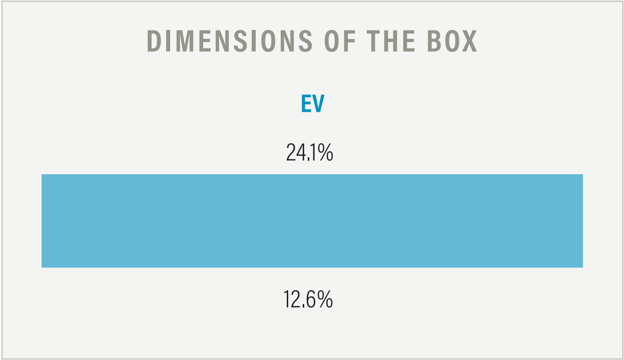


% of additional capital cost reduction	VALUE RANGE	
	Lower limit	Upper limit
EV	-12.1%	24.1%
Onshore wind	-14.4%	28.7%
Offshore wind	-19.3%	38.5%

Note: Red dots represent scenarios that meet the criterion; blue dots represent scenarios that do not.

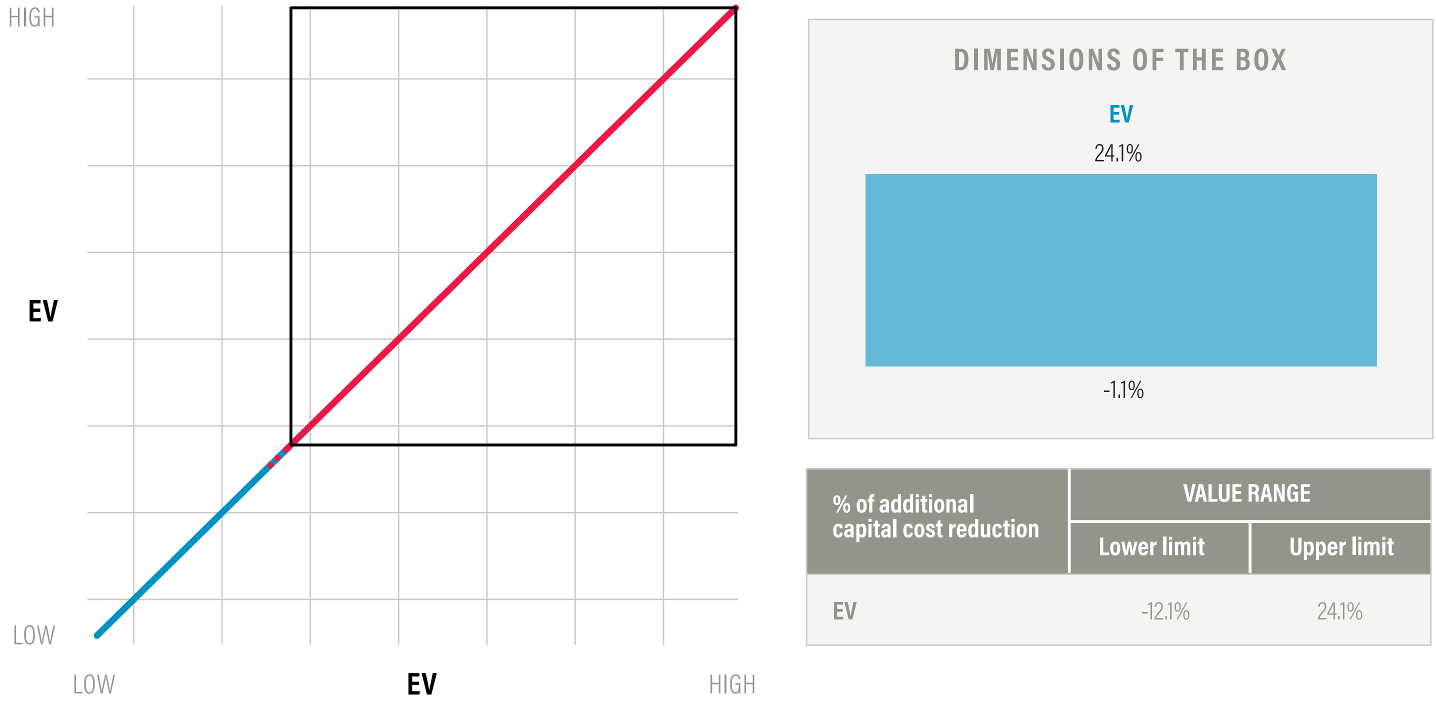
B) Regulation-oriented policy package





% of additional capital cost reduction	VALUE RANGE	
	Lower limit	Upper limit
EV	-12.1%	24.1%

Figure 7 | **Results of PRIM Analysis Applied to GHG Emissions with Tax-Oriented Policy Package**



% of additional capital cost reduction	VALUE RANGE	
	Lower limit	Upper limit
EV	-12.1%	24.1%

The analysis thus far gives indications of policy-relevant scenarios. Considering the strong influence of EV cost reduction on both emissions and cost savings, a scenario with unexpectedly modest EV cost reduction will make all three illustrative policy packages vulnerable to the risk of higher policy costs and to missing the emissions reduction target in 2050 (albeit not by much). The opposite scenario may bring an unexpected windfall of additional emissions reduction and cost savings.

Although a single factor happened to be dominant in this illustrative analysis, PRIM is capable of identifying two or more influential factors and the value ranges that significantly affect the outcomes of interest, which gives information valuable to developing policy-relevant scenarios. This is a useful feature of the scenario discovery technique.

4.5. Implications for Policy Improvements

The scenario discovery technique helps identify material uncertainties and suggests options to mitigate the vulnerability of policy packages.

This paper explores the idea of policy improvement, using the tax-oriented policy package as an example. Figure 4 shows that the tax-oriented package led to more variable net GHG emissions compared with the regulation-oriented package. The EV cost reduction is the key factor. The only policy differences in the transportation sector between the two illustrative packages described in Appendix C are those related to an EV sales mandate and fuel economy standards. It is likely that the stronger EV shift caused by the more ambitious EV sales mandate in the regulation-oriented package makes the difference.

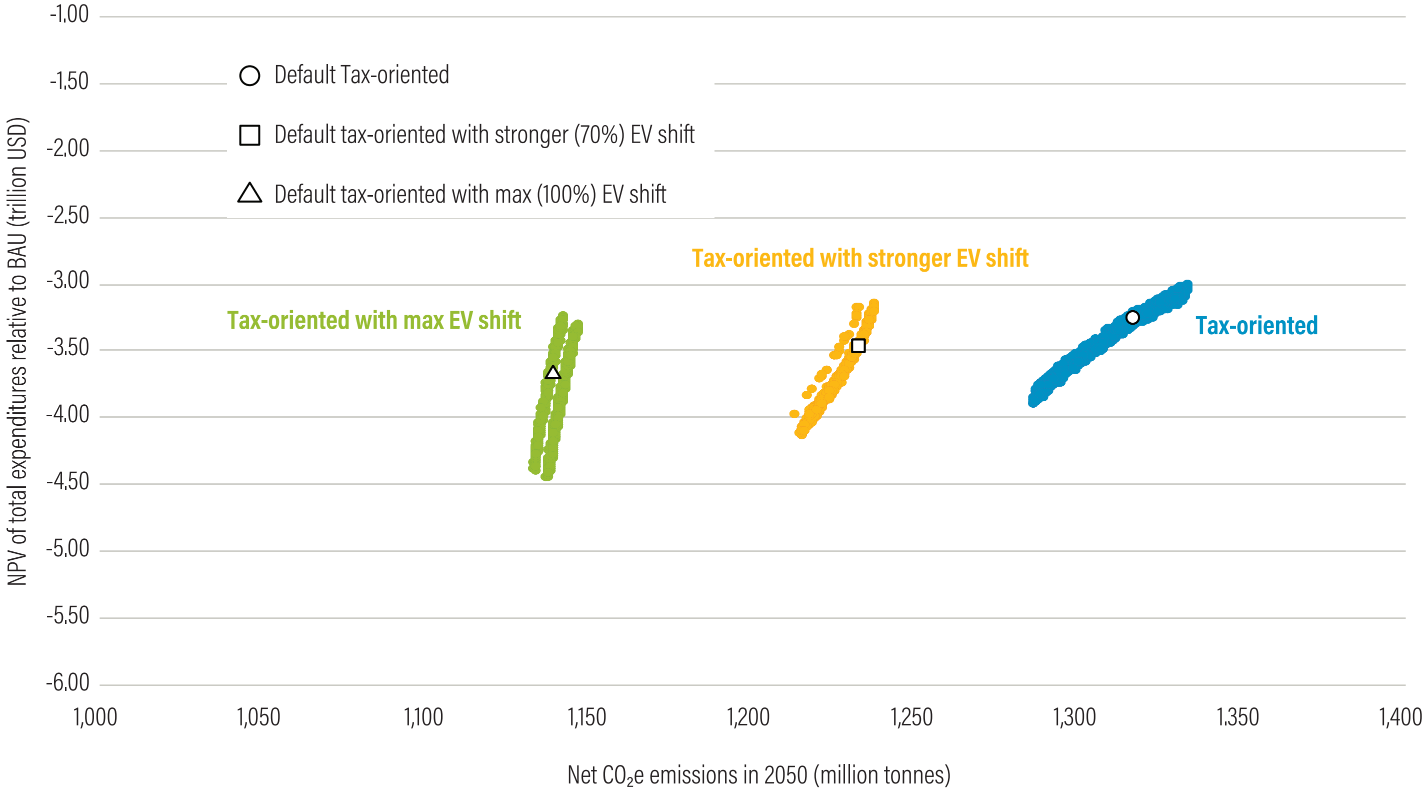
On the basis of this observation, a modified tax-oriented policy package was developed. It is the same as the original except that it also adopts an EV sales mandate for light-duty vehicles, heavy-duty vehicles, and motorcycles. Two variations were prepared, one with a 75 percent EV sales mandate by 2050 and the other with a 100 percent mandate.

Figure 8 shows the plots of three policy packages: tax-oriented, tax-oriented with a stronger EV shift (75 percent sales mandate), and tax-oriented with the maximum EV shift (100 percent sales mandate) using the same 1,000 scenarios and the default data set.

The graph shows the significant additional emissions reductions that can be expected with improved policy packages. The stronger EV shift leads to lower emissions in 2050. Moreover, the variance of plots suggests that the improved packages are subject to less variation in emissions outcomes in the face of uncertainties—that is, the improved policy packages are more robust across diverse future scenarios.

The plot distributions of the improved policy packages show unexpected clustering into two separate regions (or lines). An examination of the data showed that the clustering was caused by electricity sector emissions. It seems to be the effect of the threshold of fuel switching in the electricity sector.

Figure 8 | **Uncertainty in GHG Emissions and NPV Total Expenditures of Illustrative Improved Policy Packages That Include Different EV Mandates**



Note: The blue dots shown in this figure are the same as those in Figure 4; they appear to be different because of the difference in the plot scale between the two graphs.

4.6. Limitations of a Quantitative Approach to Scenario Analysis

The benefits and applicability of a model-assisted quantitative approach to scenario analysis should now be clear. However, there are limitations to this approach.

Because the suggested approach uses computerized models to undertake analysis, it may not always be feasible. Some countries, particularly developing countries, may not use any models to project GHG emissions, which limits the applicability of this approach. However, many countries project future GHG emissions in their LTSs, which may indicate that, at least in some cases, they already use quantitative models to make the projections.

This paper's review of LTSs shows that analysis of the relationship between future climate change, its physical effects, and adaptation actions is scarce. Although some LTSs refer to projections of climate change effects, such as temperature increase and sea-level rise, produced by climate models, these effects are not directly connected to the ultimate outcomes of concern—for example, changes in agricultural production or the number of households affected by sea-level rise. Quantitative modeling of the kind suggested in this paper could be more challenging for adaptation strategy development because of the data and technical modeling challenges inherent in projecting the rate of climate change, estimating the physical impacts of change, and linking these climate change impacts to socioeconomic outcomes of interest.

Even if models are available and already used to project GHG emissions or climate impacts, the models may not have variables that adequately represent the uncertainties of concern or the models' structures may not allow the variable representing uncertainties to vary within a set range. In some cases, the available model's ability to represent reality may be low, which negates the value of scenario analysis. More important, models may limit the scope of exploration of uncertainties to those that can be represented in the models at hand. On the basis of past examples, Trutnevyte et al. (2016, 375) noted that quantitative scenario analyses "miss surprises more often than qualitative ones . . . perhaps because the latter are less constrained by the analytics and give freer rein to the imagination."

An implication of these observations is that, although the model-assisted quantitative approach to scenario analysis is a useful tool, countries should not rely on it exclusively. Rather, they should creatively use both qualitative and quantitative approaches to explore diverse future possibilities and prepare for them. These two approaches can complement each other and be applied in combination in a process of analysis. Qualitative approaches (with expert judgment and stakeholder consultation) can explore diverse dimensions of the universe of uncertainty and policy-relevant scenarios regardless of model availability. Quantitative approaches, on the other hand, can mitigate human biases and reveal overlooked ranges or aspects of uncertainties and relevant scenarios, albeit within the limitations of model availability and quality.

5. SUMMARY AND CONCLUSIONS

Developing long-term strategies inevitably faces the challenge of uncertainties because of the strategies' long time horizons and their complex, economy-wide scope. Despite this, 11 countries had already formulated and submitted LTSs to the UNFCCC by February 2019. This paper's review of these LTSs shows that countries perceive and acknowledge various uncertainties. Some common uncertainty factors acknowledged in LTSs include the physical impacts of climate change, the completeness and accuracy of available GHG accounting data, future technological development and deployment, the availability of large-scale carbon removal technologies such as CCS and land sector sequestration, and data on various socioeconomic variables.

Countries respond to these uncertainties in various ways, including attempting to reduce them by gaining more knowledge, making assumptions, and applying sensitivity analysis or scenario analysis. Countries also use scenarios (or pathways) to depict possible alternative futures. Nine out of the 11 LTSs studied present scenarios or pathways. However, not all of the nine LTSs explicitly use scenarios to explore uncertainties and develop robust strategies.

Building on existing research, this paper has proposed an analytical framework of uncertainty and demonstrated a model-assisted quantitative approach to improve scenario analysis. The paper also suggests that countries construct scenarios around material uncertainties to explore their potential effects and use the scenarios to make their LTSs more robust in the face of uncertainty.

To demonstrate the benefits and practicality of the quantitative approach to scenario analysis, this paper developed a hypothetical example with an LTS vision of reducing national GHG emissions to 80 percent below 2005 levels by 2050, and experimented with an analysis of uncertainty regarding technological innovations. The analysis shows that the level of EV cost reduction, among cost reductions for five technologies, is the dominant influence on both net GHG emissions in 2050 and the cost-saving effect of the policies. The results of the analysis point to policy-relevant scenarios and suggest how to enhance the policies' robustness.

The analysis suggests a way to improve and strengthen scenario analysis to explore uncertainty and develop more robust LTSs. However, the approach suggested in this paper has limitations because of its dependence on model availability and quality. The review of LTSs indicates that many countries project future GHG emissions using quantitative models, which indicates the possibility of applying the suggested approach. Model-assisted analysis of adaptation strategies, on the other hand, is scarce, indicating a stronger limit on the applicability of this approach in adaptation.

Even if a model is available, the model may not have variables or a structure that can represent the uncertainties of concern. More fundamentally, it may confine the scope of exploration of uncertainties to the universe representable by the model.

Although the model-assisted quantitative approach to scenario analysis is a useful tool, countries should not rely on it exclusively. Rather, they should creatively use both qualitative and quantitative approaches to explore diverse future possibilities and prepare for them.

APPENDIX A. REFERENCES TO UNCERTAINTIES IN LONG-TERM STRATEGIES

COUNTRIES	UNCERTAINTIES ACKNOWLEDGED	HOW UNCERTAINTIES ARE HANDLED
Benin	Pressure of infectious diseases not known to the country is noted in the context of diagnosis of climate impacts.	Noted.
	Climate variability (particularly of precipitation) is perceived as a threat to the country's agriculture.	It is emphasized that adaptation strategy needs to take climate variability into account.
Canada	Amount of fugitive emissions from hydraulic fracturing to extract shale gas.	Research and development for better estimation of fugitive emissions is under way.
	Feasibility of large-scale deployment of carbon removal technologies is still unknown.	Need for more investment and innovation is highlighted to fully assess the potential of these technologies.
Czech Republic	No explicit reference to uncertainty.	
Fiji	Growth of electricity grid storage capacity.	Because the model used cannot directly account for grid storage, adjustments are made to substitutive variables and assumptions to represent it.
	Future energy storage costs.	Noted.
	Because of insufficient data, the historical and future trends of maritime transport are uncertain.	Assumptions are made for analysis and error margins are taken into account. Improved data collection is intended for the future.
	Current fuel use in air transport is uncertain because of the lack of data. The future number of tourists is also uncertain.	Assumptions are made using available data.
	Various data in land sector (forestry, agriculture, coastal wetland) are unavailable. Current mangrove area data are available but vary across sources.	Assumptions are made using available data.
	Potential of expanding mangrove area.	Further research is called for to confirm the potential.
	Current and future population of informal communities is uncertain in the context of waste management sector emissions.	Assumptions are made and error margins are taken into account.

COUNTRIES	UNCERTAINTIES ACKNOWLEDGED	HOW UNCERTAINTIES ARE HANDLED
France	In developing the reference scenario, uncertainties surrounding the impacts of some factors are considered, including the level of household borrowing for financing renovation work, the rate of building renovation in service sector, and an increase in EE in industry sector.	Sensitivity tests are undertaken to measure their impacts.
	Uncertainty in the measurement of GHG emissions from agricultural sector is noted.	Although not directly linked with this particular issue of uncertainty, a policy to promote scientific research is included in the LTS to improve measurement of emissions from the agricultural sector.
	Uncertainty in the forestry sector model and measurements is noted.	Research to reduce uncertainty is proposed.
	In the analysis of energy consumption by residential heating, uncertainty, lack of structuring, and explanatory factors are noted.	Given the uncertainty, a simplified hypothesis is adopted for the analysis.
	A difficulty in modeling household behaviors of vehicle choice is noted because of a lack of data.	Penetration rate of EVs is treated as an exogenous variable.
	A lack of information on changes in the renovation cost per dwelling over time, and to what extent these changes are affected by the surface area of the dwelling.	A set of assumptions is adopted.
Germany	It is indicated that the potential opportunities, risks, and uncertainties associated with LTS have yet to be analyzed in detail.	It is planned to analyze these in 2018.
	Uncertainties of various factors, such as fuel prices, on the estimates of GHG emission trends in the transport sector is noted.	Noted.
	There is a lack of consensus about how many potential storage sites for CCS are available in Germany.	Noted.
Mexico	The uncertainties in prediction over long-term horizons are acknowledged.	A warning is given in interpreting the results of modeling exercises.
	In medium- and long-term planning of electricity supply and demand, there are uncertainties such as fixed and variable costs and demand projections, among others.	A need for careful considerations is noted, and sector-specific models are used for better understanding.
Republic of the Marshall Islands	There are uncertainties in various current data, such as energy loss in the power grid, fuel used for power generation, and land/sea transport. Lack of reliable up-to-date quality environmental data is also regarded as a challenge.	Improving data collection is considered.
	Solar financing uncertainty is noted.	Pilot actions are envisaged to reduce uncertainty.
	Numerous critical knowledge gaps are identified, such as changes in local sea level, rainfall, temperature, cyclones, ocean acidification, and coastal hazards; impacts on economy, society, culture, communities, natural resources, and health; and feasibility and resource availability of adaptation options.	Addressing those knowledge gaps is given high priority in LTS.
	Number of people internally displaced by natural disasters is unknown.	Noted.
Ukraine	Impacts of LULUCF sector policies and measures on GHG emission dynamics is perceived to be complicated because of the uncertainty of input parameters.	Noted.

COUNTRIES	UNCERTAINTIES ACKNOWLEDGED	HOW UNCERTAINTIES ARE HANDLED
United Kingdom	Overall future projections are perceived to be uncertain. Important sources of uncertainty are: ■ type and scale of global technical innovation; ■ macroeconomic factors such as population, employment, fuel prices; ■ social and economic impacts (responses and effectiveness) of policies; ■ development of scientific and technological knowledge and evidence base; and ■ evolution of social behaviors.	A flexible and robust approach is sought by exploring different pathways.
	Three areas of technology and resource uncertainty are considered to have a big impact on the 2050 Pathways: the role of electrification, the role of hydrogen, and the role of BECCUS. Related to these, three subjects of greatest uncertainty are identified: reducing emissions from heating homes and businesses, decarbonizing the transport system, and making CCUS a viable option for industry.	Sensitivity of 2032 Pathway was tested against uncertainty factors such as technology costs, energy prices, underlying drivers of UK emissions, and non-cost barriers. 2050 Pathways are constructed in a way that reflects varied future projections in these areas of major uncertainties.
	Greenhouse gas removal technologies entail uncertainties of cost, deployment potential, and impacts on the environment.	Research and development are commissioned to improve understanding.
	Shift in consumer behavior toward more overnight EV charge is deemed uncertain.	Keep monitoring for better understanding.
	Emissions from natural resources (e.g., forests) are uncertain.	Despite uncertainty, emissions from land sector is considered relatively low.
United States	Uncertainties related to evolution of technologies, economic conditions, and social dynamics over the coming decades are pointed out. It is indicated that the analysis presented is limited in its ability to depict the complexity of real-world markets and uncertainties.	It is made clear that the intention of the analysis is not to predict with precision the long-term future but instead to provide a basis for understanding the key opportunities and challenges. Numerous pathways are explored to inform flexible policies to support a broad portfolio of technologies and robust short-term actions.
	Three major uncertainties are identified: the potential and economic viability of increased land sector carbon sequestration, the potential and economic viability of carbon removal technologies, and growth in the number of clean vehicles.	Scenario analysis is constructed in a way that explore varied future projections in these areas of major uncertainties.
	Land sector GHG accounting has difficulties with uncertainty and variability.	Efforts are being made to improve its ability to quantify land sector emissions and removals.

Note: Multiple references to the same or similar factors within the same LTS are combined, and references to uncertainties in contexts that are not specific to the LTS of the country (e.g., general statements such as uncertainty is no excuse for inaction, and global impacts of climate change are uncertain) are not included in this list.
Sources: Government of Benin 2016; Government of Canada 2016; Government of Czech Republic 2018; Government of Fiji 2019; Government of France 2017; Government of Germany 2016; Government of Mexico 2016; Government of Republic of the Marshall Islands 2018; Government of Ukraine 2018; Government of the United Kingdom 2018; Government of the United States 2016.

APPENDIX B. MITIGATION SCENARIOS AND PATHWAYS PRESENTED IN LONG-TERM STRATEGIES

COUNTRY	MID-CENTURY MITIGATION SCENARIOS AND PATHWAYS[a]
Benin	Not presented
Canada	■ A high ambition (Deep Decarbonization Pathways Project) scenario, which achieves 89% GHG emission reductions in 2050 (excluding agriculture) ■ A current technology scenario (from the Trottier Energy Futures Project), which achieves a 60% reduction in energy sector GHG emissions relative to 1990 levels ■ A new technology scenario (from the Trottier Energy Futures Project), which also achieves a 60% reduction in energy sector GHG emissions relative to 1990 levels ■ Two non-emitting electricity scenarios (both achieving a net 80% GHG emissions reduction including 15% achievement through internationally transferable mitigation outcomes and land sector credits): □ A high nuclear scenario, which is heavily dependent on nuclear electricity production □ A high hydro scenario, which relies on a mix of hydropower and wind to produce the majority of electricity ■ A high demand response scenario, which achieves a net 80% GHG emissions reduction (including 15% achievement through internationally transferable mitigation outcomes and land sector credits) by 2050 relative to 2005 levels
Czech Republic	■ Reference scenario: BAU **Scenarios not meeting the minimum 80% reduction target for 2050:** ■ State energy policy extrapolation scenario: Emission trajectory of the state energy policy, which provides the national energy sector goals and policies by 2040, is extrapolated to 2050 ■ Nuclear scenario: features extended use of nuclear power ■ "Green" scenario: features significant advance in RE development and EE ■ Economic recession scenario: assumes energy demand plunges because of an economic recession **Scenarios meeting the minimum 80% reduction target for 2050** ■ Electricity and biomass import scenario: same as the green scenario except large-scale imports of electricity and biomass (for fuel) are assumed ■ CCS technology development scenario: same as the reference scenario except a massive deployment of CCS is assumed ■ Renewable energy, nuclear energy, and energy-saving scenario: a combination of the green scenario and the nuclear scenario, with adjustments of the scale of deployment of each measure
Fiji	■ BAU unconditional scenario □ Assumes implementation of existing official policies and targets with existing technologies without reliance on external finance □ Net GHG emissions projection in 2050 significantly exceeds the 2020 level. ■ BAU conditional scenario □ Assumes implementation of existing official policies and targets conditional to external financial support □ Projected net GHG emissions in 2050 are similar to those in 2020. ■ High ambition scenario □ Pursues new policies that are more ambitious than existing ones with deployment of new technologies. □ Net GHG emissions in 2050 are projected to be about 40% below 2020 level. ■ Very high ambition scenario □ Pursues new policies that are significantly more ambitious than existing ones with deployment of new technologies and additional finance. □ Projected to achieve net zero GHG emission in around 2041 and subsequent increasingly negative emission by 2050.

COUNTRY	MID-CENTURY MITIGATION SCENARIOS AND PATHWAYS[a]
France	■ A trend-based (with existing measures) scenario, which is based on policies and measures implemented before January 1, 2014 ■ A reference (with additional measures) scenario, which includes all measures included in the country's green growth and energy transition law and is compatible with the 2050 emission reduction target of 75% reduction below 1990 level
Germany	Not presented [b]
Mexico	■ A baseline scenario, which estimates the emissions trajectory without imposing climate or energy policy constraints ■ A nationally determined contribution (NDC) policy scenario, which achieves a 22% reduction of GHG emissions by 2030 (in line with Mexico's unconditional NDC target) and 50% by 2050, both relative to 2000 levels ■ An NDC "more ambition" scenario, which achieves a 36% reduction of GHG emissions by 2030 (in line with Mexico's conditional NDC target) and 50% by 2050, both relative to 2000 levels
Republic of the Marshall Islands[c]	■ Moderate enhanced ambition scenario: assumes significant renewables penetration and efficiency improvements, which is projected to achieve 56% GHG emission reduction in 2050 relative to 2010 level. ■ Significant enhanced ambition scenario: same as the Lighthouse scenario, but the actions are delayed by 15 years because of a lack of funding, which is projected to achieve 70% GHG emission reduction in 2050 relative to 2010 level. ■ Lighthouse enhanced ambition scenario: assumes maximum efforts in deployment of RE, energy storage, electrification of transport and household sectors, and emission reduction from waste, which is projected to achieve 87% GHG emissions reduction in 2050 relative to 2010 levels.
Ukraine	**Energy sector scenarios** ■ Baseline (BAU) scenario (2050 GHG emission projected 30% below 1990 level) ■ Energy efficiency (EE) scenario: featured by increased EE (2050 GHG emission projected 47% below 1990 level) ■ EE and renewable energy (RE) scenario: policies to expand RE are added to EE scenario (2050 GHG emission projected 67% below 1990 level) ■ EE, RE, modernization and innovation scenario: policies to facilitate energy and transport sector modernization and technology development are added to the EE and RE scenario (2050 GHG emission projected 66% below 1990 level) ■ EE, RE, modernization and innovation, transformation of market and institutions scenario: policies to improve regulatory framework and support awareness raising, training, and research and development are added to the EE, RE, modernization and innovation scenario (2050 GHG emission reduction of 69% below 1990 level) **LULUCF sector scenarios** ■ BAU scenario (2050 GHG absorption projected 30% below 1990 level) ■ Forward-looking scenario: featured by protection and improved management of forests (2050 GHG absorption projected 21% below 1990 level) ■ Forward-looking with optimum forest cover scenario: "forward-looking scenario" with additional afforestation (2050 GHG absorption projected 15% below 1990 level)

COUNTRY	MID-CENTURY MITIGATION SCENARIOS AND PATHWAYS[a]
United Kingdom[d]	**All three scenarios below are projected to reduce 80% GHG emissions below 1990 levels.** ■ Electricity pathway: assumes electricity becomes the main energy source through enhanced electrification of vehicles, building heating, and industry but does not rely on CCUS ■ Hydrogen pathway: assumes widespread hydrogen use for vehicle fuel and building heating while hydrogen is mainly produced with natural gas and its accompanying CO_2 emission is captured by CCUS ■ Emissions removal pathway: assumes large-scale deployment of bioenergy with CCUS
United States	**All scenarios below except "A Beyond 80" scenario are projected to reduce 80% GHG emissions below 2005 levels. "A Beyond 80" scenario is projected to reduce emissions more than 80%, but the specific number is not provided in the LTS.** ■ Benchmark scenario as a starting point for the analysis ■ No carbon dioxide (CO_2) removal technology scenario, which assumes that engineered CO_2 removal technologies such as BECCS are unavailable ■ Limited sink scenario, which assumes not only limited availability of CO_2 removal technologies but also limited success in maintaining and enhancing the land sink ■ No CCUS scenario, which achieves 80% reductions by 2050 without the use of CCS ■ Smart growth scenario, which portrays a different pathway to decarbonization in the transportation and buildings sectors ■ Limited biomass scenario, which explores an alternative to the benchmark scenario with lower bioenergy consumption and no deployment of BECCS ■ "A Beyond 80" scenario, which assumes stronger global action to reduce emissions and more rapid advances in low-carbon technologies

Notes:

[a] Some countries indicate that they explored many other pathways and scenarios but only refer to them without details or do not list them all in the LTS. The table includes only those main pathways and scenarios presented and explained in LTSs.

[b] Germany's LTS was developed using various existing scenarios (Wagner and Tibbe 2019), but those scenarios are not described in the LTS.

[c] Apart from the three scenarios, the LTS of the Marshall Islands shows the NDC trajectory, which is a linear extrapolation of the 2010–2030 emissions reduction trajectory envisaged in the NDC, but it is not treated as a scenario here.

[d] In addition to the three mid-century pathways, the LTS of the United Kingdom describes a "2032 Pathway," which is a detailed illustration of one of several plausible pathways to meet the United Kingdom's legally binding fifth carbon budget (2028–2032).

Sources: Government of Benin 2016; Government of Canada 2016; Government of Czech Republic 2018; Government of Fiji 2019; Government of France 2017; Government of Germany 2016; Government of Mexico 2016; Government of Republic of the Marshall Islands 2018; Government of Ukraine 2018; Government of the United Kingdom 2018; Government of the United States 2016; Ross and Fransen 2017.

APPENDIX C. COMPARISON OF THREE ILLUSTRATIVE POLICY PACKAGES

All policies are additional to the BAU scenario. Policy parameters expressed in the percentage term increase linearly from zero to reach the values specified in the table below in 2050. A detailed explanation of each policy lever can be found at the EPS website: https://us.energypolicy.solutions/docs/policy-design-index.html and https://us.energypolicy.solutions/scenarios/home.

All policy levers are arbitrarily set for the purpose of this analysis without any assessments of their plausibility. Authors do not endorse any particular policy measures or their combinations.

POLICY LEVERS[a]		1. TAX-ORIENTED	2. INTERMEDIATE	3. REGULATION-ORIENTED
Transportation				
EV sales mandate	Passenger light-duty vehicles	—	50%	100%
	Passenger heavy-duty vehicles	—	50%	100%
	Freight heavy-duty vehicles	—	50%	100%
	Passenger motorcycles	—	50%	100%
Feebate[a]		100%	100%	100%
EV perks[b]		Yes	Yes	Yes
Fuel economy standards (% improvement relative to BAU)	Gasoline engine light-duty vehicles	37%	65%	100%
	Diesel engine heavy-duty vehicles	37%	50%	65%
	Gasoline engine motorcycles	37%	50%	75%
	All aircraft	30%	40%	50%
	All rail	20%	20%	20%
	All ships	20%	20%	20%
Transportation demand management	Passengers	100%	100%	100%
	Freight	100%	100%	100%

POLICY LEVERS[a]		1. TAX-ORIENTED	2. INTERMEDIATE	3. REGULATION-ORIENTED
Building				
Building EE standards for new buildings (% improvement relative to BAU)	Urban residential heating	15%	20%	22%
	Urban residential cooling and ventilation	25%	30%	38%
	Urban residential envelope	25%	30%	38%
	Urban residential lighting	25%	30%	40%
	Urban residential appliances	25%	30%	38%
	Urban residential other components	10%	10%	10%
	Rural residential heating	15%	20%	22%
	Rural residential cooling and ventilation	25%	30%	38%
	Rural residential envelope	25%	30%	38%
	Rural residential lighting	25%	30%	40%
	Rural residential appliances	25%	30%	38%
	Rural residential other components	10%	10%	10%
	Commercial heating	15%	20%	22%
	Commercial cooling and ventilation	25%	30%	38%
	Commercial envelope	25%	30%	38%
	Commercial lighting	25%	30%	40%
	Commercial appliances	25%	30%	38%
	Commercial other components	10%	10%	10%
Improved labeling		Yes	Yes	Yes
Contractor education and training		Yes	Yes	Yes
Building component electrification	Urban residential	30%	65%	100%
	Rural residential	30%	65%	100%
	Commercial	30%	65%	100%
Increased retrofitting	Heating	—	2.0%	3.9%
	Cooling and ventilation	—	2.0%	3.9%
	Envelope	—	2.0%	3.9%
	Lighting	—	2.0%	3.9%
	Appliances	—	2.0%	3.9%
	Other components	—	2.0%	3.9%

POLICY LEVERS[a]		1. TAX-ORIENTED	2. INTERMEDIATE	3. REGULATION-ORIENTED
Electricity				
Demand response		100%	100%	100%
Early retirement of (coal) power plants		—	2,000 MW/year	10,000 MW/year
Increase transmission relative to BAU		65%	75%	113%
Renewable portfolio standard		—	62%	88%
Nuclear capacity lifetime extension		—	10 years	20 years
Reduced transmission and distribution loss		20%	30%	40%
Industry				
Co-generation and waste heat recovery		100%	100%	100%
Cement clinker substitution		—	—	100%
Early retirement of industrial facilities		—	—	100%
Worker training		—	—	100%
Improved system design		100%	100%	100%
Industry EE standards (% improvement relative to BAU)	Cement	20%	30%	35%
	Natural gas and petroleum	20%	30%	35%
	Iron and steel	20%	30%	35%
	Chemicals	20%	30%	35%
	Mining	20%	30%	35%
	Waste management	20%	30%	35%
	Agriculture	20%	30%	35%
	Other industries	20%	30%	35%
Natural gas to electricity switching		20%	30%	40%
Coal to natural gas switching		20%	30%	40%
Methane capture		100%	100%	100%
Methane destruction		100%	100%	100%
Reduce F-gases		100%	100%	100%

POLICY LEVERS[a]	1. TAX-ORIENTED	2. INTERMEDIATE	3. REGULATION-ORIENTED
Land			
Afforestation and reforestation	100%	100%	100%
Livestock manures	100%	100%	100%
Cropland management	100%	100%	100%
Improved forest management	100%	100%	100%
CCS			
Fraction of potential additional CCS achieved	35%	65%	100%
Carbon Tax Rate (increasing linearly from $0/metric tons CO_2e in 2018 to the rate specified below in 2050)			
Transportation sector	$300	$180	$60
Electricity sector	$300	$180	$60
Residential building sector	$300	$180	$60
Commercial building sector	$300	$180	$60
Industry sector	$300	$180	$60

Notes:

a Feebate imposes a fee on the sales of high-emission vehicles and uses the collected fees to subsidize the sales of low-emission vehicles. The value is set as a percentage of the global best practice feebate rate.

b "EV perks" refers to a range of policies that provide nonmonetary benefits for EVs, such as exclusive parking spaces and highway lanes for EVs, building more EV charging stations, and so on.

ABBREVIATIONS

BAU	business as usual
BECCS	bioenergy with carbon capture and storage
BECCUS	bioenergy with carbon capture, usage, and storage
CCS	carbon capture and storage
CCUS	carbon capture, usage, and storage
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
EE	energy efficiency
EPS	Energy Policy Simulator
EV	electric vehicle
FCV	fuel cell vehicle
GDP	gross domestic product
GHG	greenhouse gas
LTS	long-term strategy
LULUCF	land use, land-use change, and forestry
$MtCO_2e$	million metric tons of carbon dioxide equivalent
NDC	nationally determined contribution
NPV	net present value
O&M	operation and maintenance
PRIM	patient rule induction method
PV	photovoltaic
RE	renewable energy
UNFCCC	United Nations Framework Convention on Climate Change

ENDNOTES

1. The UNFCCC website with information on long-term strategies is https://unfccc.int/process/the-paris-agreement/long-term-strategies.
2. The Energy Innovation: Policy and Technology LLC website is https://www.energypolicy.solutions/.
3. Various studies calculate learning rates for different technologies. See, for example, "Renewable Power Generation Costs in 2017" (International Renewable Energy Agency 2018) and "Assumptions to the Annual Energy Outlook 2018: Electricity Market Module" (U.S. Energy Information Administration 2018).
4. The value ranges were set arbitrarily for the illustrative purpose of this analysis but they are not excessively wide or narrow in consideration of the dispersion of existing cost reduction estimates. See, for example, Osmundsen (n.d.) (Figure 4) for solar photovoltaic system and Wiser et al. (2016) (Figure 1) for wind power.

GLOSSARY

Material uncertainty: Uncertainty whose potential impacts on outcomes of interest are significant.

Parameter uncertainty or parametric uncertainty: Uncertainty that exists in input data or parameters used in the analysis because of their incomplete or insufficient quality or quantity in terms of, e.g., coverage, resolution, accuracy, and representativeness.

Scenario: A description of the plausible future development of the matters of interest on the basis of a set of assumptions. A scenario is not a prediction or forecast of the future.

System uncertainty or structural uncertainty: Uncertainty in the model used in the analysis, which results from incomplete knowledge, intrinsic unpredictability, or the complexity of the system that the model tries to represent.

Uncertainty: "[A] cognitive state of incomplete knowledge that results from a lack of information and/or from disagreement about what is known or even knowable." (Intergovernmental Panel on Climate Change 2014, 155)

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