Opportunities and Challenges in the Visualization of Energy Scenarios for Decision-Making

Preprint

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National Renewable Energy Laboratory

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Opportunities and Challenges in the Visualization of Energy Scenarios for Decision-Making

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Abstract

Scenario studies are a technique for representing a range of possible complex decisions through time, and analyzing the impact of those decisions on future outcomes of interest. It is common to use scenarios as a way to study potential pathways towards future build-out and decarbonization of energy systems. The results of these studies are often used by diverse energy system stakeholders — such as community organizations, power system utilities, and policymakers — for decision-making using data visualization. However, the role of visualization in facilitating decision-making with energy scenario data is not well understood. In this work, we review common visualization designs employed in energy scenario studies and discuss the effectiveness of some of these techniques in facilitating different types of analysis with scenario data.

Index Terms: Visualization, energy scenarios, decision-making

1 Introduction

The decarbonization of our energy and transportation systems is a critical problem that has far-reaching repercussions and requires the enactment of complex and difficult decisions. Real-world decisions such as these often encompass several facets of our communities and culture, and affect all aspects of society. Understanding how choices made today might shape our energy systems is crucial information for reaching future energy goals.

Scenario analysis, a formalized process of grouping assumptions and decisions over time to study their impact, is one way to inform complex decision-making under uncertainty about the future. While there is no established singular definition, generally the literature considers scenarios as a set of significantly different reasonable narratives that are forward-looking and incorporate external context (*i.e.*, assumptions) for the purpose of decision-making [7]. Computational modeling is a key part of scenario analysis by incorporating assumptions and decisions in models and creating data that can be used to assess future impact. Scenarios are grounded in expert opinions on feasible futures, but the large scope and expanding interactions between sectors that are necessary to consider in future energy planning requires numerous experts across multiple disciplines such as economics, community engagement, land siting, and electrical engineering. Even small perturbations from a particular scenario are non-trivial to produce and require expert judgment, which makes it difficult to automate the creation of new scenarios. Although experts may inform scenario design, it is ultimately communities that make decisions, hopefully leveraging what is learned in the scenario study. Visualization is essential to help diverse users analyze scenarios and make critical decisions, yet little work explores the challenges associated with creating such visualizations.

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In this work, we review the current landscape of visualizations of scenario data. We discuss and illustrate the effectiveness of common visualization techniques in facilitating decision-making with a publicly available scenario study use case. Specifically, we discuss visualization designs for land assessment decision-making using land use data from the 100% clean electricity by 2035 scenario study [8], which outlines four scenarios achieving clean electricity that investigate the roles of transmission expansion, as well as technology advancement and availability. There are numerous results from this study, such as land requirements, levels of generation types, and greenhouse gas emissions at various times in the future. In this work, we focus primarily on the resulting land use in each scenario, as this informs land assessment decisions for land managers. From this case study, we identify and present challenges and opportunities for visualization of scenario data.

2 Background & Related Work

Scenarios are a prevalent planning and decision-making technique for capturing future goals and assessing impacts of various decisions and assumptions on those goals [23]. A scenario represents a future state of the world given current knowledge and a collection of assumptions about how the world will progress over time. The design of scenarios is similar to "what-if" reasoning, which is a grounded thought experiment for extrapolating and testing causality [24]. However, scenario studies are distinct from "what-if" reasoning in that the goal is to understand the *impact* of causal relationships rather than reasoning about the validity of those relationships. Furthermore, scenario analysis is a projection of how the world *could* evolve if particular decisions are made and certain assumptions are, in fact, valid. It is not itself a forecast, although forecasts could be included as part of the analysis. The quantification of the impact of scenario assumptions, for example, greenhouse gas emissions, jobs, or cost of the energy transition, can then inform decision-making [9]. For complex problems like energy planning, it is common to use large interlinked computational models to quantify aspects about the future (*e.g.*, see Figure 3 in Chapter 2 [6]). For example, a model that outputs total electricity demand over time given different assumptions about the electrification of residential homes is an input to another model that optimizes electricity production to meet that demand, and so on. Practically, this means generating new data realizations outside of the predefined set of scenarios is difficult because it requires coordinating simulations between multiple computational models. This is one reason visualizations typically only use the data generated for each scenario, which is a significant difference from visualization systems that enable"data sculpting" [12].

Scenario studies present challenges for visualization because of the uniqueness of the data. Scenario data is similar to ensemble data in that it is a set of modeling or measured outcomes. However, scenario data is distinct from ensemble data in that computation of statistics is not well-defined because of the importance of the narrative elements of scenarios. One consequence of this is that we cannot compute statistics across scenarios in the same way as we do with Monte-Carlo type (*e.g.,* random sampling) ensemble datasets.

Specifically, mathematical operations on the assumptions that distinguish scenarios are not well-defined, because assumptions are at best discrete categories (*e.g.,* low demand or advanced technology availability). Given potential disconnects between the assumptions of scenarios, we cannot apply classical statistical or interpolation techniques to the data, because we lose the narrative components that are core to scenarios. Therefore, applying ensemble and uncertainty visualization techniques used in previous work to scenario data is not straightforward [13, 21, 22, 26].

2.1 Scenarios for Energy Systems

Scenario analysis is used extensively to study possible transitions in energy systems, and the impact of the features of those transitions [2, 23]. In particular, scenario studies are well-suited for illuminating causal relationships between decisions and quantitative features, which is highly relevant for energy planning. For example, two recent studies analyzed possible pathways towards 100% decarbonization for the communities of Los Angeles, California [6] and Puerto Rico [3]. In these studies, scenarios represented multiple assumptions, including possible policies, amount of distributed energy, and land availability for renewable resources.

Once a set of scenarios are defined, computational modeling can then represent the associated assumptions as they arise in various facets, such as generation build out, generation production, distributed energy adoption, and greenhouse gas emissions. For assumptions that are directly captured by a model, for example percentage of distributed energy, it is generally straight-forward to represent the assumption in a computational model. However, not every assumption can be directly represented and more steps might be needed to embed the assumption into a model. For example, certain policy decisions may need to be broken down and assessed by multiple models [6]. Once the fundamental aspects of scenarios are modeled and analyzed, we can then look at predictions of the future, such as emissions, jobs, and costs. Often, these future outputs are a key factor in decision-making with scenarios, because they describe factors relevant across stakeholders.

How scenarios are defined influences their utilization in a decision-making context. For example, scenarios that only differ by one assumption can be directly compared to assess the impact of that assumption, but direct comparison is more difficult when scenarios differ by more than one assumption. On the other hand, it is not possible to understand the impact of multiple assumptions without directly embedding all of them into a scenario. For example, there may be overlapping impacts of assumptions on distributed solar, such as levels of residential electrification or natural gas price, but without directly incorporating both of these assumptions together we cannot easily determine the combined impact from studying them individually. We discuss how scenario definitions, assumption modeling, and decision-making goals influence possible visualizations and interactions of scenario data further in Section 4.

3 Visualization of Energy Scenarios

Numerous examples of data visualizations for energy scenario data are available in the literature and online [3, 6, 8, 18, 20, 17]. While insights from individual scenarios are valuable, comparing scenarios to discern the impacts of varying assumptions is crucial. Comparative visualizations highlight distinct facets of scenario data, and the differences between scenarios often contain more informative insights than any single scenario. However, comparison is a lower-level analytical user task than decision-making [1], and comparison alone likely cannot support decision-making given the complexity and interdependence of factors in energy scenarios. Effective decision-making in energy planning and policy requires integrating visual insights with broader contextual understanding, stakeholder engagement, and rigorous analysis of the complex assumptions underlying the scenarios.

To highlight the gap between the current approaches for visualizing scenario data and what is needed for effective decision-making, we review the most common visualization designs for scenario data. We then show visualizations we designed to improve upon the existing approaches using data from a publicly available scenario study. We analyze existing visualization strategies by their use of comparative techniques. Gleicher et al. [11] organize comparative techniques into three main types: juxtaposition, superposition, and explicit encoding. These techniques provide different ways to visualize and compare energy scenario data, each with its strengths and limitations depending on the analytical goals and complexity of the data.

Juxtaposition involves showing scenario data separately, often in different plots placed near each other in visual space or sequentially shown in animations. Each scenario or scenario facet is presented in its distinct visual representation, which can be placed near each other for comparison across scenarios or facets. We found several examples of bar charts, line charts, and maps placed side-by-side for various kinds of scenario data [3, 6, 10, 18, 20, 19]. Juxtaposition makes it easier to read individual values of scenario data, but it is more challenging to compare values and trends across scenarios or facets because users have to move across different visual spaces. Moving between plots or visual spaces to compare scenarios may limit the ability to grasp complex interdependencies and trade-offs crucial for decision-making.

In contrast to juxtaposition, superposition displays multiple scenarios on the same plot or visualization. The superposition technique is also quite common in the literature. We found multiple examples of scenario data placed together in the same bar chart, line chart, or overlapping line and bar charts [3, 10, 6, 20, 18, 19]. This combination allows for direct comparison between scenarios within the same visual context. Superposition can highlight similarities and differences more effectively across scenarios but may lead to issues like over-plotting or visual clutter, especially as the number of scenarios increases. Decision-makers may struggle to extract clear insights or prioritize actions when faced with visually dense information of complex overlapping data points or patterns.

The explicit encoding class of techniques directly expresses comparisons through derived data values (e.g., the difference in a value between two scenarios). Explicit encoding effectively expresses specific comparisons and does not inherently have the same issues with visual space and over-plotting as the number of scenarios increases. However, it may limit the ability to discern exact values for individual scenarios compared to juxtaposition or superposition techniques. For example, Manogaran et al. show several facets of multiple scenarios by comparing the increase in various metrics from the business-as-usual scenario [17]. The abstraction or aggregation of detailed scenario information may limit decision-making, failing to represent individual data points or contextual nuances. Furthermore, visualizations using explicit encoding are tailored to specific comparisons or derived metrics, and they may not accommodate evolving decision-making needs or unexpected queries from stakeholders, limiting flexibility in exploring alternative scenarios or factors.

While it is instructive to assess current approaches to scenario visualization, we further illustrate how the comparative techniques result in different visual designs of the same scenario data. We visualize wind and solar capacity and siting (location) scenario data from the scenario study by Denholm et al., which outlines four scenarios to achieve 100% clean electricity by 2035 [8]. The energy scenarios examined include “All Options,” where technology advancements continue in line with NREL’s Annual Technology Baseline [25], encompassing direct air capture (DAC) technology deployment, in contrast with the other scenarios that assume DAC does not achieve

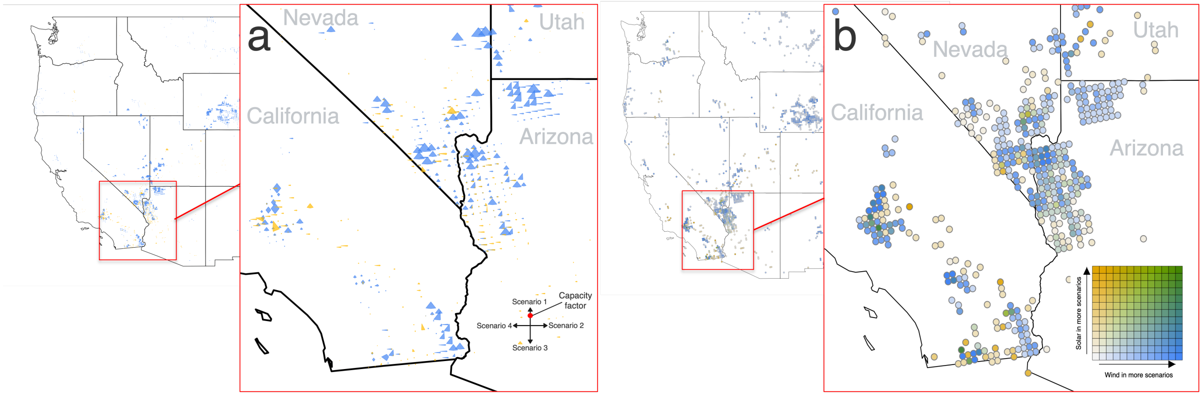

Figure 1: Two visualizations of renewable site location and capacities for four different scenarios. a) Each site has a radar plot where the distance from the center indicates the capacity for the labeled scenario, as shown in the legend. Wind and solar sites are plotted as separate colors (blue and yellow, respectively). b) An aggregated visualization of scenario data where each site is colored according to the number of scenarios it occurs in and the resource type.

necessary cost and performance targets for large-scale deployment. The "Infrastructure" scenario anticipates progress in transmission technologies and expanded transmission capacity. In contrast, the "Constrained" scenario imposes additional limitations on new generation and transmission deployment, thereby restricting capacity expansion and increasing deployment costs for specific technologies. Lastly, the "No CCS" scenario assumes carbon capture and storage (CCS) technologies do not reach cost-competitive deployment levels, emphasizing a shift from fossil fuels to alternative energy sources and technologies. Specifically, our focus lies in identifying the parcels of land utilized due to their significance to local communities and the type of generation they accommodate, which directly impacts land assessment and usage requirements. Figure ES-2 in their study illustrates the juxtaposition technique with this scenario data [8], where the location and capacity of each site is shown on a map, and there is one map for each scenario. We do not reproduce a juxtaposition visual design of this use case in this work, and note that studies on the juxtaposition strategy for data comparison on maps have found it to be less effective than superposition [16].

Figure 1 shows two alternative visual designs of the scenario data that utilize the superposition and explicit encoding techniques. Specifically, rather than four individual maps, we plot all scenario data on a single map. In Figure 1a, a radar plot is drawn at each site location. The generation capacity for a scenario is represented by the distance from the center of the radar chart. Separate radar charts are drawn for wind (blue) and solar (yellow). Unlike the juxtaposition technique, the superposition technique in Figure 1a allows us to immediately identify which parcels of land occur in many scenarios, as they have larger radar charts. However, sites that only occur in one or two scenarios, or that have both wind and solar, are harder to read, which we address in an alternative design in Figure 1b. Here, each site is colored according to the number of times it occurs in a scenario, and whether it is wind, solar, or both, using a bivariate colormap. Now each site is clearly visible, and we can still identify parcels of land that occur in more scenarios. However, the capacity information is now lost.

Our example case study illustrates the difficulty in designing comparative visualizations for scenario data. In particular, even with only four scenarios and three data attributes, the design space is large. Energy scenarios often contain information about many complex interdependent factors, and no single comparison can sufficiently address all possible decisions that could be made with scenarios. Furthermore, scenario assumptions, which underscore the narrative elements of the scenario, are an important element for decision-making that are often not the focus of scenario data visualizations. We explore these gaps further in the next section.

4 Visualization for Decision-Making with Energy Scenarios

Scenario studies for decarbonization transitions are an important analytical tool for communities, yet, we know that our ability to explicitly facilitate decision-making with scenario data is lacking [6]. One major hurdle is that visualizations designed for decision-making differ from those targeted for comparison because comparison is but one part of the decision-making process. We need to better understand how to design visualizations for scenario data and how the data facilitate critical decisions. We examine opportunities and challenges for visualization in facilitating decision-making with energy scenario data.

As we discussed in the previous section, comparative visualizations are typically not sufficient to enable decision-making on their own, though they are likely an important component of a larger decision-making visualization system. From our example use case, both visualizations in Figure 1 indicate which parcels of land are more likely to be built on according to the number of scenarios it occurs in; however, they do not easily facilitate comparison of land usage between scenarios because of the aggregation of information. Both visualizations provide an *overview* of land usage, but they do not allow a user to investigate the impact of particular assumptions of the scenarios on land usage.

Figure 2 shows a third visualization design of our example use case, focusing on two scenarios that differ by a single assumption—the scale of the transmission system's future expansion. We separate sites according to whether they exist in both scenarios (purple) or only in one or the other scenario (blue or green). This simple encoding illuminates a significant amount of useful information for analysis and decision-making. First, it immediately highlights the sites the model determines will be built out no matter which scenario occurs (*i.e.*, whether we choose to expand transmission significantly or not). Second, we can immediately identify locations where significant differences exist between the two scenarios or where the decision actually changes land usage. We zoom-in on one such area, where we can see many blue sites in Montana, while Wyoming has many green sites. In other words, the decision to expand the transmission system induces a trade-off in land usage between Montana and Wyoming. Furthermore, we can see that the green sites in Wyoming are closer to sites that exist in both scenarios. So, in the case where transmission is built out more, the number of sites in Wyoming is *expanded upon*. On the other hand, in the case where transmission is not built out more, *new clusters* of generation are built out in Montana. This is additional useful

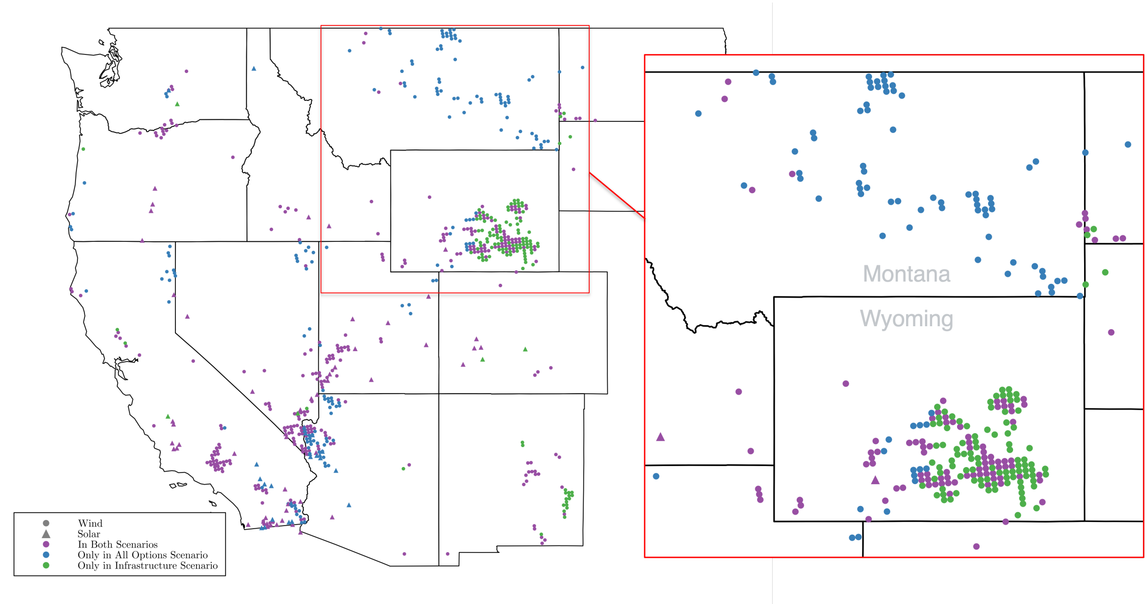

Figure 2: Example of a visualization geared more towards trade-off analysis, as it compares differences in siting of renewable generators more explicitly between two scenarios than those in Figure 1. Sites that occur in both scenarios are purple, while sites that only occur in one of the scenarios are blue or green. Wind and solar are drawn as circles or triangles, respectively.

information when deciding how much to build out the transmission system, as there may be less resistance to expanding on land near already dedicated sites rather than allocating new areas.

4.1 Challenges and Opportunities

Our example use case highlights several challenges in designing appropriate visualizations for decision-making with scenario data.

1. **Scalability:** The breadth of scenario data is significant, and reasoning among the facets and between assumptions is non-trivial for large-scale data.
2. **User Centric Design:** The complexity of the decisions made with scenarios and diversity of the stakeholders requires supporting numerous low-level analytical tasks that are difficult to enumerate and design for in decision-support systems.
3. **Scenario Design:** The design of the scenarios significantly influences which analyses, uncertainty quantification, and reasoning are valid. Integrating these goals within the current scenario design processes is a demanding and multi-disciplinary effort.

One opportunity to address the first two challenges is to guide users towards the information they need for a decision within a visualization system. We could enable users to indicate their preferences for specific outcomes, properties of future states, or assumptions about the future as one approach. With preference information, a visualization system could then determine which scenario information to present. Multiple criteria decision-making is one way to mathematically formalize this process [14]. However, user externalization of preferences is still a challenging problem [15], and it only works if users are aware of their preferences. A second possible approach could be to enable users to determine their preferences for particular facets or outcomes by helping them understand important trade-offs between outcomes and showing how preferences influence the "best" solution. A final possible approach for addressing these challenges is facilitating knowledge sharing among diverse experts participating in these decisions. A visualization system could indicate how experts evaluate relevant facets of scenario data and allow non-experts to utilize this information in their own assessments. Leveraging the strengths of diverse groups in decision-making with scenario data has significant potential in visualization systems but requires careful consideration of bias and equity.

Addressing the final challenge requires multi-disciplinary approaches that involve community stakeholders, computational modelers, statisticians, and visualization scientists. Scenarios are typically considered independent, such that a valid interpolation between them is not guaranteed to exist. When scenario assumptions are independent but are not independently assessed, it is difficult to isolate which assumption contributes to differences between scenarios, which further exacerbates the first two challenges. One possibility to address this issue is to train surrogate models for the simulations utilized in scenario studies [4, 5]; however, it is not always computationally feasible to generate the necessary amount of training data for adequate surrogate performance. This challenge calls for improved scenario study planning, where community stakeholders can indicate the information they want to learn and assess with the study, computational modelers can indicate how they can capture and assess that information, and statisticians can identify valid analyses of the resulting data. There is an opportunity for visualization to facilitate this kind of planning, as it involves provenance capture (*i.e.*, what are the assumptions, and how and where are they modeled?), sensitivity analysis (*i.e.*, how much can we derive and learn from the scenarios as they are defined?), and a balancing of costs (*i.e.*, the trade-off between modeling detail, ability to quantify uncertainties, and the costs of achieving that level of detail).

5 Conclusions

In this work, we discuss the difference between scenario data and other common data types in visualization, like ensemble data, and how that impacts visualization approaches. We reviewed common visualization techniques for scenario data and demonstrate these techniques through an example use case. We note important gaps in only approaching the visualization of scenario data from the context of facilitating comparison. We enumerate multiple challenges in designing visualization systems that enable decision-making with scenario data, and opportunities to address those challenges. Overall, more holistic approaches surrounding particular decision-making tasks with scenario data, like trade-off analysis, are fruitful directions for future research.

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