A Net Present Value-at-Risk Objective Function for Uncertainty Mitigation in the Design of Hybrid Ground-Coupled Heat Pump Systems

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The design by optimization of hybrid ground-coupled heat pump (Hy-GCHP) systems is a complex process that involves dozens of parameters, some of which cannot be known with absolute certainty. Therefore, designers face the possibility of under or oversizing Hy-GCHP systems as a result of those uncertainties. Of course, both situations are undesirable, either raising upfront costs or operating costs. The most common way designers try to evaluate their impacts and prepare the designs against unforeseen conditions is to use sensitivity analyses, an operation that can only be done after the sizing.

Traditional stochastic methods, like Markov chain Monte Carlo, can handle uncertainties during the sizing, but come at a high computational price paid for in millions of simulations. Considering that individual simulation of Hy-GCHP system operation during 10 or 20 years can range between seconds and minutes, millions of simulations are therefore not a realistic approach for design under uncertainty. Alternative stochastic design methodologies are exploited in other fields with great success that do not require nearly as many simulations. This is the case for the conditional-value-at-risk (CVaR) in the financial sector and for the net present value-at-risk (NPVaR) in civil engineering. Both financial indicators are used as objective functions in their respective fields to consider uncertainties. To do that, they involve distributions of uncertain parameters but only focus on the tail of distributions. This results in quicker optimizations but also in more conservative designs. This way, they remain profitable even when faced with extremely unfavorable conditions.

In this work, we adapt the NPVaR to make the sizing of Hy-GCHP systems under uncertainties viable. The mixed-integer non-linear optimization algorithm used jointly with the NPVaR, the Hy-GCHP simulation algorithm and the g-function assessment methods used are presented broadly, all of which are validated in this work or in referenced publications. The way in which the NPVaR is implemented is discussed, more specifically how computation time can be further reduced using a clever implementation without sacrificing its conservative property. The implications of using the NPVaR over a deterministic algorithm are investigated during a case study that revolves around the design of an Hy-GCHP system in the heating-dominated environment of Montreal (Canada). Our results show that over 1000 experiments, a design sized using the NPVaR has an average
return on investment of 126,829 $ with a standard deviation of 18,499 $ while a design sized with a deterministic objective function yields 137,548 $ on average with a standard deviation of 33,150 $. Furthermore, the worst returns in both cases are respectively 35,229 $ and -32,151 $. This shows that, although slightly less profitable on average, the NPVaR is a better objective function when the concern is about avoiding losses rather than making a huge profit.

In that regard, since HVAC is usually considered a commodity rather than an investment, we believe that a more financially stable and predictable objective function is a welcome addition in the toolbox of engineers and professionals alike that deal with the design of expensive systems such as Hy-GCHP.