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Towards improved guidelines for uncertainty analysis of carbon capture and storage techno-economic studies

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Abstract

Uncertainty analysis is a key element of sound techno-economic analysis (TEA) of CO_2 capture and storage (CCS) technologies and systems, and in the communication of TEA results. Many CCS technologies are novel concepts, that are still in the early (pre-commercial) stages of development. Therefore, uncertainties in their technology performance and cost are often substantial, making it imperative that they be characterized, and their impacts reported. Although uncertainty analysis itself is not novel, with some methods already frequently used by the CCS TEA community, a document that provides a comprehensive overview of methods and approaches, as well as guidance on their selection and use, is still lacking. Given its importance, we seek to fill this gap by providing a critical review of uncertainty analysis methods along with guidance on the selection and use of these methods for CCS TEAs, highlighting good practice and examples from the CCS literature. There are many opportunities to bring the use of uncertainty analysis to a higher level than currently practiced. This review of and guidance on available methods is intended to help accelerate continued methods development and their application to more robust and meaningful CCS performance and cost studies.

Keywords: CCS; Techno-economics; Guidelines; Local and global uncertainty analysis; Pedigree analysis; Pseudo-statistical approach.

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1. Introduction

While a number of large-scale CCS (CO_2 capture and storage) facilities have successfully been built and entered into operation at industrial facilities and (to a lesser extent) power plants, CCS remains an effective but relatively expensive technology for mitigating greenhouse gas emissions. This has spurred extensive research and development (R&D) efforts to reduce the cost of CCS, especially the cost of CO_2 capture. As a result, many CO_2 capture technologies are still in an early stage of development for both the power and industrial sectors. Accordingly, there are large uncertainties in estimates of their future technical and cost performance. This makes reaching informed decisions on technology policy, R&D funding, and investment strategies more difficult due to the lack of transparency on what the uncertainties are and their significance for the outcomes of interest. Thorough uncertainty analysis should therefore be included in any techno-economic study on CCS technology, especially in the case of emerging technologies that currently lack commercial deployment and experience.

Frequently, uncertainty analysis is used only to assess the impact of a limited number of parameters (such as financial/economic indicators), often through single parameter sensitivity analyses. In such cases, however, multi-parameter or global methods would be more justified and provide a deeper understanding of the impact of performance and cost uncertainties. Furthermore, newly developed methods that have proven to be helpful are yet to be adopted as common practice. Therefore, an international group of leading institutions in CCS techno-economic analysis set out to develop guidelines on improved uncertainty analysis for CCS costing studies. In this work, we will present these guidelines. The aim of this effort is threefold: first, to raise awareness of uncertainty analysis and available techniques for CCS techno-economic studies; second, to provide guidance on the sound use of specific methods and approaches; and third, to increase the use of these uncertainty analysis methods,. A full, open access, journal paper has been published in 2020, reporting on these aims [1].

This work is part of a larger effort among leading institutions in CCS cost evaluations being carried out under the auspices of the IEAGHG CCS Cost Network. Building on an earlier white paper and cost guidelines developed by researchers active in this network [2], our collaborative effort is aimed at drafting a complementary set of CCS costing guidelines for three new topics: (1) one looking into methods for carrying out costing of novel (low Technology Readiness Level) technologies; (2) improved guidelines for cost evaluation of CCS from industrial applications; and, (3) quality assurance and uncertainty evaluations of data and models used in CCS cost analysis (the focus of this paper). Each of these three efforts has resulted in open access journal publications [1], [3], [4] and will be published as a common report under the auspices of the participating institutions.

2. Short summary of the uncertainty guidelines

The uncertainty guidelines paper outlines the landscape of techno-economic modelling studies (simplified, rigorous/detailed, and in-between) and discusses the different purposes of uncertainty analysis (answering “what will” or “what if” kind of questions [3], model testing, or factor prioritization [5]). It continues to describe existing uncertainty analysis methods: from local (one-at-a-time to N-ways sensitivity analysis [6]) to global (e.g. using Monte Carlo simulation [7]) and provides examples of these from the CCS literature. These methods are described following a *what*, *how*, and *when* structure, providing guidance on the use of such methods and when they should (and should not) be used. The guidelines then review newly developed methods such as pedigree analysis [8] (Table 1), the pseudo-statistical approach [9], and the use of surrogate models for global uncertainty analysis of complex integrated techno-economic models that are too computationally intensive to use directly. These discussions led to a guidance matrix and decision scheme for selecting uncertainty analysis methods and approaches for specific purposes, model type, and level of technology development (reflected by the Technology Readiness Level scale). These guidelines will also help researchers and technology developers to critically analyze the techno-economic performance of the CCS technology under consideration.

Opportunities that can be achieved through advanced use of uncertainty analyses, such as design of experiments for CCS pilots (Figure 1) or design of CCS chains under uncertainty, are also discussed. Finally, the publication addresses the lack of uncertainty analysis options in widely used commercial process modelling software and discusses other software tools for undertaking uncertainty analysis.

Table 1. Example of a pedigree matrix used in the EDDiCCUT project to qualitatively assess the strength of data input for cost assessment [10]**.**

SCORE	Proxy	Reliability of source	Completeness (only for equipment list)	Completeness (all other parameters)	Validation process
4	A direct measure of the desired quality	Measured/official industrial, vendor, and/or supplier data	Representative data for all line items (processes, instruments, electro, civil, mechanical, etc.)	Complete data from a large number of samples over a representative period	Compared with independent data from similar systems that have been built
3	Good fit to measure	Qualified estimate by industrial expert supported by industry data	Representative data for all process equipment (equipment list, heat and mass balance, PFD)	Complete data from a large number of samples but for unrepresentative periods or from representative periods but for a small number of samples	Compared with independent data of similar systems that have not been built
2	Correlated but does not measure the same thing	Reviewed data derived from independent open literature	Representative data for most important process equipment (equipment list, heat and mass balance, PFD)	Almost complete data but from a small number of samples or for unrepresentative periods or incomplete data from adequate number of samples and periods	Validation measurements are not independent, include proxy variables or have a limited domain
1	Weak correlation but commonalities in measure	Non-reviewed data from open literature	Data from an adequate number of process parameters eat and mass balance, PFD)	Almost complete data but from a small number of samples and unrepresentative periods	Weak and indirect validation
0	Not correlated and not clearly related	Non-qualified estimate or unknown origin	Only high level or incomplete data available	Incomplete data from a small number of samples for an unrepresentative period	No validation performed

Proxy: refers to how good or close a measure of the quantity that is modelled is to the actual quantity one wants to score. *Reliability of source:* evaluates the origin of the collected data. *Completeness:* this criterion assesses the coverage of the data, taking into account the information reported for process inputs, outputs, and associated stressors. It considers not only the amount but also the specific relevance of the presented data. *Validation:* refers to the degree to which data and assumptions used to produce the numeral of the parameter has been cross-checked against independent sources.

3. Key messages

- Proper use of uncertainty analysis in the performance of CCS TEAs can provide policy analysts, decision-makers and others with a more robust understanding of the actual or expected technical and cost performance of CCS technologies, especially novel and emerging technologies that are not yet commercial.
- The key to starting any uncertainty analysis is to first thoroughly define its purpose, and then to ensure that the most suitable type of uncertainty analysis for that purpose is selected. The choice strongly depends on the existing knowledge of the investigated technology and the associated TEA model and its inputs.
- Although so-called one-at-a-time sensitivity analysis is most often applied, this method is quite limited. A better practice is to use probabilistic uncertainty analysis if probability can be quantified, or one-way or N-ways sensitivity analysis if probability cannot be credibly quantified. The latter is best suited to answer prognostic questions, but its utility depends on whether credible probability density functions can be assigned to input parameters.
- Ideally, quantitative uncertainty analysis is complemented with qualitative uncertainty methods to provide insights into the kinds of uncertainty that are unquantifiable, but relevant to policy and decision making. Indeed, much uncertainty in novel technology assessment resides in areas that are not quantifiable. Methods to characterize such uncertainties thus provide a more complete impression of the reliability, quality, and robustness of models and their results.
- Further expanding the capabilities of commercial and other process simulation software to include advanced global uncertainty approaches would be very helpful. There exist open-source, comprehensive, advanced uncertainty analysis toolboxes, but these require some skill in programming, perhaps providing a barrier for some TEA practitioners. Therefore, further improvement of the user-friendliness of these toolboxes (e.g., by including graphic user interfaces) would aid in the further adoption of advanced uncertainty analysis

methods.

- Finally, the importance of transparent communication on the methods used, the results and their interpretation should not be underestimated. Uncertainty analysis should support decision-making and therefore additional efforts to guide users to properly interpret the information provided are often needed.

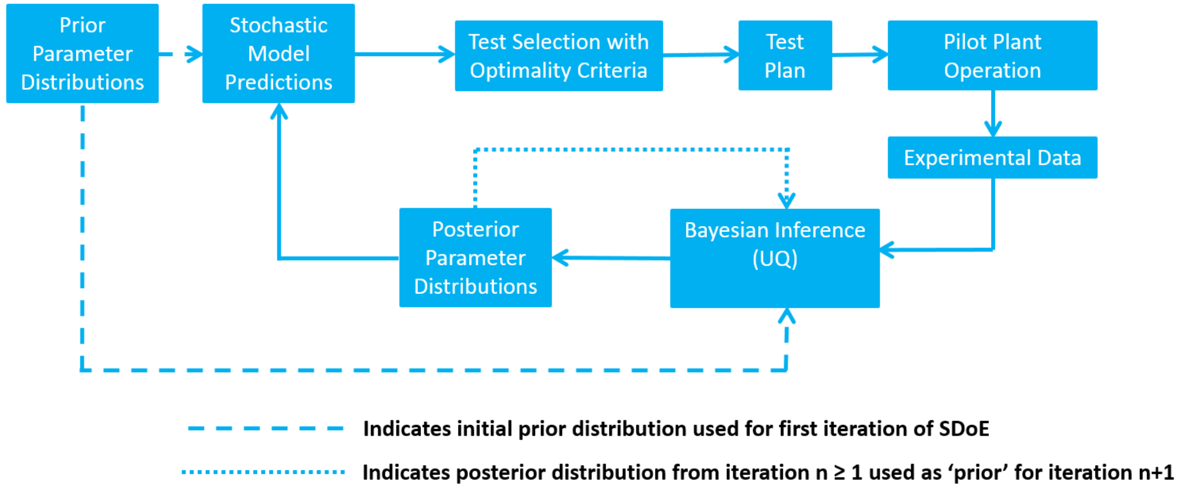

Figure 1. Schematic of Bayesian Sequential Design of Experiments implemented for pilot plant campaigns, as developed in Carbon Capture Simulation for Industry Impact (CCSI²). Adapted from [11]**.**

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