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A review of uncertainty characterisation approaches for the optimal design of distributed energy systems

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ABSTRACT

Energy models are valuable tools that are commonly employed for the optimal design of distributed energy systems (DES). However, the model-based design process of DES can be affected by uncertainty, which can lead to suboptimal design decisions and is introduced by aspects like the stochastic nature of renewables or the unknown future global energy and economy outlook. A critical first step of any effort to examine and incorporate uncertainty in the design process of DES includes the performance of a thorough uncertainty characterisation (UC). The UC task comprises the identification of the sources of uncertainty in the model's parameters and the assignment of a mathematical description to their uncertainty. The aim of this paper is to identify and categorise the most important uncertain parameters in typical DES design models and review the approaches used in the literature to represent their uncertainty. The uncertain aspects investigated pertain to the availability of renewable energy (wind and solar), the economic and environmental dimensions of energy carriers in a DES, the costs and technical characteristics of the technologies composing a DES, and, finally, the uncertain energy demands that a DES must satisfy. The analysis reveals the diversity and the varying complexity levels of the approaches used to characterise each parameter's uncertainty, as well as the specific parameters on which studies in the literature have mostly focused. Additionally, this review can serve to assist modellers who wish to introduce uncertainty considerations in their DES design model with the selection of appropriate UC approaches. Finally, in discussing the results of this review, directions for more effective UC in DES design are discussed, as well as suggestions for the integration of uncertainty in the design process of DES.

1. Introduction

1.1. Distributed energy systems (DES)

In an effort to alleviate the consequences of climate change, the future energy system vision involves a paradigm shift towards distributed energy systems (DES). A definition of a DES is given in [1] as *"a system where energy is made available close to energy consumers, typically relying on a number of small scale technologies"*. The siting of DES contributes to a reduction of energy distribution losses and allows the utilisation of locally available renewable resources. Additionally, DES can couple sectors, like electricity, heating, and cooling with technologies like combined heat and power (CHP), heat pumps, absorption chillers etc. Therefore, in such cases, DES are also commonly characterised as multi-energy systems (MES) [2]. Extensive reviews of DES technologies, their applications and their benefits have been published in [3,4].

A typical domain of application for DES involve buildings in urban environments [5], motivated by the high global degrees of urbanisation [6], the cities' high energy demand density, and the potential for urban renewable energy. These typical cases of distributed energy systems will be considered in this review.

Abbreviations: ACH, Air Changes per Hour; AML, Algebraic Modelling Language; AMY, Actual Meteorological Year; AR, Autoregressive; ARIMA, Autoregressive Integrated Moving Average; ARMA, Autoregressive Moving Average; ARMA-GARCH, Autoregressive Moving Average – Generalized Autoregressive Conditional Heteroskedasticity; BPS, Building Performance Simulation; CHP, Combined Heat and Power; DES, Distributed Energy System; EBC, Energy in Buildings and Communities; EMY, Extreme Meteorological Year; GEV, Generalized Extreme Value; GSA, Global Sensitivity Analysis; GSHP, Ground-source Heat Pump; HVAC&R, Heating, Ventilation, Air-Conditioning & Refrigeration; IEA, International Energy Agency; LCA, Life Cycle Assessment; LSA, Local Sensitivity Analysis; MES, Multi-Energy System; OAT, One-at-A-Time; OU^2, Optimisation under Uncertainty; PDF, Probability Density Function; PV, Photovoltaic; RO, Robust Optimisation; SA, Sensitivity Analysis; SP, Stochastic Programming; TMY, Typical Meteorological Year; UA, Uncertainty Analysis; UC, Uncertainty Characterisation

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1.2. Modelling of DES

Modelling has been an inherent part of the energy domain assisting energy design decisions, supporting energy policy, and providing insights on how energy systems might evolve in the future. A series of studies have reviewed the wide range of energy models either from a broad perspective [7] or for specific subsectors of the energy field [8–11], with optimisation methods appearing as one of the most prevalent techniques used [12–17].

Optimisation techniques are also a key element of DES models, which can be broadly split into two basic types: *design* models & *scheduling/operation* models [18,19]. The former category entails the selection, siting, and sizing of technologies that will compose a DES considering their operational characteristics and constraints, while optimising for desired performance criteria. The latter category seeks to optimize the operation of generation and storage technologies in a DES of known structure and capacities along some time horizon (*e.g.* day-ahead). In this work, the focus is placed on models for the optimal DES design. Comprehensive reviews on optimisation for the optimal design and operation of DES systems are given in [19,20], while multi-criteria decision making is addressed in [21–23].

In terms of techniques used to solve the optimisation problems, mathematical programming techniques are mostly employed, but metaheuristic algorithms have also been used [24]. In the literature, a large number of studies have adopted optimisation techniques to design DES across multiple scales ranging from single buildings (*e.g.* [25–29]) to the urban neighbourhood/district (*e.g.* [30–36]), and the community/city scale (*e.g.* [37–39]).

1.3. Uncertainty and DES

The model-based design process of a DES is irrevocably affected by uncertainty though, which can be defined as *“any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system”* [40]. The stochastic nature of renewable energy, the inability to predict precisely the evolution of energy prices and the uncertain long-term energy and climate outlook render uncertainty considerations essential. Even though uncertainty, in some cases, can be reduced by obtaining additional information, it is hard to eliminate completely all its manifestations. Therefore, as stated in [41] *“uncertainties are always present at the design phase and combine in a random manner, leaving the designer with a moderate or highly uncertain scenario under which he must make design decisions”*.

Uncertainty could emerge due to the inherently random nature of processes present in the system (*aleatory* uncertainty) or due to the lack of knowledge or data (*epistemic* uncertainty) [42]. Uncertainty can then affect the models through model-parameter and model-inherent uncertainty. Model-parameter uncertainty, which is the focus of this review, refers to the uncertain nature of model input parameters *e.g.* due to lack of data, imprecise assumptions etc. On the other hand, model-inherent uncertainty refers to uncertainty in the form of the model *e.g.* due to limited knowledge about certain physical processes [43]. Such an uncertainty type, due to its model specific nature, might be difficult to treat in a rigorous and consistent manner [44].

Nevertheless, DES design is usually performed in a deterministic fashion with designers assuming perfect knowledge of all the model input parameters. Consequently, the results of the model and the success of the DES design are highly dependent on the values given to the deterministic parameters as any deviations due to uncertainty can potentially render a system's design suboptimal.

1.4. Scope and aim of this review

Any effort to integrate uncertainty considerations in a DES design model embarks by performing a detailed *Uncertainty Characterisation* (UC). The UC task entails (i) the identification of the uncertain model parameters and (ii) the assignment of an appropriate mathematical representation to their uncertainty. While, as discussed in Section 1.3, overlooking uncertainty entails the risk of suboptimal decisions, failing to identify one (or more) uncertain parameter(s) or assigning an invalid representation of parameter uncertainty can also lead to suboptimal DES designs. Therefore, the effective characterisation of uncertainty is crucial for the design of robust DES against uncertainty.

The characterisation of uncertain parameters has a domain-specific tint, meaning that the uncertain parameters per modelling domain will differ and similarly the ways to characterise their uncertainty. While appropriate UC approaches have been investigated for other fields (see *e.g.* the Probabilistic Model Code [45] by the Joint Committee on Structural Safety (JCSS)), a similar effort does not exist for DES design models.

Hence, the ambition with this paper is to present a systematic and critical review of the main uncertain parameter categories in DES design models and of the approaches used in the literature to characterise their uncertainty. Additionally, this paper could serve as a foundation for future studies seeking to investigate uncertainty in the context of DES design.

The paper is organised as follows: Section 2 discusses the approaches to perform uncertainty characterisation and presents the structure of a typical DES design model to facilitate the identification of uncertain parameters. Additionally, it briefly discusses the mathematical techniques to incorporate uncertainty in a DES design model. Sections 3–5 discuss parameter uncertainties pertaining to the inputs of a DES, the DES itself and the output of the system or the energy demands, respectively. Section 6 discusses some key issues emerging from this review, while Section 7 provides the concluding remarks.

2. Characterisation of uncertainty in DES design models

2.1. Approaches for uncertainty characterisation

Regarding the first UC task, namely the identification of uncertain model parameters, a safe approach would be to treat all input parameters as uncertain. If, however, the total number of uncertain parameters is large, this approach could lead to overly large problem sizes and cause computational tractability issues. In such cases, a preselection of parameters takes place, usually, based on literature suggestions or on the modeller's experience [46,47].

With regards to the second task, namely the assignment of mathematical descriptions to uncertain parameters, the available approaches can be divided into probabilistic methods, which treat the parameters as random variables following certain probability density functions (PDF), and non-probabilistic approaches, which include interval analysis, fuzzy set theory and possibility theory [48,49] and stochastic processes like Markov chains.

Nikolaidis et al. [50] argue that an interval containing all possible realisations of a parameter is an easy-to-understand approach and, thus, it is preferred by most people. However, Sander et al. [51] argue that the lack of information about the central tendency, the distribution shape etc. render probabilistic methods more preferable. The selection of the characterisation approach is also influenced by the computational method used to study uncertainty as some methods require probabilistic information (*e.g.* Stochastic Programming [52]), while for others interval uncertainty suffices (*e.g.* Robust Optimisation [53]).

When probability distributions are used for the uncertain parameters, they should ideally be based on observation data; however, such data is sometimes missing or sparse. For instance, even though one could assign probability distributions to wind speed variations using extensive collections of measured data [54], it would be difficult to perform a similar task for the uncertain future natural gas prices. Therefore, in order to estimate input distributions, *expert judgement* can be used in the case that no data is available to characterise the uncertainties, *statistical inference* when a large amount of data is available,