UQOP 2019
Uncertainty Quantification & Optimization Conference
18-20 March, Paris, France

Robust design optimization of a hydrogen-based solar energy storage system using an efficient stepwise regression method for sparse polynomial chaos expansions

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Keywords: Regression-based sparse polynomial chaos expansion, robust design optimization, photovoltaic-electrolyzer system, levelized cost of hydrogen.

ABSTRACT

To tackle the dual challenge of complying with increasing energy demand and reducing fossil-based energy supply, power-to-H_2 is a viable solution. In this framework, the design of a directly coupled photovoltaic-electrolyzer system is widely studied [Maroufmashat, 2014, García-Valverde, 2011]. In these studies, the main focus lies on designing the number of electrolyzers in series and parallel with deterministic model parameters (i.e. perfectly known and fixed parameters) to optimize the system performance. However, by considering deterministic model parameters, the inherent uncertainty of the system performance during real-life operation is disregarded (e.g. unexpected costs). This limitation can lead to suboptimal design decisions.

To address the limitation of deterministic model parameters and to validate the use of a directly coupled photovoltaic-electrolyzer system as the foundation for a seasonal energy storage solution, we performed a techno-economic-environmental design optimization under parameter uncertainties (i.e. robust design optimization), including the addition of a fuel cell and energy demand to the photovoltaic-electrolyzer system. This work provides the hydrogen-based energy

system robust designs which are least sensitive to the inherent parameter variations and illustrates the contribution of each system parameter to the total variation of the levelized cost of hydrogen and levelized cost of emissions.

To perform the uncertainty quantification in the robust design optimization process, we used a robust, efficient stepwise regression method for building the sparse Polynomial Chaos (PC) expansions [Abraham, 2017]. In this method, an automated search procedure is applied to determine the most significant PC contributions. In previous work at our research group [Abraham, 2017], the efficiency and robustness of the method was proven by illustrating its superior performance compared to the method based on Least Angle Regression (LAR) for sparse PC expansions [Blatman, 2009]. To further improve the computational efficiency of the robust design optimization algorithm, we applied a stochastic dimension reduction method based on Sobol' indices, where the stochastic parameters with negligible contribution to the objective variance are highlighted and further considered as deterministic [Turati, 2017].

The robust designs for the levelized cost of hydrogen and levelized cost of emissions ensure the highest cross-field performance quality over the system lifetime. If a trade-off exists between optimizing the mean objective and minimizing the objective standard deviation, the gain in robustness comes at the expense of a loss in mean performance. Therefore, an optimal design under uncertainty is determined out of the Pareto set of design solutions. Moreover, by considering various locations, several uncertainty ranges are applied (e.g. difference in uncertainty on the electricity price from the grid for various locations). As a result, different scenarios are evaluated, resulting in specific robust designs according to the location characteristics.

Next to that, by performing a global sensitivity analysis through PC-based Sobol' indices for each stochastic model parameter, the most significant contributors to the objective variance are highlighted. Consequently, guidelines are provided for further enhancement of the system robustness and therefore its performance quality (e.g. bulk manufacturing of the system technologies when the variance of the levelized cost is dominated by CAPEX, or more demonstration projects and continuous high-quality system maintenance for a dominating OPEX uncertainty).

Future works will investigate the integration of imprecise probabilities in the robust design optimization framework.

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