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Meta-analysis of energy scenario studies: Example of electricity scenarios for Switzerland

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ABSTRACT

We present a meta-analysis of long-term energy-system scenario studies. The meta-analysis comprises a qualitative taxonomy of modeling approaches and a quantitative decomposition of scenario results across heterogenous studies. The analysis is exemplified by technology-detailed scenario studies of the Swiss electricity system. In the decomposition approach, we assess the variability across scenario results by a principal component analysis, which provides a low-dimensional approximation of multidimensional data. Additionally, by means of a distance measure, the extremality of a scenario result is evaluated, and a minimal set of representative scenarios is determined with respect to a considered scenario result. The proposed methods contribute to the analysis of commonality of modeling approaches and of multidimensional results across heterogenous scenario studies.

1. Introduction

A major purpose of scenario studies is to support decision makers and other stakeholders. In this paper, we are concerned with quantitative models of energy system scenario studies and the corresponding scenario results. In energy system scenario studies, a *scenario* usually encompasses not only model output, but also parameter assumptions and qualitative assumptions that drive scenario results, where the results usually consist of a diversity of numbers; *a scenario result* in our terminology is a subset of the reported numbers, which consist generally of post-processed output of a model and may be augmented by some of the parameter assumptions. An energy-system scenario study usually reports a single scenario or several scenarios, which are targeted for decision makers and other stakeholders. The subsequent studies of the Swiss electricity scenario studies, which serve as an example, are compatible with this definition; related notions are for example in Refs. [1–3].

A decision maker faces the problem to retrieve the assumptions that drive scenario results, and to judge modeling limitations. Unfortunately, assumptions and limitations are sometimes partially concealed in the studies. And even if they can be retrieved, a comparison of scenarios across different studies is still difficult because assumptions and modeling approaches may differ in multiple ways.

To help decision makers, who are sometimes confused with the many different scenarios, this paper contributes to the assessment of possible commonalities of heterogeneous energy system scenario studies. We focus on technology-rich (bottom-up) studies, which provide a sufficiently high detail in a multidimensional scenario result that is available in a sufficiently large number of studies for quantitative assessment.

We consider a qualitative comparison (taxonomy) of the studies and several quantitative methods for scenario results. The taxonomy is not needed for the quantitative methods, but complements them. The combination of taxonomy (which points to the methodological limits of studies) with the quantitative analyses (which assess scenario results) can provide a more complete meta-analysis for heterogeneous scenario studies.

1.1. Qualitative comparison

As a qualitative meta-analysis, we consider a taxonomy of bottom-up modeling approaches of energy scenario studies to evaluate their commonalities. The taxonomy should help decision makers, as well as modelers and scenario analysts to assess the studies' limitations and trade-offs. The taxonomy is exemplified by scenario studies of the Swiss electricity system.

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Attempts to classify energy system models are various; see Refs. [4–17]. The research gap is that those classifications focus on single models, but not on energy system scenario studies, which employ usually a combination of models; hence, our emphasis is on the evaluation of model combination, which conveys implicit limitations, which are sometimes hidden from the reader of such studies.

1.2. Quantitative comparisons

We assess the statistical variability of a multidimensional scenario result across the studies by a PCA (principal component analysis) and by using a distance measure.

Distilling meaningful scenarios out of a large set of possible input and output pairs of a model is an active research area. Scenario discovery techniques are used for example in Refs. [18–23]. A related approach is the clustering technique of scenario outcomes in Refs. [24,25].

PCA was applied to scenario discovery in Ref. [2], where the parameter input space of a model is rotated such that scenarios (results and corresponding input ranges) can be better identified. Statistical cluster-identification and PCA was also applied in Ref. [26] and a case study of a renewable energy portfolio model is presented. In the majority of the approaches, an uncertain parameter is considered as an input to a single model (e.g. a computer simulation model, which runs several times with Monte-Carlo sampling of the uncertain parameter).

In our case, PCA is applied across scenario results of several different studies having different, heterogenous modeling approaches; statistical sampling of model output is not involved. The PCA is not used primarily to discover scenarios, or to perform robustness analysis for scenarios which are numerically evaluated from a single model, but to capture the commonalities in a given set of scenario results across heterogenous studies that apply different modeling approaches. The goal is that PCA can explain the variability of a multivariate scenario result by an approximation through the use of a few principal components of low dimensionality and of maximal cumulative variance; these few principal components can be evaluated more easily by decision makers. In addition, the obtained few components (with the corresponding estimated variance) can be used as low-dimensional input to other models that need input parameters from the energy system, for example to model a whole economy. Such economy-wide models may be large-scale, and such that low-dimensional input is numerically favorable.

In a second quantitative approach, we use a distance measure between scenario results across different studies. Distance measures in scenario analysis were used in Refs. [1,27,28]. In Ref. [1], a scenario is defined as a vector, where each component has finitely many values; the distance between two scenarios is the number of components that are not equal. In contrast, we consider vectors of continuous numbers with the Euclidian distance measure. In Refs. [27,28], the feasible set of possible energy-system configurations of a single model is considered, where the set is additionally constrained such that a point in the set has to be in the vicinity of the cost-optimal solution. Basically, the distance measure is the difference in cost (or, alternatively, in other objectives of relevance), and a major goal is to evaluate the robustness of a model. Our distance measure as well as the research questions are different: (i) How to identify scenarios that contribute to the variability of a multidimensional scenario results across studies (evaluation of extremality)? (ii) How to find a minimal set out of a given set of scenarios that provide the best approximation of the whole set in terms of a multivariate scenario result (identification of a minimal set)?

1.3. Is quantitative analysis of scenarios over heterogenous studies possible?

For energy scenario studies with a larger scope, a statistical comparison is usually not possible because of the heterogeneities in input, in modeling choice, and in reported results. Heterogeneity in input assumptions can be caused by different parameter values (e.g. different discount rate, starting year, time horizon, or time step of the modeling). Heterogeneity is also caused by different boundary conditions (e.g. different geographical scope) and the choice between target or explorative scenarios. Moreover, heterogeneity is caused by model choice (e.g. optimization vs. simulation) and the different incorporation of behavioral or market aspects. Finally, the reporting is heterogeneous: For example, cumulative system cost may be reported as discounted or as undiscounted cost, which prohibits a proper comparison.

Despite the heterogeneity across scenarios, we may be tempted to accept the average of results across scenarios as a forecast. In the case of climate models, Ref. [29] states that "an average of multiple models may show characteristics that do not resemble those of any single model, and some characteristics may be physically implausible." This holds also for energy scenario models. For example, a driver for technology deployment is the cost of the technology. In reality, if the cost of a technology is in the future higher than for another technology (and the technologies are perfect substitutes in all other aspects), then the more costly technology may not be deployed at all. Thus, averaging over two scenarios where in each scenario the other technology has lower costs respectively yields a scenario where both technologies are deployed, which may not be realistic. Hence, a meta-analysis cannot rely on statistical averaging.

1.4. Case study of Swiss electricity scenarios

Swiss electricity scenarios of studies that apply bottom-up modeling approaches are used as an illustration throughout the paper. In particular, the annual supply mix of the electricity technologies at the time horizon is chosen as the multidimensional scenario result across studies for the quantitative meta-analyses because it constitutes a major result across the studies, and it is reported in a relatively large set of studies.

The Swiss case study is relevant on its own because it provides an overview of the considerable modeling efforts in the developed country Switzerland to cope with the energy transition. The electricity system of Switzerland is faced with a phase-out of nuclear plants and is therefore confronted with a major restructuring of generation capacities. The restructuring of the electricity sector is a challenge also for other countries, such that the Swiss case can serve as an example.

The studies were selected as follows: (i) They are published in the years 2011–2013, after the decision of the Swiss Federal Council to gradually phase-out nuclear power and the launch of the policy initiative Energy Strategy 2050 in 2011; (ii) they provide detailed results on the electricity system, hence they include one or several bottom-up models. Studies focusing on economic aspects of the whole Swiss energy system were not considered [30–32]. The studies are listed in Table 1.

More information on the scenario studies can be found in the appendix. Methodologically oriented readers may skip all parts referring to the case study.

1.5. Structure of the paper

Section 2 introduces the taxonomy for energy-system scenario studies that use technology-detailed modeling (the result of the taxonomy is also shown here, because it consists of a single table for