Driven by carbon-neutrality, the deployment of photovoltaic arrays and wind turbines increases rapidly in the power, heating and mobility sectors. To comply with the needs of each sector, these renewable energy systems are coupled with different energy storage technologies and energy conversion technologies, resulting in a diverse set of hybrid renewable energy systems. Designing such a hybrid renewable energy system requires information on the technical, economic and environmental performance of each component, as well as information on the climate and energy demand. These parameters are likely to vary during the system lifetime (i.e., aleatory uncertainty), and data resources on these variations are usually limited (i.e., epistemic uncertainty). Considering these uncertainties in the design of hybrid renewable energy systems is still an exception rather than the norm. Although, disregarding uncertainty can result in a drastic mismatch between simulated and actual performance, and thus lead to a kill-by-randomness of the system. In other fields, such as structural mechanics and aerospace engineering, robust design optimization has already resulted in improved product quality, by providing designs that are less sensitive to the random environment. Despite its potential, applying robust design optimization on hybrid renewable energy systems is not yet studied. Therefore, the research question of this thesis reads:

What is the added value of robust design optimization to hybrid renewable energy systems?

To answer this question, I followed three steps. First, I developed a surrogate-assisted robust design optimization framework, using state-of-the-art optimization and uncertainty quantification algorithms. Despite being limited to problems with a low stochastic dimension (i.e., less than 15 uncertainties), this framework allows defining robust designs for two-component renewable energy systems, optimized for a single quantity of interest. However, hybrid renewable energy systems are typically multi-component systems, with multiple, cross-field objectives (i.e., technical, economic and environmental objectives). Hence, in the second step of this thesis, I modified the uncertainty quantification algorithm. This modification allowed to handle a large stochastic dimension, and thus to define robust designs for complex, multi-component hybrid renewable energy systems in a holistic context. In the third and final step, I proposed an imprecise probability method, to distinguish between epistemic and aleatory uncertainty on a parameter. In this new formulation, the robust design is optimized for the irreducible, aleatory uncertainty, and the global sensitivity analysis is reserved for the reducible, epistemic uncertainty.

The robust design optimization algorithm has been applied on three specific hybrid renewable energy systems: a photovoltaic-battery-hydrogen system, a renewable-powered hydrogen refueling station and a photovoltaic-battery-heat pump system with thermal storage. The results indicate that the robust designs are characterized by a higher penetration of renewable energy systems and by considering energy storage: Coupling battery storage and hydrogen storage to a grid-connected photovoltaic array reduces the standard deviation of the levelized cost of electricity by 42%; A photovoltaic-battery-heat pump with thermal storage system reduces the standard deviation of the levelized cost of exergy by 36%, as opposed to the photovoltaic-battery-gas boiler system; Shifting towards a bus fleet that partly consists of hydrogen-fueled buses (54% of the fleet) reduces the standard deviation of the levelized cost of driving (36%), the mean of the carbon intensity (46%) and the standard deviation of the carbon intensity (51%), at the expense of a limited increase in the mean of the levelized cost of driving (11%).

Conclusively, robust design optimization provides an added value in the design of hybrid renewable energy systems, the method complies with the computational burden of holistic design expectations, and it is adaptable to more advanced uncertainty characterization techniques.