0.1 Objective Design

In this proof of concept, we choose to simply maximize estimated AEP, subject to separate wind and solar nameplate capacity constraints of 75 MW and 50 MW, respectively. As confirmed in Table ??, these capacity constraints were chosen to yield similar solar and wind AEPs of approximately 110 GWh at the high-correlation location. We use up to 50 1.5 MW turbines with a minimum spacing of 200 m between turbines and between turbines and solar modules. Other objectives are possible and could simply be dropped in, such as capacity factor, net present value, payback time, or carbon payback time. One objective of particular interest for hybrid plants is maximizing utilization of a limited grid interconnect, which demonstrate can be similarly optimized with this approach in section 0.3. Further, the objective function could be made to additionally account for factors such as cabling, interconnect, maintenance costs, land use restrictions, and budgets. Other modifications are also possible, such as eliminating capacity constraints and instead simply using net present value as the objective as is allowing the algorithm to trade off between wind turbines and solar modules to find an optimal mix of the two. Similarly, the objective could be modified to generate layouts that improve existing sites by determining the best locations for additional turbines and solar modules. We chose AEP as our objective instead of NVP or other complex objectives because AEP provides a clear yet challenging objective function without the additional complexity and sensitivity to assumptions which an objective such as net present value brings with it. In a NPV objective, uncertain revenue must be forecasted due to time-varying prices, whereas AEP with fixed capacities can stand-in for a constant price of energy, providing an objective which is similar to a practical objective like NPV, but simple and clear enough to provide a proof-of-concept.

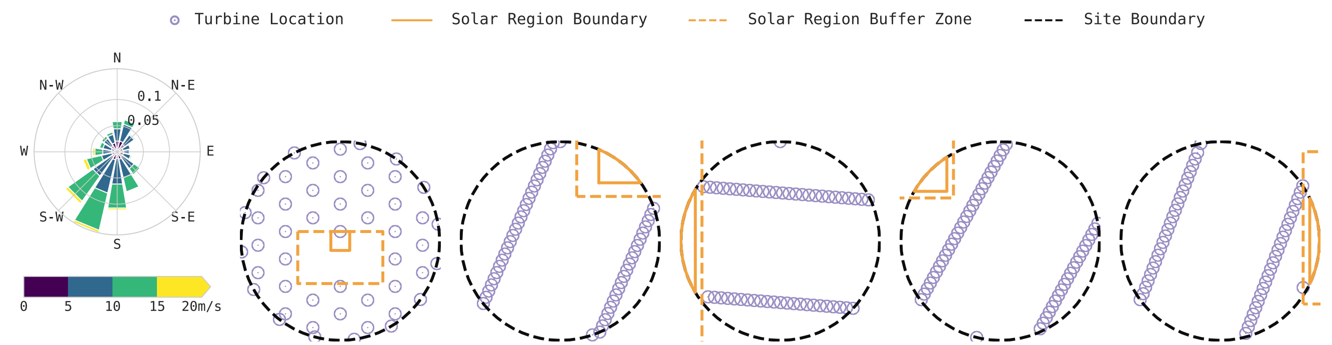
0.2 A Closer Look at the Generated Layouts

0.3 Optimizing Alternate Objectives: Interconnect Utilization

To evaluate the flexibility of the parameterized layout optimization approach, we generated the layouts shown in Figure 3, maximizing interconnect utilization instead of AEP for a range of interconnect capacities for high-correlation location and irregular boundary. Because low interconnect capacities do not realize the benefit of peak energy production, the effect of losses during peak production times is unimportant. Therefore, as the interconnect capacity increases, turbines are shifted from the boundary to the interior grid, reflecting the increased importance of minimizing wake losses when energy production is high. As the interconnect capacity rises above peak production levels, the optimized layouts for 60 and 65MW become similar to those found by maximizing AEP in Figure 2.

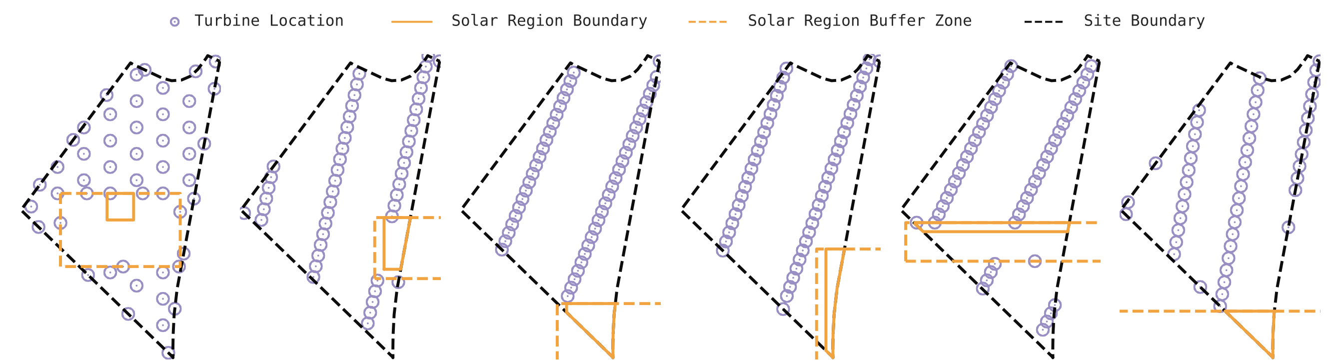
1 Conclusions

In this paper, we presented four distinct contributions. First, the idea of using parameterization to reduce the complexity and dimensionality of the hybrid layout optimization problem. Parameterization can also restrict generated layouts to those with certain desirable characteristics, such as a regular inner turbine grid and a consolidated solar patch. And we proposed a particular parameterization for the hybrid wind and solar plant problem. We proposed this parameterization as a starting point that can be extended and adapted to meet the needs of different decision makers, site types, and objectives. Next, we proposed the use of the evolution strategies class of derivative-free stochastic optimization algorithms to solve the parameterized layout problem. Evolution strategies are well-suited to this problem due to their nonconvex nature, the difficulty of generating derivatives from the objective function, high flexibility in the nature of the objective function, and evolution strategies' ability to generate a variety of high-performing candidate solutions. We proposed an adaptation of hard siting constraints to soft constraints and parameterized projections that make the problem amenable to derivative-free optimization. Then, we presented experimental results on four test problems demonstrating the ability of this approach to generate good optimized layouts for a variety of site types. Finally, we took a closer look at the optimization process and presented a brief tutorial on how to inspect, understand, and debug the parameterized derivative-free approach to solving the hybrid layout optimization problem. Our proposed approach shows a viable path for hybrid plant developers to easily generate efficient, maintainable, and aesthetically pleasing layouts using modest computational resources. Future work includes expanding the parameterization to include additional design pa-



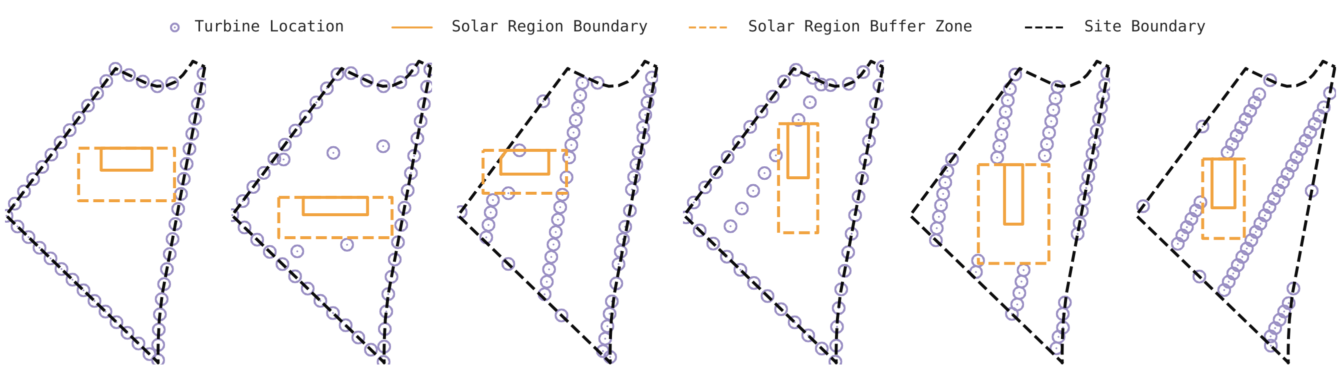
(a) Wind Rose (b) Baseline (c) Solution 1c (d) Solution 1d (e) Solution 1e (f) Solution 1f

Figure 1. CMA-ES solutions for the high-correlation location and circular boundary. Turbine locations are marked in purple, the solar region is drawn with an orange solid line, and the surrounding solar buffer zone is marked with a dashed orange line.



(a) Baseline (b) Solution 2b (c) Solution 2c (d) Solution 2d (e) Solution 2e (f) Solution 2f

Figure 2. CMA-ES solutions for the high-correlation location and irregular boundary.



(a) 40MW interconnect (b) 45MW interconnect (c) 50MW interconnect (d) 55MW interconnect (e) 60MW interconnect (f) 65MW interconnect

Figure 3. Solutions generated for the high-correlation location and irregular boundary for a range of interconnect capacities, maximizing mean interconnect utilization instead of AEP.

rameters such as wind and solar capacity mix, turbine type, and site size and shape; adding more detailed objective functions such as net present value and internal rate of return; and accounting for land use restrictions and costs.